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SUSTAINABLE UNIVERSITY BUILDING DESIGN WITH INTEGRATED 2-TUPLE WITH QFD

Deniz Uztürk

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SUSTAINABLE UNIVERSITY BUILDING DESIGN WITH INTEGRATED 2-TUPLE WITH QFD

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LIST OF SYMBOLS

ASHRAE	: American Society of Heating and Air-Conditioning Engineers
BEER	: Building Energy Efficiency Retrofit
BREEAM	: Building Research Establishment Environmental Assessment Method
CN	: Customer Need
DEMATEL	: The Decision -Making Trial and Evaluation Laboratory
DR	: Design Requirements
EPC	: Energy Performance Contracting
GB	:Green Building
HoQ	: House of Quality
I	: Importance of design requirements
ICT	: Information and Communications Technology
IR	: Interrelations of design requirements
LEED	: Leadership in Energy and Environmental Design
MCDM	: Multi-criteria Decision Making
MULTIMOORA	: Multi-objective optimization by ratio analysis plus the full multiplicative form
P	: Priorities of design requirements
QFD	:Quality Function Deployment
RM	: Relation Matrix
SB	: Sustainable Building
TOPSIS	: Technique for Order Preference By Similarity to Ideal Solution
VIKOR	: Viekriterijumsko Kompromisno Rangiranje

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ABSTRACT

The world faced numerous technological achievements, enormous natural resource usage and population growth since the industrial revolution. Nowadays, we start to see the after-effects of this gigantic growth of human species. Because of this effect, awareness for our planet earth has started. Sustainability has entered our lives.
In parallel to population increase all over the world, the concept of resource efficiency is entering local agenda. One of the fields where resources are intensively used is buildings. Humans affect the environment they live in and construct spaces to sell and work. Buildings considerably affect their environment and are responsible for roughly one-sixth of fresh water use, one-quarter of its wood harvest, and two-fifths of its material and energy flows. The impacts caused by buildings are not limited to the location where they are located and directly or indirectly affect soil, water and air quality, ecosystems.

In a world where awareness about sustainability continues to rise rapidly in every industry, investigating sustainable building (SB) is a very promising area of work. This area is ready for new developments to achieve high-level green technologies aiming at the comfort and health of the stakeholders. Stakeholder expectations provide valuable data for the design of a building. These expectations are like a customer requirement for a product design. At this point, the most critical issue is making the design according to customer expectations. To realize this goal, a very well-known approach, called Quality Function Deployment (QFD), can be useful, which is available for translating customer needs into design parameters.

The main objective of this M.S. thesis is to analyse end user preferences for sustainable building with QFD approach. Normally, the QFD approach is a way to gain insight about customer expectations to uncover the positive quality requirements for the product.

In our case, customer requirements are buildings' stakeholder's desires and the design parameters are our technical requirements. The main idea is to have a user-friendly SB design. To accomplish a QFD-based SB design approach, it will be applied to a university building, which will be given in the next sections.

2-Tuple is chosen as a technique to study in this M.S. thesis. Detailed literature survey about 2-Tuple was made to see the different application areas for 2-Tuple linguistic representation. Due to this detailed literature survey; the advantages of 2-Tuple method are detected to use it in multi-criteria decision making (MCDM) problem. 2-Tuple's easy computational steps and its strength against loss of information, provide a good environment to handle the impreciseness and multi-granularity of linguistic data in MCDM.

To test its advantages and plausibility, 2-Tuple model is applied with QFD method for university buildings. As a result of this application, the ranking of the technical requirements for a user-friendly sustainable university building are obtained. The first three requirements are "Absorptive and reflective surfaces and materials into the space", "LED Lightings" and "Contributing community on that site".

ÖZET

Dünya, sanayi devriminden beri çok sayıda teknolojik gelişme, muazzam doğal kaynak kullanımı ve insan nüfusu büyümesi ile karşı karşıya kalmaktadır. Günümüzde, bu büyük büyümenin artçıl etkileri gözlemlenmeye başladı. Bu etkiler sonucunda, gezegenimiz için yeni bir bilinç gelişmeye başladı. Bu bilinçle birlikte sürdürülebilirlik hayatımıza girdi. Dünya'nın her yerinde insan nüfusunun büyümesine paralel olarak kaynakların verimli kullanımı konsepti her bir ülkenin yerel gündemine yerleşti. Kaynakların verimli kullanımının büyük önem taşıdığı bir sektör de inşaat sektörüdür. İnsanoğlu bulunduğu alanı değiştirerek, yaşayacak ve çalışacak yerler inşa etmektedir.

Bu binalar da çevreyi değiştirerek, bulundukları alanda bazı değişikliklere yol açmaktadır. Bu etkiler sadece bulundukları bölgelerle sınırlı kalmamakta ve direkt veya endirekt olarak toprağı, suyu ve hava kalitesini, ekosistemi etkilemektedir.
Her bir endüstri için sürdürebilirlik üstüne bir bilincinin hızla büyüdüğü bir dünyada, sürdürülebilir binalar (SB) üzerine çalışmalar yapmak gelecek vadeden bir çalışma alanı olmaktadır. Bu alan, paydaşlarının rahatı için yüksek seviye yeşil teknolojilere ulaşmak için gelişmelere açık bir alandır. Paydaşların istekleri tasarım aşamasında çok önemli bilgiyi oluşturmaktadır. Bu beklentiler, istekler bir ürünün tasarımındaki müşteri gereksinimleri kısmına denk gelmektedir. Bu durumda, önemli olan nokta bu gereksinimleri göz önünde bulundurarak bir tasarım yapmak olmaktadır. Bu amacı gerçekleştirmek için ise, Kalite Fonksiyon Göçerimi (KFG) olarak bilenen yöntem, kullanmak çok yararlı olacaktır. Zaten KFG yönteminin müşteri gereksinimlerini teknik gereksinimlere aktarmadaki gücü yaygın olarak bilinmektedir.

Bu tezin asıl amacı, son kullanıcı gereksinimlerini belirleyerek, KFG metodu yardımıyla sürdürülebilir bir bina tasarımını yapmaktır. Normalde, KFG yöntemi, belirli bir ürün ya da servis için müşteri isteklerini kalite gereksinimleri olarak ürüne veya servise aktarmada kullanılmaktadır. Ama bu tezde KFG yöntemi bir bina tasarımı için kullanılacaktır.

Uygulamada, müşteri gereksinimleri binanın paydaşlarının isteklerinden oluşacak ve tasarım gereklilikleri de teknik kriterleri oluşturacaktır. KFG temelli bir SB tasarımı yapabilmek için ise bu yöntem üniversite binasına uygulanacaktır.
İkili sözel gösterim yöntemi bu tezde KFG içinde uygulanacak teknik olarak seçilmiştir. 2-Tuple hakkında detaylı bir literatür taraması yapılmış olup, bu tarama sonucunda ikili sözel gösterim yönteminin çok değişkenli karar verme (ÇDKV) problemlerinde kullanılmasındaki avantajlar belirlenmiştir. Sahip olduğu kolay hesap adımları ve bilgi kaybını önlemedi gücü sayesinde ikili sözel gösterim yönteminin ÇDKV probleminde kullanılmasına karar verilmiştir.

Bu avantajlarını test etmek için de, KFG ile üniversite binası tasarı konusunda uygulaması yapılmış ve sürdürülebilir üniversite binası için teknik gereksinimlerin sıralaması yapılmıştır. Bu uygulama sonucunda ilk üç gereklilik şu şekilde ortaya çıkmıştır. “İçerisi için yansıtıcı ve emici yüzeylerin, materyallerin kullanımı”, “LED ışıklandırma” ve “Bölgedeki topluma katkıda bulunma”.

1 INTRODUCTION

Sustainability become of the important trending notions in our century with the rising awareness about the human effects on our earth. When it comes the concept of sustainability, the concept is addressed in three different dimensions such as, environmental, economic and social. These three notions are the three main components of sustainability. The main purpose in these components is to be stable or sustained in any situation. For this purpose, efficient usage of economic, environmental and social sources is very important.

Sustainability could be a good strategy or a path to follow for any industry to achieve a durable and adaptable system. In construction sector where there is non-stop activity to build new environment, sustainability is a very big necessity to have business continuity. Since the existence; human kind has a huge instinct to create its own environment to live and work. While building, new environments create its own different system that affects the other ones around it. Even today, human continue to construct new buildings and environments; however, its after effects are getting stronger than before. Sustainable buildings (SB) are on the table to minimize these after effects newly built environments.

SB requires a new architectural approach that seeks to reduce the overall adverse impacts of buildings by aiming at better resource efficiency, such as lower use of materials, energy, and development space over the lifetime of buildings.

Sustainable architecture, in this sense, considers a variety of parameters for a more conscious design and planning that conserves energy, water and other natural resources within the built environment. When you think of sustainable building; economical, environmental and social aspects of the construction projects must be evaluated separately.

At this point environmental evaluation phase is one of the important parts of the assessment where all the energy and resource efficiency is placed.

In the building sector, realization of sustainable building remains at a low rate, despite the increased need for it (Kang, 2015). This low rate is a consequence of challenges of environmental and economic issues. To achieve an appropriate level of sustainability in a building, some principles must be applied such as (Verkehr, 2001):

- Lowering the energy demand and the consumption of operating materials
- Utilization of reusable or recyclable building products and materials
- Extension of the lifetime of products and buildings
- Risk-free return of materials to the natural cycle
- Comprehensive protection of natural areas and use of all possibilities for space-saving construction

For some these principles could be challenging and hard to apply. Although a prioritization of these principles could be done to achieve a sustainable building step by step. For this purpose, the needs and the requests of the building's stakeholders could be good guidance how to prioritize the sustainability principles for a building.

Including stakeholder preferences is a complicated path where different opinions should be developed from various sources. At the end, they should unify to accomplish a sustainable design for a building. For this aim, it exists different analytical approaches exist in the literature.

Different multi criteria decision making (MCDM) approaches could be used to handle the complications of this application. In this M.S. thesis, Quality Function Deployment

Method (QFD) is chosen to translate stakeholders' requests into building design requirements.
As known, QFD is a very strong and easy-to-use method for developing, planning and designing stage for a company to produce a product or a service (Akao, 2004).
Furthermore, in MCDM problems, decision makers frequently need to express their opinion with linguistic variables. Using linguistic variables provide them to be more objective and flexible for their evaluations.

In every industry, engineers or managers always faced to cases where they need to decide which the best for the product or company is. In a world like this, 2-Tuple linguistic representation model is a useful tool to simplify these decision-making cases. It has many advantages and widely used model in recent years. That is the reason why it has been chosen as a technique to study in this study.

On the other hand, in a world where sustainability continues to rise rapidly in every industry, investing sustainable building is a very open area and not enough studies have done about this subject. This area is ready for new developments to achieve high-level green technologies with the comfort and health of the stakeholders. So, to have great balance between green, comfort of the stakeholders and technical requirements QFD is one of the good models to practice where it is an easy method to transform linguistic data to the engineering data. There are not so much studies in the literature from recent years, about QFD and sustainable building together. As a result, this application area is chosen to study in this Master of Science (M.S.) thesis.

The aim of the study is to provide an integrated 2-Tuple with QFD method for a sustainable university building design.
The originality of this study comes from its application area of sustainable university building for integrated 2-Tuple with QFD methodology for the first time.

The remaining parts of this M.S. thesis are organized as follows: The following section presents literature review for SB, QFD and 2-Tuple linguistic approach. In Section3, methodology of the study is given with the computational steps. Latter the case study for the proposed methodology for a sustainable university building design is given with the detailed requirement explanation and with the discussions and results of the applied case study are given. Finally, conclusions and perspectives are given in the last section.

2 LITERATURE REVIEW

In this M.S. thesis, main purpose is to detect the end-user preferences and their design requirements with a detailed literature review then choose important design requirements with a QFD method. For this purpose, first a detailed literature survey was made to learn about the works that have been done in this area. 2-Tuple linguistic representation method is also chosen as an analytical method to study within this M.S. thesis with QFD.

First, the research has been made in SB subject to see purposes and topics of the studies in this area. Also, this literature research about SB, gave too much idea while detecting end-user requirements for a SB. Then a complete research was made to see tools used in SB subject. Different MCDM tools have been applied to this subject. According to all these academic and applied cases, requirements in the QFD method have evolved.
Second part of the literature review is about the studies about SB with QFD application. Latter is for 2-Tuple method. Detailed research was made to find out what kind of analytical methods are used with 2-Tuple representation and which subjects are chosen to study with these methods. This research provides us to choose the most suitable and less used method with 2-Tuple within the sustainable building subject.

2.1 Sustainable Building

Sustainability is defined as the quality of not being destructive for the environment or natural resources (Dictionary, 2010). Furthermore, it aims to support long-term ecological balance. When it comes to SB, the main purpose stays the same: creating the building which is not harmful to its environment.

Actually, being less harmful to the environment is the "green" notion of the SB, yet it still has two more notions to accomplish which are "economic" and "social". In a SB these three notions need to be emphasized to have a good SB design.

Sustainable construction is a responsible management of unpolluted built environment with resource efficient and ecological principals (Benzu, 2010). This is the basis of a good quality SB design.

SB design and construction some main issues and challenges. These issues should be well planned and designed during and before construction. These issues are (UNEP, 2001):

- Management and Design
- Product and Building Performance
- Energy and Resource Consumption
- Urban Energy Efficiency
- Urban Eco-Efficiency
- Planning and Decision Making Process

Management and Design is very important due to its key role to every single stakeholder of the building. Generating new architectural aspects, consistent education and training for the human resources, developing the environmental quality and making further researches for sustainable building design are the fundamental components of the management and design.

Product and Building Performance is crucial because, new products and a good performance of the building are crucial for the development of sustainability (UNEP, 2001).

Energy and Resource Consumption, is the principal action to conserve ecosystem. By taking into consideration of life-cycle of materials and with use of recycled materials it is easy to achieve a good SB design.

Urban Energy Efficiency is a challenging issue in SB design; because for this phase different variety of actions is need to be considered. Energy efficiency should be maintained during construction, retrofitting, transportation and building planning (UNEP, 2001).

Urban Eco-Efficiency is very critical to improve as a strategy for sustainable development within cities and communities (UNEP, 2001). Supporting the developments for the performance of individual communities, companies and facilities for sustainability development is the principal aim and consequence of the urban eco-efficient strategy.

Planning and Decision Making Process is the stage where the new and applicable sustainability strategies should evaluate. Different variety of elements need to be considered for this phase and challenging decision making processed need to be achieved to reach good quality sustainability strategy.

In reality, hole system of SB design is a complex decision making process. To be able to handle this process different techniques of decision making could be used to improve the system. Decision making mechanisms have been applied to SB in the literature. Beside that studies; different selection methodologies have also been applied to this subject.

In the literature, the concept of SB is a part of studies that deal with sustainable materials for the design in 2005 (Godfaurd, Clements-Croome, & Jeronimidis, 2005). Another field is eco-cities in also 2005 (Crabtree, 2005). Through the following years, studies about material selection have been an important part of SB literature (Thormark, 2006; Castro-Lacouture et al., 2009; Akadiri, Olomolaiye, & Chinyio, 2013; Marzouk et al., 2013). Subsequently, mobile rating systems have started in related research, where rating systems are introduced to standardize SB design and retrofit processes. There are various mobile SB assessment models in different forms, including models introduced by renowned architecture and engineering firms. Well-known models in this genre can be described as ‘private governance’ initiatives. Some of the widely-recognized examples of these SB design systems are the Building Research Establishment Environmental Assessment Model (BREEAM), the Leadership in Energy and Environmental Design (LEED), ASHRAE Green Guide, GreenCalc, Green Star and GB Tool (Faulconbridge, 2015).

With all of these different rating systems, studies tackled with the question of which one to use or how to evaluate them (Kibert & Charles, 2007; Haapio & Viitaniemi, 2008; Erten, 2010; Pushkar & Shaviv, 2016). Following the concept of rating systems, other models seeking SB retrofit cases start to emerge. Designing new buildings still have their importance; but on the other hand turning existent buildings into "green" structures have become an important subject in the literature (Juan, Gao, & Wangc, 2010; Xu, EdwinHon-WanChan, & Qian, 2011; Olander, 2015; Xu et al., 2015).

Designing new SB has a particular importance throughout the years and a lot of studies and analyses are carried out about this subject (Häkkinen, 2007; Gram-Hanssen & Jensen, 2008; Simmon, 2010; Zhou & Chen, 2010; Fujita & Takewaki, 2011; Wood et al., 2014; Mansour & Radford, 2016; Wu, Ng, & Skitmore, 2016; Shafaghat et al., 2016). With designing SB, new works have done in recent years about specific areas such as indoor design and day lighting for buildings (Shafaghat et al., 2015; Junjie et al., 2015; Wei, Ramalho, & Mandin, 2015; Yu & Su, 2015).
Yet, no studies have been done about end-user requirements in a university building where it has many everyday occupants. That is why a university case is chosen to apply in this study.

2.2 Sustainable Building and QFD

QFD was first introduced by Shigeru Mizuno and Yoji Akao at the end of 60's. In the field for Customer Needs (CNs) QFD is a strong approach with good applications. (Akao, 2004). Various studies discussed QFD and its applications in different areas. The main idea of QFD approach is how to balance CNs. Prearranging CN is the main and first step for QFD. In this study it will be used to design a sustainable university building. For this purpose, a detailed research about SB and QFD applications has been made.

Generally, the main idea of QFD is a usage for SB is to design a sustainable building envelop. Two different studies about envelop design have been made in the literature in 2013 and 2015 by using HoQ for assessing building envelops (Singhaputtangkul et al., 2013) and proposing a decision tool for envelop evaluations (Singhaputtangkul et al., 2015). Also in 2015 HoQ of QFD has been used to design a green hospital with its stakeholders (Wood et al., 2014). Also in 2014, QFD has been used as a decision making tool for retrofitting cases (Menassa et al., 2014).

There is very little work done on this area, as you can see from the research done. There is no study for the complete design of a building that is particularly sustainable by user preferences. This study area and method were chosen because of this lack in the literature.

2.3 2-Tuple Linguistic Approach

This model is first represented by Herrera and Martinez in 2000 (Herrera & Martinez, 2000). Later, many recent studies discussed the approach.

The 2-tuple linguistic model and its extensions have been applied to a wide variety of topics, mainly for decision-making and decision analysis problems (Herrera, Martinez, & Sanchez, 2005). These applications range from evaluation processes for different aims to industrial ones passing by resource management, Internet based purposes, human resources and so on. Different analytical techniques are used with 2-Tuple to study these subjects

2-Tuple model is a useful way to deal with different forms of linguistic information. For this purpose, in 2001, Herrera and Martinez represented its advantages and computational steps to deal with multi-granular linguistic information (Herrera & Martínez, 2001). Also, its advantages and computational steps to deal with non-homogenous information were given in (Herrera, Martinez, & Sanchez, 2005). Later

the application area of 2-Tuple model was evaluated within different application areas such as engineering evaluations (Martinez et al., 2007), safety and cost analysis (Martínez et al., 2005) and sensory evaluations (Martinez et al., 2007) by Martinez and Herrera.
These applications have lead up novel studies in the evaluation process such as evaluation model for intellectual capital of enterprise (Tai & Chen, 2009), supplier evaluation (Karsak & Dursun, 2015).

Also, fuzzy linguistic is a very widely used methodology with 2-Tuple method. Different variety of subjects are studied with fuzzy linguistic have been evaluated with 2-Tuple model. In 2013, cooperate social responsibility assessment (Costa & Menichini, 2013)and new product development (Tsai & Chen, 2013)was made with common application of 2-Tuple and fuzzy linguistic together. Afterwards in 2014, evaluation of RFID technologies in supply chain (Chuu, 2014) has been studied within the application of fuzzy linguistics with 2-Tuple. Later in 2015, fuzzy linguistic is used to improve customer service time table in ICT sector (Andrés et al., 2015) and hesitant fuzzy is used with 2-Tuple in developing a web tool for decision making in housing market (Montes et al., 2015). And recently, in 2016 fuzzy linguistic has been used with 2-Tuple model in environmental impact significance assessment (YelenyZulueta et al., 2016).

As the application area expands, it is being used in different analytical MCDM methods in evaluations such as VIKOR in HR evaluation methodology (Liu & Wu, 2012).
VIKOR method is one of the most preferred method with 2-Tuple in literature with selection problems. It is applied in material selection problem (Liu, Liu, & Wu, 2013) site selection for waste management (Liu et al., 2014). Another preferred MCDM method with selection problem with 2-Tuple is TOPSIS. It has been used in robot evaluation and selection (Liu et al., 2014) and personal selection (Dursun & Karsak, 2010)subjects.

Other MCDM methods have been also used with 2-Tuple technique such as DEMATEL in calculation CO_2 capture in iron and steel industry with Delphi method (Quader et al.,

2016) and in health-care waste treatment with MULTIMOORA (Liu et al., 2015). Also, MULTIMOORA has been studied with 2-Tuple in health-care waste treatment selection and SERVQUAL-SICTQUAL is studied with 2-Tuple in quality service in ICT sector One example of QFD utilization with 2-Tuple exists in the literature (Andrés et al., 2015). Its study area is supplier evaluation and selection (Karsak & Dursun, 2015).

With all these several types of MCDM study done with 2-Tuple model is widely open area to study. Due to its compatibility with decision-making problems 2-Tuple is a preferred model for using with different MCDM tools. In this study; it is decided to use with QFD method due to the lack of studies with the combination of 2-Tuple and QFD. All the advantages of 2-Tuple for dealing with multi-granular data and dealing with linguistic information will be useful to apply in with QFD on the sustainable building subject.

3 METHODOLOGY

3.1 Proposed Approach

In this M.S. thesis an integrated 2-Tuple with QFD method is proposed to apply for a sustainable building design. QFD approach is applied to rank the design requirements for sustainable building according to the end-user preferences of the building's stakeholders. The main aim to use 2-Tuple technique within the QFD method is to eliminate the loss of linguistic information during the calculations and avoid the complications as a consequence of multi-granular data caused by different evaluations from different experts. In this section first the computational steps of QFD with 2-Tuple will be given, later 2-Tuple's steps and definitions will be explained in details and finally computational steps of proposed methodology will be given. The Figure 3.1summarizes the steps of the proposed methodology.

3.2 Quality Function Deployment

In the field for reflecting the CNs on product design QFD is a famous approach (Akao, 2004). Numerous studies discussed QFD and its applications in different areas. The main idea of QFD approach is how to balance CNs. Prearranging CNs is the main and first step for QFD.

In the construction of HoQ, group of decision makers are involved to every step of the process, and they are required to give their opinions about the importance of CNs, correlations between DRs, and relationships between CNs and DRs. Therefore, the QFD analysis process is a typical group decision making problem (Li, 2012).

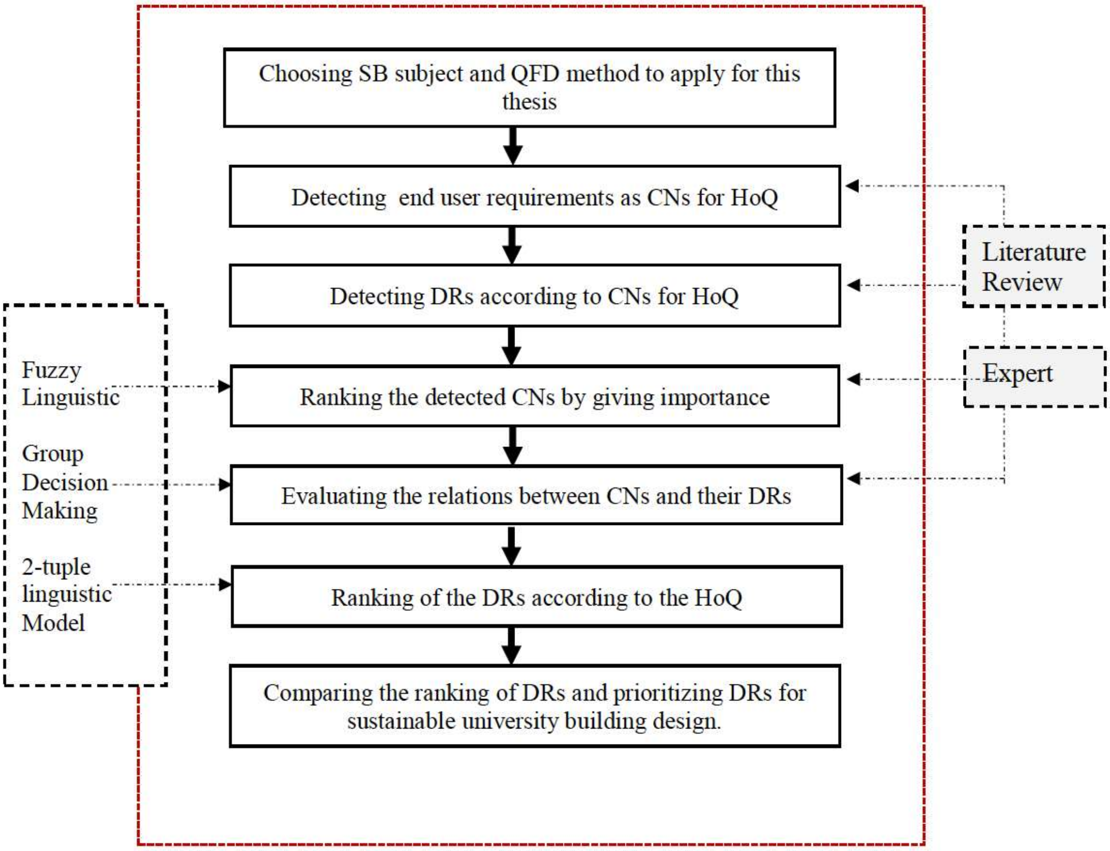

Figure 3.1 Steps of proposed methodology

Due to its closeness to the group decision making process and its soft computing steps HoQ is chosen to apply in this study and Figure 3.2shows the parts of the HoQ and the parts will be explained in detailed as follows (Akao, 1990):

- CN: This part called customer needs. The initial step to construct a HoQ is to determine the customer needs. CN guides to determine product or service's properties according to customer.
- I: This part is the importance of the customer requirements. It indicates their importance relatively with each other. In a short way, it is the rating of the customer requirements for a product or a service.
- DR: This part is design requirements. It is all the engineering needs for the customer requirements. They are directly related to the customer needs.

- RM: This matrix is the main part of the HoQ; because it is the stage where all the relation between DRs and CNs are investigated.

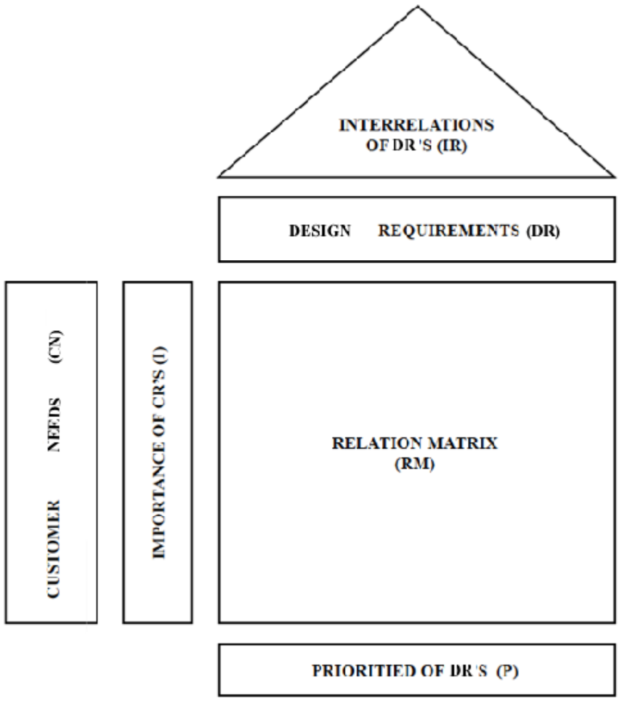

Figure 3.2 House of Quality

- IR: The roof of the HoQ is for the interrelations of technical requirements. It shows the inner dependencies between DRs.
- P: This is the results obtained from the HoQ steps. It gives the overall ranking of DRs according to the customer needs.

The mains steps of calculating the DRs with HoQ of QFD are as follows (AUT University):

1. *Voice of the customer:* The first step in a QFD project is to identify who the customers are. Then the decision maker (DM) team gathers information from customers on the requirements they have for the product or service. That information will produce a data for CN section for the HoQ. In this study this part will use the data from the experts and literature review which contains information about green requirements for a warehouse.

2. *Regulatory Requirements:* Not all product or service requirements are known to the customer, so the team must add to document strictly obligated requirements or regulatory. In this study customers are the experts and literature research so the requirements are generated according to them.
3. *Customer Importance Ratings*: Customers rate the importance of each requirement then this importance will be used in relationship matrix. In this study, three different experts give importance of CNs with different linguistic sets, then the aggregation of three experts evaluation will be used as an importance weight in the relation matrix.
4. *Customer Rating of the Competition:* Understanding how customers rate the competition can be a tremendous competitive advantage. In this step asking the customers about the rating of the product or service in relation to the competition, is a good idea. In this study, competition part of the HoQ will not be used for the calculations.
5. *Technical Descriptors - "Voice of the Engineer":* Technical descriptors may exist that your organization is already using to determine product or service specification, however new measurements can be added to ensure that your product is satisfying customer needs. These are the engineering requirements for a product or a service.
6. *Direction of Improvement:* After defining the technical descriptors, the direction of each descriptor must be made. In this study, directions will not be used in the calculation; because all descriptors have same directions.
7. *Relationship Matrix:* The relationship matrix is the area where the relationship between CNs and the company's ability is determined by the decision makers. The team asks the question, "what is the strength of the relationship between the technical descriptors and the CNs?" Relationships can both be weak, moderate, or strong and carry a numeric value of 1, 3 or 9. In this study, relationship between the requirements are more complicated than being symbolised with numeric values or three level linguistic scale; so, every expert expressed themselves in different linguistic scales and the relation between CNs and DRs are shown with 2-Tuple linguistic form. Also, the calculations are made with 2-

Tuple linguistic information for not having a loss of information between various stages during the calculations.

8. *Organizational Difficulty:* This part is for rating the DRs in terms of organizational difficulty. Some DRs could conflict with each other and that can cause a difficulty. In this study, organizational difficulty is not needed to have the relative importance for the DRs.
9. *Technical Analysis of Competitor Products:* Team conducts a comparison of competitor technical descriptors for a better understanding for the competition. This process involves reverse engineering competitor products to determine specific values for competitor technical descriptors. In this study, there exists no parts for competition; because there is no competitor in a sustainable building design.
10. *Target Values for Technical Descriptors:* At this stage, the QFD team begins to establish target values for each DR. Target values represent "how much" for a DR, but in this study, there is no need for quantitative targets for each DR. The main idea is just accomplishing them in a level of sustainable building design.
11. *Correlation Matrix:* This is the part where all the relations between DRs are examined. Negative relations between DRs must be well examined to reduce the physical contradictions later. In this study, there is no need for a roof matrix due to the parallelism of the DRs.

3.3 2-Tuple Linguistic Representation Model

In real world, vagueness and imprecision are the problems that we deal with when it exists linguistic input for a problem in a case. Most of the cases, experts who are part of these problems, use linguistic descriptors to handle these problems; but sometimes these linguistic descriptors are not enough to eliminate this uncertainty and vagueness. Therefore, the use of linguistic modelling; in problems dealing with non-probabilistic uncertainty seems logic and has produced successful results in different fields such as: situation awareness, decision models, information retrieval, risk assessment, engineering evaluation, sensory evaluation, performance appraisal, recommender systems, data mining, and social choice. (Martinez & Herrera, 2012)

First, the probabilistic methods have been proposed to handle the impreciseness of linguistic data; but in some cases, probabilistic approaches haven't been enough to translate linguistic data directly into numbers (Mendel et al., 2010). At this point, fuzzy logic process has been proposed to turn the linguistic information into quantitative data manipulatively (Mendel et al., 2010). This manipulative process is called translation in computing with words (CW) (Herrera & Martinez, 2000). Another important step in CW is the retranslation process where most of the losses of information are in this phase where the quantitative data is turned into linguistic form (Herrera & Martinez, 2000). The loss of information while retranslating the information is the reason of the outliers in the resulting data; to eliminate this loss of information 2-Tuple linguistic method is proposed. (Herrera & Martinez, 2000)

- *Definitions and Equations for 2-Tuple Linguistic Representation:*

The 2-tuple fuzzy linguistic representation model represents the linguistic information by means of a 2-tuple, (S, α), where
S is a linguistic label;
α is a numerical value that represents the value of the symbolic translation (Herrera & Martínez, 2001).

Definition 1 (Herrera & Martinez, 2000)*:* S the linguistic label is defined at once and it is used to express the linguistic levels.
A linguistic label set, which is $(g + 1)th$ level, has its components as following:

$$(S_{g+1} = \left(S_0, S_1, S_2, \dots, S_i, \dots S_g\right)) \tag{3.1}$$

- Linguistic label set is shown as fuzzy triangular numbers ($S_i = (a_i, b_i, c_i)$) and it is defined as defined as in Eq. (3.2).

$$\begin{cases} a_i = 0; \\ a_i = \dfrac{i-1}{g}, 1 \le i \le g \\ b_i = \dfrac{i}{g}, 0 \le i \le g; \\ c_i = \dfrac{i+1}{g}, 0 \le i \le g-1 \\ c_g = 1 \end{cases} \tag{3.2}$$

For every linguistic label set a_i, b_i, c_i values will be differed. They will be calculated with Eq. (3.2).

For 5 level linguistic set;

The label set is defined as; $S_5 = \{S_0, S_1, S_2, S_3, S_4\}$ and the values for $S_0 = (a_0, b_0, c_0)$, $S_1 = (a_1, b_1, c_1)$, $S_2 = (a_2, b_2, c_2)$,$S_3 = (a_3, b_3, c_3)$, $S_4 = (a_4, b_4, c_4)$

When the values for a_i, b_i, c_i are calculated with Eq. (2);

$$S_5 = \{(0,0,0.25), (0,0.25,0.5), (0.25,0.5,0.75), (0.5,0.75,1), (0.75,1,1)\}$$

are obtained for label set with 5 level. The set is represented in the graph as it is in Figure 3.3.

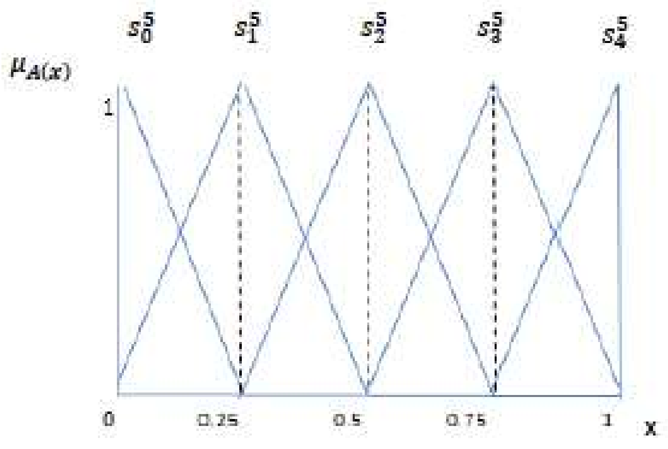

Figure 3.3 Graph of the label set with 5 level

- Symbolic translation value(α), is defined between the values $[-0.5, 0.5)$ and it show the deviation from the main basic linguistic label sets.

For example, for a linguistic label set with 6 level, the representation of $(S_3, -0.2)$ is shown in the Figure 3.4.

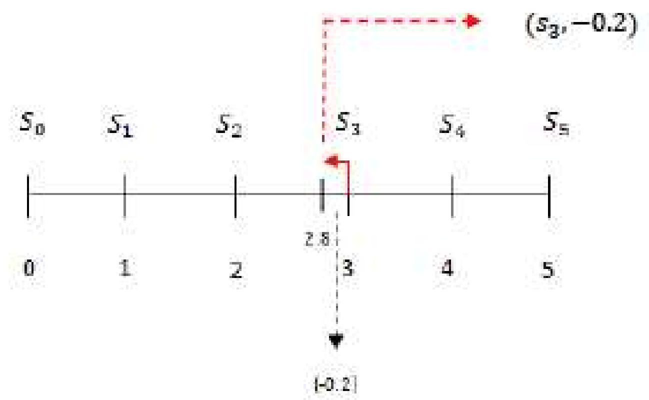

Figure 3.4 Representation of αin 6 level linguistic label set

Definition 2 (Martinez & Herrera, 2012): Let β be the result of an aggregation of the indices of a set of labels assessed in a linguistic term set S, i.e., the result of a symbolic aggregation operation. $\beta \in [0, g]$, being (g+1) the cardinality of S.
Let $i = round\ (\beta)$ and $\alpha = \beta - i$ be two values, such that, $i\epsilon[0, g]$ and $\alpha\epsilon[-0.5, 0.5)$. According to these definitions the equation for a 2-Tuple representation is defines as in Eq. (3.3).

$$\Delta: [0, g] \quad \rightarrow \quad \mathcal{S} \times [-0{,}5{,}0{,}5)$$
$$\Delta(\beta) = \begin{cases} Si & i = round(\beta) \\ \alpha & \alpha \in [-0{,}5{,}0{,}5) \end{cases} \tag{3.3}$$

where round is the usual rounding operation, S_i has the closest index label to "β," and "α" is the value of the symbolic translation (Martinez & Herrera, 2012).

Example:

Let us suppose a symbolic aggregation operation over labels assessed in $S_5 = \{S_0, S_1, S_2, S_3, S_4\}$ that obtains $\beta = 3.68$ as its result, then the representation of this counting of information by means of a 2-tuple will be (Herrera & Martínez, 2001):

$$\Delta(3.68) = (S4, -0.32) \tag{3.4}$$

As it shown in the Eq. (3.4) $i = rou \quad (\beta)$and $round(3.68) = 4$ then $i = 4$. The symbolic translation value is the deviation from S_4 and it is -0.32. When the label set is represented as linguistic variables;

$S_5 = \{None, Low, Medium, High\ , Perfect\}$ the $\beta = 3.68$ is also could be represented as $(Perfect, -0.32)$. The graphical representation of the $\beta = 3.68$ is shown in the Figure 3.5.

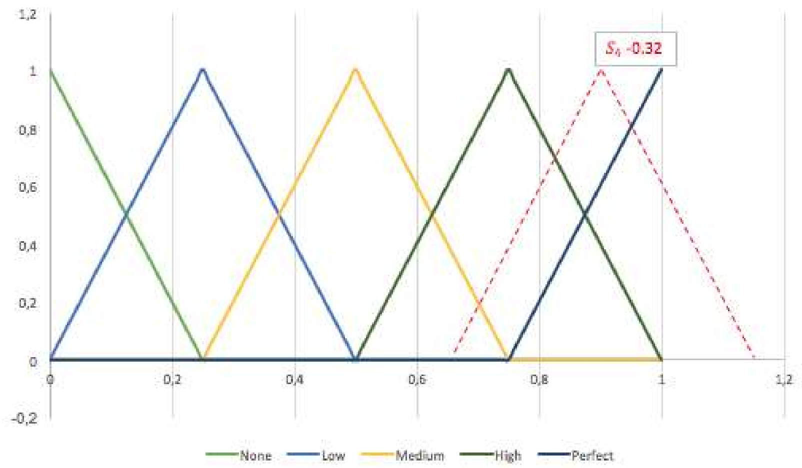

Figure 3.5 Example of 2-tuple representation in 5 level label set in graph

Definition 3 (Herrera & Martinez, 2000)*:* The comparison of linguistic information represented by 2-Tuples is carried out according to an ordinary lexicographic order.

Let (S_i, α_i) and (S_j, α_j) be different 2-Tuple values. Their comparison will be done with these rules in Eq. (3.5):

- If $i < j (S_i, \alpha_i)$then is smaller than (S_j, α_j)
- If $i = j$ then

1. If then $\alpha_i = \alpha_j$then$(S_i, \alpha_i) = (S_j, \alpha_j)$
2. If $\alpha_i < \alpha_j$ then $(S_i, \alpha_i) < (S_j, \alpha_j)$ (3.5)
3. If $\alpha_i > \alpha_j$then $(S_i, \alpha_i) > (S_j, \alpha_j)$

Definition 4: When there is a negation, 2-Tuple is calculated as it is in Eq. (3.6).

$$Neg(S_i, \alpha_i) = \Delta(g - (\Delta^{-1}(S_i, \alpha_i))) \tag{3.6}$$

Definition 5 (Herrera & Martinez, 2000)*:* Aggregation operators for linguistic 2-Tuple model are to combine the information in 2-Tuple according to altered criteria.

Arithmetic Mean:

This aggregation operator is a classical aggregation operator for 2-Tuple. It is defined as in Eq. (3.7), where $\{(r_1, \alpha_1), \dots, (r_n, \alpha_n)\}$ is a set of 2-Tuples and $\vec{x}$ is their arithmetic mean.

$$\vec{x} = \Delta\left(\sum_{i=0}^{n} \Delta^{-1}(r_i, \alpha_i)\right) = \Delta\left(\frac{1}{n}\sum_{i=1}^{n} \beta_i\right) \tag{3.7}$$

Weighted Average Operator(WAO):

This weighted aggregation operator, provide us to combine values with different importance. Weighted average operator is defined as in Eq. (3.8) where $\vec{x}$ is the weighted average of the 2-tuple set $\{(r_1, \alpha_1), \ldots, (r_n, \alpha_n)\}$ and $\{(w_1, \alpha_1), \ldots, (w_n, \alpha_n)\}$ are the 2-tuple weights of each value in 2-Tuple set.

$$\vec{x} = \left(\frac{\sum_{i=1}^{n} \Delta^{-1}(r_i, \alpha_i) \times \Delta^{-1}(w_i, \alpha_i)}{\sum_{i=1}^{n} \Delta^{-1}(w_i, \alpha_i)}\right) = \Delta\left(\frac{\sum_{i=1}^{n} \beta_i \times w_i}{\sum_{i=0}^{n} w_i}\right) \tag{3.8}$$

Ordered weighted Aggregation (OWA) Operator:

OWA operator is preferred when the weights are associated to a fixed position and it is defined as it Eq. (3.9) where $\{(r_1, \alpha_1), \ldots, (r_n, \alpha_n)\}$ is a set of 2-tuples and $\{w_1, \ldots, w_n\}$ is the weight vector that satisfies:

1) $w_i \in [0,1]$ and
2) $\sum w_i = 1.$

$\mathcal{F}$ (OWA operator) is computed as:

$$\mathcal{F}\big((r_1, \alpha_1), \ldots, (r_n, \alpha_n)\big) = \Delta\left(\sum_{j=1}^{n} w_i \cdot \beta_j^*\right) \tag{3.9}$$

Where, $\beta_j^*$is the jth largest value of the β_i values.

Definition 6: Dealing with non-homogenous information without loss of information, is the one of the most important advantages of 2-Tuple representation model. Different methods are used to translate different values in different forms; such as intervals, numerical values and fuzzy numbers; into 2-Tuple form.

Transformation of non-homogenous data (Çelebi, 2014)*:* Let N be a numerical value, an interval, a triangular fuzzy number. The transformation of N into 2-tuple linguistic label set if computed as in Eq. (3.10).

$$\tau\ : [0,1] \rightarrow F(Sg+1)$$
$$\tau\ (N) = \{(s_i, \alpha_i) | i \in [0,1 \dots g]\} \tag{3.10}$$
$$\alpha_i = max_y min\{\mu_N(y), \mu_{Si}(y)\}$$

Here, $\mu_N(y)$ *and* $\mu_{Si}(y)$ are the membership function values of N and s_i respectively. Then the transformation of 2-Tuple label set into 2-Tuple representation model is computed as in Eq. (3.11).

$$X: F(St) \rightarrow [0, g]$$
$$X(F(S_t)) = X\left[(s_{i,}, \alpha_i)\ i\ \in [0,1, \dots g]\right] = \sum_{i=0}^{g} i\alpha_i \Big/ \sum_{i=0}^{g} \alpha_i\ =\ \beta \tag{3.11}$$

On this study for the application of the methodology, 2-Tuple linguistic label sets will be used to evaluations for each expert. 2-Tuple linguistic sets are chosen because of their accuracy and to be able to make proper and more exact translation during calculations.

3.4 Integrated 2-Tuple with QFD

In this study, integrated 2-Tuple with QFD method is chosen to study due to its good applications in translating customer needs into design requirements. 2-Tuple QFD corroborate with the usage of numerical values, intervals and fuzzy numbers and linguistics. However, in this study only the fuzzy linguistic will be used with 2-Tuple linguistic label sets due to their accuracy and to provide a flexible environment to experts during their evaluations. The computational steps of 2-Tuple QFD is as follows:

1. Assigning an objective of the study. Then defining a problem related to it. After; detect requirements for this objective and form a decision making (DM) group to solve the problem.

2. Selecting a linguistic comparison scale for each decision maker to represent their own opinion about the problem assigned. Different scales could be chosen according to the experience of experts in the case study. Table 3.1, Table 3.2and Table 3.3 show the different scales for different experts with their triangular numbers.

Table 3.1 Label Set for First Expert (Herrera, Herrera-Viedma, & Martínez, 2000)

Label Set for 5 scale	**Abbreviation**	s_i^5	**Triangular Fuzzy Numbers**
None	N	s_0^5	(0, 0, 0.25)
Low	L	s_1^5	(0, 0.25, 0.5)
Medium	M	s_2^5	(0.25, 0.5, 0.75)
High	H	s_3^5	(0.5, 0.75, 1)
Perfect	P	s_4^5	(0.75, 1, 1)

3. Detecting the CNs about the problem for QFD and taking their related importance from DM group. The importance taken from the DM group is in a Label Set form.
   3.1. Making the aggregation of data with different granularity

Table 3.2 Label Set for Second Expert (Herrera, Herrera-Viedma, & Martínez, 2000)

Label Set for 7 scale	**Abbreviation**	s_i^7	**Triangular Fuzzy Numbers**
None	N	s_0^7	(0, 0, 0.17)
Very Low	VL	s_1^7	(0, 0.17, 0.33)
Low	L	s_2^7	(0.17, 0.33, 0.5)
Medium	M	s_3^7	(0.33, 0.5, 0.67)
High	H	s_4^7	(0.5, 0.67, 0.83)
Very High	VH	s_5^7	(0.67, 0.83, 1)
Perfect	P	s_6^7	(0.83, 1, 1)

Table 3.3 Label Set for Third Expert (Herrera, Herrera-Viedma, & Martínez, 2000)

Label Set for 9 scale	Abbreviation	s_i^9	Triangular Fuzzy Numbers
None	N	s_0^9	(0, 0, 0.12)
Very Low	VL	s_1^9	(0, 0.12, 0.25)
Low	L	s_2^9	(0.12, 0.25, 0.37)
Almost Medium	AM	s_3^9	(0.25, 0.37, 0.5)
Medium	M	s_4^9	(0.37, 0.5, 0.62)
Almost High	AH	s_5^9	(0.5, 0.62, 0,75)
High	H	s_6^9	(0.62, 0.75, 0.87)
Very High	VH	s_7^9	(0.75, 0.87, 1)
Perfect	P	s_8^9	(0.87, 1, 1)

4. Detecting DRs for QFD according to the CNs.

At this step, DRs need to be well evaluated in accordance with CNs, to be able to get logical relations between them during the relation matrix construction.

5. Constructing the relation matrix for HoQ to determine pair wise relations between CNs and DRs.

This step is to determine the level of relations between CNs and DRs. Several types of scales could be used for experts to express their opinion about the degree of relation between each CN and DR. Using fuzzy linguistic scales is preferred in this proposed method to provide convenience for experts. Furthermore, the transformation of fuzzy linguistic information into 2-Tuple model is very useful for not losing any information during the translation process.

6. Aggregating the different scaled data gathered from the different experts.

Here fuzzy linguistic scales are preferred as it is mentioned in the previous step. The aggregation process will be done after translating the data into 2-Tuple format.

   6.1. Translating the linguistic label sets into 2- Tuple format and unify them under the same linguistic label set with Eq. (3.10) and Eq. (3.11). It is better to unify them under the linguistic term set which has largest number of items (Li, 2012).
   6.2. Aggregate the data under the same granularity with Eq. (3.8)

At this step, one of the 2-Tuple aggregation operator will be used. It is preferred to use Weighted Average Operator (WAO); because different experts have different weights according to their knowledge about the subject.

7. Calculating the importance of the DRs.

At this step, the importance of CNs and their relationship with DRs will be taken into consideration to calculate the importance of DRs.

The importance of DR will be calculated with the following relation (Li, 2012):

$$(v_j, \alpha_j) = 1/m \sum_{i=1}^{m} \Delta^{-1}(r_i, \alpha_i) \times \Delta^{-1}(s_{ij}, \alpha_{ij}) \tag{3.12}$$

where, m is the number of CNs, (v_j, α_j) is the importance of DRs as a result, (r_i, α_i) is the weights of each CN and (s_{ij}, α_{ij}) is the values in relationship matrix for ith CN and jth DR.

The importance is measure for DRs on the total impact on CNs. DR with the highest importance is needed to be paid attention during the designing phase.

4 QFD FOR SUSTAINABLE UNIVERSITY BUILDING

4.1 Sustainable University Building

Sustainable university is a guidance to apply sustainability besides its appreciation the concept of sustainability (University of Plymouth). Its design should consider the "Triple Bottom Line" of sustainability which is environmental impacts, social concerns and economic performance. Sustainable university building should emphasize its social concerns balancing it with economic performance due to its different variety of stake holders and its role for guidance to apply sustainability.

Recent works done about sustainable universities and applied cases for sustainable universities are the basis for this study to detect the requirements for a QFD application for sustainable university building design. In this section detected requirements will be given according to these recent works and applied cases. Table 4.1 shows the recent works about sustainable universities.

Applied cases for university buildings are gathered from the LEED website (Wilber, 2014) where the best universities applied for LEED certification are given.

Table 4.1a Recent studies about sustainable university

Year	Writer	Aim of the study
2017	Yukiko Yoshida, Yoshiyuki Shimoda, Takumi Ohashi	Evaluating strategies toward achieving a sustainable campus at Osaka University, Japan (Yoshidaa, Shimoda, & Ohashi, 2017)
2016	Chris Shiel et al.	Examining engagement of universities for sustainable capacity building in communities (Shiel et al., 2016)
2015	Alia Abdullah Saleh, Abdul Hakim Mohammed, Mat Naim Abdullah	Discussing the critical success factors of sustainable university (Saleh et al., 2015)

Table 4.1b Recent studies about sustainable university

Year	Writer	Aim of the study
2015	Ramos et al.	Providing significant steps for the higher education by exploring new and rethink theories, approaches, concepts, methods, and frameworks, as well as providing case studies and guidelines for practitioners for sustainable university (Ramos et al., 2015)
2015	Disterheft et al.	Detecting critical success factors for sustainable universities with participatory approaches (Disterheft et al., 2015)
2014	Derahim et al.	Determining the current level of sustainability knowledge, awareness, attitude and willingness to participate in sustainable development programmes, of UKM's staff (Derahim et al., 2014)
2013	Mostafa Nejati, Mehran Nejati	Investigating the perceptions of university students towards factors of a sustainable university (Nejati & Nejati, 2013)
2006	Luis Velazquez, Nora Munguia, Alberto Platt, Jorge Taddei	Presenting a model to progress to advanced steps to become a sustainable university (Velazquez et al., 2006)

Two types of criteria are needed to be detected for the sustainable university building design. First one is the stake holders' opinions as an end-user preference. It will contribute the CN part of the QFD. Later, the second part is the DR which contains the engineering criteria for a sustainable university building. DRs will be generated from the CNs firstly, then for the final list a literature review and experts' opinion will help.

CNs are the expectations of end-users from the university building in order to be sustainable. Different CNs have different effects on DRs and these relations will provide us to gather the ranking of DRs according to CNs with integrated 2-Tuple with QFD.

4.2 Determining Customer Needs for Sustainable University Building

CNs are evaluated according to detailed literature review about sustainable university building and experts' opinion for this M.S. thesis application.

- *Sustainable Sites (CN1) (Gillis, 2013)**:***

Sustainable site is the key of the sustainable building design. Selection of the area where and how the building will be constructed is very important. While planning, site properties are the backbone of sustainable building.

- *Location (CN1.1) (Sternsdorff, 2017):*

Whether a building is net zero energy, part of its sustainability is related to its land use. Deciding which land to develop is also very important decision while designing a sustainable building. Various properties such as land and geostatistical properties of location must be well evaluated during designing phase.

- *Habitat of the site (CN1.2) (Sternsdorff, 2017):*

The main goal of the sustainability is to preserve the nature, and reduce the impacts of human on nature. According to this aim, in designing phase of sustainable building the flora and the fauna of the site must be preserved and the effects of the building on the nature must be decreased. Site selection must be done with less harm on its habitat.

- *Community of the site (CN1.3) (Sternsdorff, 2017)*

While choosing a site to develop, first the community and the street life of the area must be well investigated and the contribution of the project to the community is very important to be sustainable design.

- *Development of the site (CN1.4) (Sternsdorff, 2017)*

Sites that have not been built on before are called "greenfield" sites, and are best left unbuilt. Sites that have already been built on are called "grey-field" sites. Building on them avoids the destruction of wild lands or farmlands. Sites that have been polluted by former development or industry are called "brownfield" sites. It is an ecological benefit to clean up brownfield sites and redevelop them so they can become a productive part of society.

- *Construction and Design (CN2) (Sternsdorff, 2017):*

Design and the construction is a very important phase after site selection. During designing all the sustainability requirements for a building must be well evaluated to be applied during construction without any misleading.

- *Energy Management (CN2.1) (USBC, 2016)*

The aim of an environmentally sustainable building is to reduce the energy, material and the water use. To reach that goal, energy management in a building starting from a designing phase through the life of a building is very important.

- *Thermal Comfort (CN2.2) (USBC, 2016)*

Thermal comfort of the building is one of the major requirements that effects most of the occupants of the building. Occupants should have excellent quality air inside the building.

- *Building Orientation (CN2.3) (Crisman, 2014)*

Building's orientation is very significant for buildings gain from the natural climate of the area and especially from the sun. It must be well decided during the designing phase.

- *Acoustic (CN2.4) (Paradis, 2014)*

Acoustics is the interdisciplinary science that deals with the study of all mechanical waves in gases, liquids, and solids including topics such as vibration, sound, ultrasound and infrasound. Space acoustics are growing attention in sustainable projects; buildings like universities where a lot of people share shared places acoustic is very crucial requirement in a designing phase.

- *Occupants Productivity (CN2.5) (Maytum & Fuertes, 2016)*

Productivity is a measure of the efficiency of a person, machine, factory, system, etc., in converting inputs into useful outputs and it is very essential in a workplace. University buildings are both workplaces and educational places. So, the productivity of occupants is very important in every way to be successful university, and it must be well planned while designing the building.

- *Social (CN3) (Sternsdorff, 2017)*

Social sustainability is a process for creating sustainable, successful places that promote wellbeing, by understanding what people need from the places they live and work. This fraction of sustainability generally doesn't have enough attention in the projects. But social and the ethics part of the sustainability must be the key value while designing.

- *Eco-friendly and unique design (CN3.1) (Sternsdorff, 2017)*

The design of a building is one of the critical points that has least attention during planning. Functionality is very important but on the other hand new architectural approach in ecologic way is very necessary for sustainability.

- *Safety (CN3.2) (Wood et al., 2014)*

Safety of workers during construction and safety of occupants through the life of the building is very crucial. Human work and life must be very important as a policy of sustainable project.

- *Social Security and Rights(CN3.3) (Sternsdorff, 2017)*

Sustainable projects must be socially defender of rights of individuals. Sustainable projects give importance to individuals and they should guarantee their rights.

- *Equal Opportunity (CN3.4) (Sternsdorff, 2017)*

Equal opportunity is a stipulation that all people should be treated similarly, unhampered by artificial barriers or prejudices or preferences, except when distinctions can be explicitly justified. In sustainable building project, as a social fraction equal opportunity to everyone to work or access to university is essential.

- *Awareness about sustainable strategies for building occupants and public (CN3.5) (Singhaputtangkul et al., 2015)*

Sustainable projects give importance to environment and society; still they should try to diffuse this awareness to the rest of the community

- *Economic (CN4) (USGBC, 2009)*

Economic aspect of the sustainability generally relies on profitability and continuity; but a recent UNEP report proposes a green economy defined as one that “improves human well-being and social equity, while significantly reducing environmental risks and ecological scarcities”: it "does not favour one political perspective over another but works to minimize excessive depletion of natural capital".

- *Reducing life-cycle cost (CN4.1) (USBC, 2016)*

Life-cycle cost (LCC), refers to the total cost of ownership over the life of an asset. To make a better decision during designing phase, LCC must be completely analysed for materials of building.

- *Reducing cost (CN4.2) (Singhaputtangkul et al., 2015)*

Reducing the cost is an effortless way to increase profitability. Minimizing all types of costs will help for economical sustainability.

- *Flexibility and adaptability (CN4.3) (Sternsdorff, 2017)*

Flexibility is used as an attribute of several types of systems. In the field of design, it refers to designs that can adapt when external changes occur.

Adaptability in general, can be seen as an ability to change something or oneself to fit to occurring changes.

Both notions are related to external changes, so the project must grow parallel to the external changes.

- *Business continuity (CN4.4) (USBC, 2016)*

Business continuity encompasses planning and preparation to ensure that an organization can continue to operate in case of serious incidents or disasters and is able to recover to an operational state within a reasonably brief period. Sustainable business, must keep functioning to protect the interest of its occupants.

In this study, these CNs are the most important guide to detect the DRs. During the QFD application their pair wise evaluations will be done to rank the DRs according to CNs.

4.3 Determining Design Requirements for Sustainable University Building

DRs are first detected according to the CNs. Detailed literature review has been formed a basis for the DRs and the experts has assessed detected DRs to form the final list of requirements.

- *Climate of the site (DR1) (Gillis, 2013)*

The climate of a location is affected by its latitude, terrain, and altitude, as well as nearby water bodies and their currents. Regarding to these properties, feasible and optimum location selection with least environmental effect, must be well done during the designing.

- *Transportation through the site (DR2) (Sternsdorff, 2017)*

Transportation is the movement of people, animals and goods from one location to another. Transport links are central to site quality. For a university building, accessibility is very important. Accessibility of the nearest stop on the public transport network (bus, local train, tram, etc.), cycling infrastructure at the location, quality of the road connection, parking plan, transport plan and traffic plan are very essential for designing

- *Water resources of the site (DR3) (Sternsdorff, 2017)*

Water resources of the site are the natural waters passing through or born in the project's area. They must well preserve and must use with least harm on nature without polluting. The aim is therefore to disturb the natural water circuit as little as possible.

- *Local infrastructure (DR4) (Sternsdorff, 2017)*

Capacity of local infrastructure of the site should be investigated in detail. Infrastructure that already exists could preserve during the project or it can be redeveloped to be more functional for the local community

- *Affected species by the building in the site (DR5) (Sternsdorff, 2017)*

What kind of living species effect from this project? Optimum solution is affecting no species but the main goal of a sustainable site planning is to affect the species with minimum harm. (except endangered species

- *Nature of life in that area (DR6) (Sternsdorff, 2017)*

How the life between the community and the nature works in that location? The main goal should keep the relation at same level after the project or develop it in a better, sustainable way for community and the nature.

- *Contributing the community on that site (DR7) (Sternsdorff, 2017)*

Bringing new and positive values for the local community is very important for a sustainable project. Project can bring dense and sustainable development to the area also it can propose services such as banks, libraries, post offices and restaurants to the local community

- *Nature of street life in that area (DR8) (Sternsdorff, 2017)*

Buildings do not stand alone; they are set within a built context of surrounding buildings. Other buildings and other facilities around that area plus their public usage, compose the nature of street life of the site. Project should be evaluated without disturbing the nature of street life in that area

- *Predevelopment of the site (DR9) (Sternsdorff, 2017)*

Has the site been previously developed? Developing pre-developed sites and making them more ecologic should be the goal for designing a sustainable university building.

- *Fixed Light windows for skylight (DR10) (Ander, 2014)*

Skylights are light transmitting windows forming all, or a portion of, the roof of a building's space for day lighting purposes. They can be used for natural solar heating or cooling and for ventilation of building

- *LED lightings (DR11) (Maytum & Fuertes, 2016)*

An LED lamp is a light-emitting diode (LED) product which is assembled into a lamp (or light bulb) for use in lighting fixtures. LED lamps have a lifespan and electrical efficiency greater than incandescent lamps, and they are more efficient than most fluorescent lamps. Utilization of LED lamps for lighting of building can augment the energy efficiency of the building.

- *Sensor Utilization (DR12) (Ander, 2014) (Maytum & Fuertes, 2016)*

In the broadest definition, a sensor is an object whose purpose is to detect events or changes in its environment and sends the information to the computer which then tells the actuator (output devices) to provide the corresponding output. For a building design; sensors can be useful for energy efficiency. Utilization of daylight and occupancy sensors can help to diminish electricity usage of building

- *Building forms and dimensions (DR13) (Crisman, 2014)*

Building's shape, size and form is central for designing the university building. After the site selection, optimum sizing and forming should be done for a sustainable project.

- *Types, sizes and shapes of openings (DR14) (Green Building Technologies, 2007)*

Building openings provide light, ventilation and climate control for rooms. At the same time, they are essential functional and design elements of facades, enabling communication between indoor and outdoor spaces as transparent or translucent structural components. Heat emitting windows and their typologies are very important for the climate of the building

- *Low flow plumbing fixing (DR15) (WBDG Sustainable Committee, 2015)*

Water efficiency is one of the most important notions in a sustainable building. Utilization of low flow fixtures in every faucet of the building can help diminish water usage in the building.

- *Rainwater storage (DR16) (Wood et al., 2014)*

Rainwater management is very crucial while designing sustainable site. Polluted rainwater shouldn't mix with natural water due to the risk of polluting it. Storage of rainwater could be done with underground storage above the green lands and the water could be reuse to water the plants on the land

- *Native plants for landscaping (DR17) (Sternsdorff, 2017)*

Native plants are plants that have developed, occur naturally, or existed for many years in an area. They are familiar with the climate of the area and they don't need any extra care and water to grow. Native plants are an effective way to reduce the water usage for a sustainable project

- *Waste generation areas (DR18) (Gillis, 2013)*

Waste is an unwanted or unusable material. But with some recovery methods, reusing some waste is possible. To be able to reuse the waste, they should be separated by their materials. For that reason, in a sustainable building, waste separation and waste generation areas are very important for sustainable material use and energy efficiency.

- *Natural conditioning in building (DR19) (Green Building Technologies, 2007)*

Natural ventilation is the process of supplying air to and removing air from an indoor space without using mechanical systems. It is an energy efficient way to ventilate the building. Utilization of solar heating, passive cooling and passive ventilation with opening are very easy to apply when it is well planned during the designing phase. Also, utilization of slot diffusers and restroom fans are the way to diffuse the clean air in the hole building

- *Building Envelop Quality (DR20) (Portland Cement Association, n.d.)*

With good building envelop, space heating demand can be reduced, high level of thermal comfort can be achieved, and also it is an easy way to prevent damages to the building fabric.

- *Absorptive and reflective surfaces and materials into the space (DR21)* (Sternsdorff, 2017)

For optimum speech intelligibility, you need to exploit the reflection of sound on walls, floors, and ceilings in areas like classes in a university building. In most cases, however, you will want to reduce reflections to create a more private, intimate atmosphere by using absorptive materials for meeting rooms and laboratories.

- *Blocking the noisy places (DR22) (Sternsdorff, 2017)*

Blocking the noise is a way to fight against the noise pollution in the building. Some parts of the building could not separate from the hole structure and they make noise at the same time, in that case it is easy to block the area with absorptive material for the acoustic comfort of the hole building.

- *Non-toxic low-VOC glues and paints (DR23) (USBC, 2016)*

Volatile organic compounds (VOCs) are organic chemicals that have a high vapour pressure at ordinary room temperature. Their high vapour pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air. This vaporised and sublimated material is dangerous for human health and nature.

- *Environmentally friendly material use (DR24) (USBC, 2016)*

Recycled, reusable and eco-friendly material use is very crucial in a sustainable building project to reduce the carbon-foot print of the building. Also, it is to minimize the waste during construction and through the life of the building.

- *Innovative architecture (DR25) (Sternsdorff, 2017)*

The built environment defines the public realm and sets the scene for important parts of our social life. Buildings are key contributors to creating spaces offering an attractive quality of life. These duties of buildings challenge them to have a better, innovative and sustainable architectural design. Design quality is very important for a visual comfort of the building for its occupants.

- *Perform proper building operations and maintenance (DR26) (USGBC, 2009)*

Doing proper building operations and maintenance has a major effect on a building's cost and its environmental impact in use. Well-maintained building components last longer and it is safe for its occupants.

- *Make social security for all workers of sustainable building(DR27)* (Sternsdorff, 2017)

All the workers of the building should work in accordance with the law. They should all have their social security from government and right to use it when it is needed.

- *Give equal opportunity to everyone to work for sustainable building(DR28) (Sternsdorff, 2017)*

Employment equity is very important subject for the social aspect of the sustainable buildings. This is like an affirmative action task for a sustainable building. Hiring workers just because they are good and capable about their work without discrimination of any group is the main goal of this task.

- *Give equal opportunity to everyone to access to sustainable building (DR29) (Sternsdorff, 2017)*

The aim is to make the complete built environment available to every person without obstacle and in principle without external assistance. This makes it possible for disabled people to lead independent lives and to participate fully in all aspects of life.

- *Access for everyone to behaviour changing awareness about sustainable strategies through internet (DR30)* (Sternsdorff, 2017)

Sustainable university, should diffuse the awareness about sustainability and sustainable construction through social media, internet and publications which should be accessible for everyone.

- *Publish real time on internet about energy and water consumption, temperature and humidity readings (DR31) (Sternsdorff, 2017)*

This real-time application can elevate awareness about climate change in public. The real time information about the building's activities and workshops about the sustainability can grow a great awareness about climate change, and other dangers about the planet.

5 CASE STUDY: INTEGRATED 2-TUPLE WITH QFD FOR SUSTAINABLE UNIVERSITY BUILDING DESIGN

5.1 Application of the Proposed Methodology

To test the plausibility of the proposed integrated 2-Tuple with QFD method is applied to the sustainable university design problem. The application area is very trendy in Turkey with the retrofitting actions in universities and new university constructions all around the country. QFD will provide the importance of the selection criteria about sustainable university building according to the end-user preferences of the building's stakeholders.

Computational steps of the integrated 2-Tuple with QFD for sustainable university building design are as follows.

1. Assigning the objective of the study as a design of sustainable building with end-user preferences. Deciding the number of DM to solve the problem. In this study three different DM are chosen as an expert about the sustainability subject. One of the DMs is an expert/academician about sustainable buildings and their designing criteria, another one is a counsellor about sustainability subject and the last one is an academician who works about sustainability subject.

2. Selecting the linguistic comparison scale for each DM to represent their opinion. As mentioned in the previous step, three different experts with different back grounds are used in this application as a DM.

Due to this different back grounds and experience about the sustainable building subject, each expert has different scale to evaluate the problem. Furthermore, each expert has different importance for the aggregation phases in the application. The linguistic scales are shown in the Table 3.2-3.4 in previous section, for each expert with their triangular fuzzy number representation. The expert/academician from sustainable building subject, has done the evaluations in label scale S^9, counsellor about sustainability, has done evaluations in S^7, and the academician has done evaluations in S^5 due to their experience levels about the sustainable building subject. The importance of experts is given according to their scale and it is calculated as in Table 5.1 and the transformation of their importance to 2-Tuple is done with Eq. (3.10) and (3.11).

Table 5.1 Importance of Experts

Experts (DMs)	**Scale**	**Importance**	**2-Tuple in S^9**
EX1	7	0,33	(S_3, -0.39)
EX2	9	0,43	(S_3,0.46)
EX3	5	0,24	(S_2, -0.08)
Total	**21**	**1,00**	

3. Detecting CNs for sustainable university and their relative importance.

Previous section about the criteria for QFD, the evaluations of each expert and the criteria are given. The evaluations for CN1 is given as an example in the Table 5.2 and the aggregated relative importance is given in Table 5.3and Table 5.4.

Table 5.2 Evaluations of CN1 by experts

CN1	**Importance**					
	1st expert in S_5		**2nd expert in S_7**		**3rd expert in S_9**	
	Linguistic	*2-tuple*	*Linguistic*	*2-tuple*	*Linguistic*	*2-tuple*
Sustainable Sites	H	$(S_3^5, 0)$	VL	$(S_1^7, 0)$	M	$(S_4^9, 0)$

Importance of CNs for 2 levels will be used as the weights of the CNs while calculating the rank of the DRs.

Table 5.3 Importance of 1st level CNs

1st level CNs	**Aggregated Importance in S^9**
Sustainable Sites	$(S_4, -0.25)$
Construction and Design	$(S_5, 0.19)$
Social	$(S_3, 0.03)$
Economic	$(S_3, 0.48)$

The aggregation process is applied by using Eq. (3.10) and (3.11) The application of them is shown for CN1 as an example.

Table 5.4 Importance of 2nd level CNs

2nd level CNs	**Aggregated Importance in S^9**
Location	$(S_8, -0.30)$
Habitat of the site	$(S_1, 0.42)$
Community of the site	$(S_1, 0.42)$
Development of the site	$(S_7, -0.32)$
Energy Management	$(S_3, -0.39)$
Thermal Comfort	$(S_3, 0.46)$
Building Orientation	$(S_5, 0.26)$
Acoustic	$(S_2, 0.06)$
Occupants' Productivity	$(S_8, -0.30)$
Eco-friendly and unique design	$(S_2, 0.06)$
Safety	$(S_4, -0.10)$
Social Security and Rights	$(S_3, 0.46)$
Equal Opportunity in employment	$(S_2, 0.06)$
Awareness for sustainable strategies for buildings' occupants and public.	$(S_1, 0.42)$
Reducing life-cycle cost	$(S_8, -0.30)$
Reducing investment cost	$(S_2, 0.06)$
Flexibility and adaptability	$(S_3, 0.46)$
Business continuity	$(S_4, -0.10)$

First step is to aggregate the information with different granularity under the same one. It is better to unify them under the highest number of the label set not to lose any detailed information. The intersection of these different label sets must be obtained to be able to transform them between each other. Figure 5.1 and Figure 5.2 shows the intersection of S^5 with S^9 and S^7 with S^9 respectively.

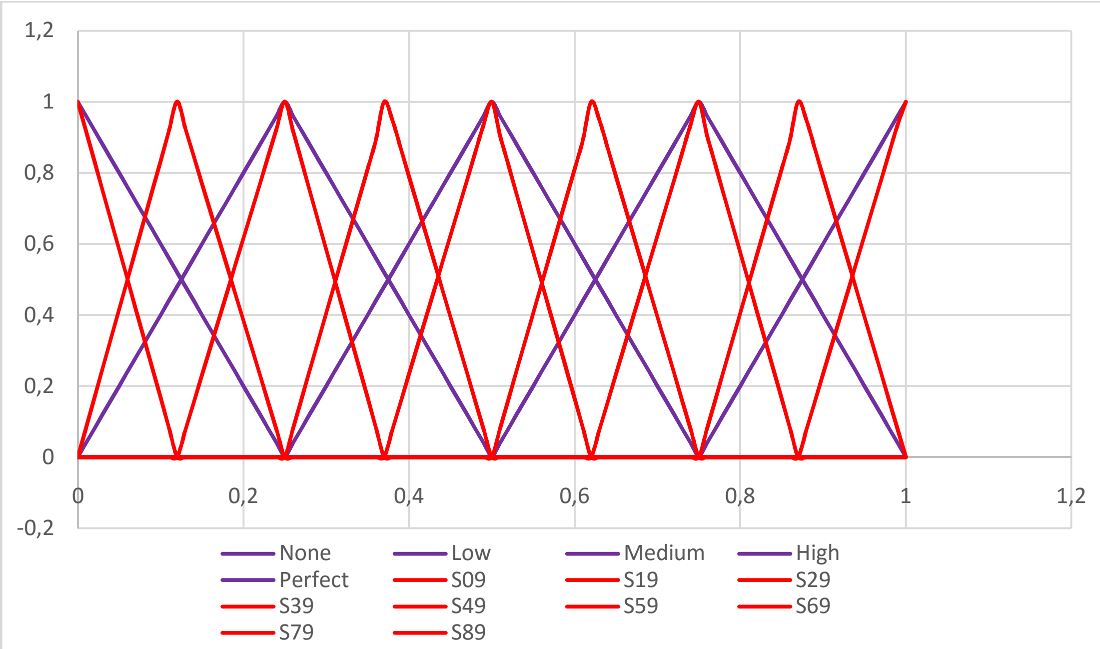

Figure 5.1 Intersection of S^5 with S^9

First experts label set is S^5, it is need to be transformed into S^9. The intersection of their triangular values must be obtained to transform it into S^9. The 2-Tuple value of CN1 from the first expert is $(S_3^5, 0)$.

The intersection points of $(S_3^5, 0)$ on S^9 are;

S_4^9 on (0.58,0.33), S_5^9 on (0.67,0.63), S_6^9 on (0.75,1), S_7^9 on (0.84,0.73) and S_8^9 on (0.92,0.39).

Intersected label set for S_3^5 in S_9 is shown as follow;

$$S = \begin{Bmatrix} (S_0^9, 0); (S_1^9, 0); (S_2^9, 0); (S_3^9, 0); (S_4^9, 0.33); \\ (S_5^9, 0.63); (S_6^9, 1); (S_7^9, 0.73); (S_8^9, 0.39) \end{Bmatrix}$$

The Eq. () is used to transform the label set into 2-Tuple. The application is as follow;

$$\frac{(0.33 \times 4) + (0.63 \times 5) + (6 \times 1) + (0.73 \times 7) + (0.39 \times 8)}{0.33 + 0.63 + 1 + 0.73 + 0.39} = 6.07 = \beta$$

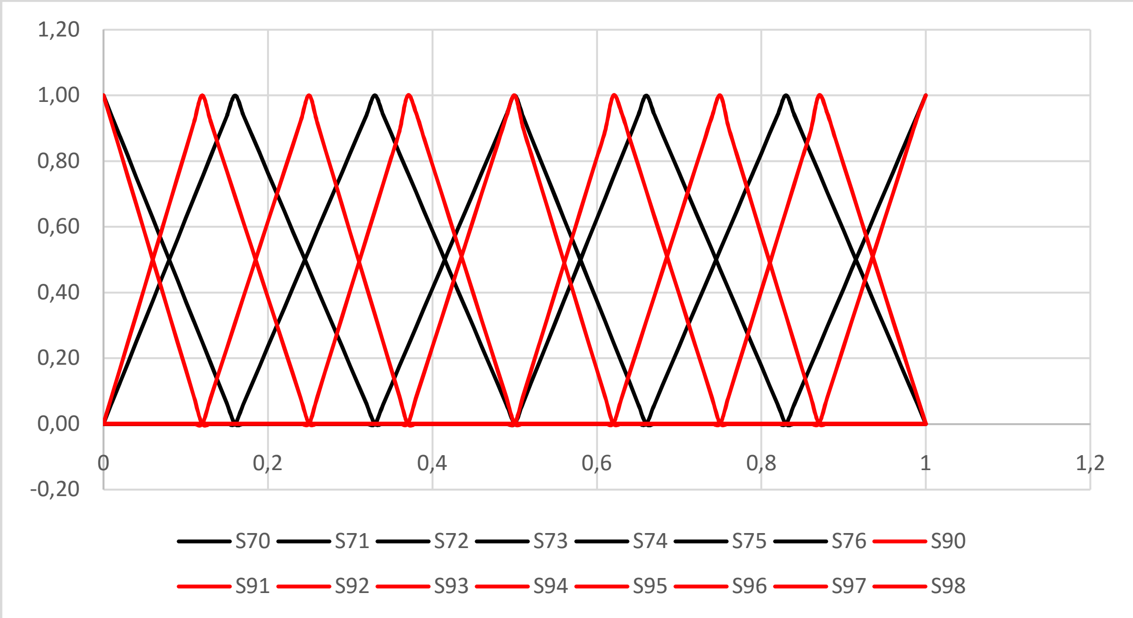

Figure 5.2Intersection of S^7 with S^9

β value is transformed into 2-Tuple form by applying Eq. (3.10).

$$round(\beta) = 6 = i$$
$$\alpha = \beta - i = 6.07 - 6 = 0.07$$

The 2-Tuple representation of S_3^5 in S_9 is equal to;

$$(S_6, 0.07)$$

Second experts label set is S^7, it is need to be transformed into S^9. The intersection of their triangular values must be obtained to transform it into S^9. The 2-Tuple value of CN1 from the first expert is $(S_1^7, 0)$.

The intersection points of $(S_1^7, 0)$ on S^9 are;

S_0^9 on (0.05,0.42), S_1^9 on (0.14,0.85), S_2^9 on (0.21,0.68) and S_3^9 on (0.29,0.32)

Intersected label set for S_3^5 in S_9 is shown as follow;

$$S = \begin{Bmatrix} (S_0^9, 0.42); (S_1^9, 0.85); (S_2^9, 0.69); (S_3^9, 0.32); (S_4^9, 0); \\ (S_5^9, 0); (S_6^9, 0); (S_7^9, 0); (S_8^9, 0) \end{Bmatrix}$$

The Eq. (3.10) and (3.11) is used to transform the label set into 2-Tuple. The application is as follow;

$$\frac{(0.42 \times 0) + (0.85 \times 1) + (0.69 \times 2) + (0.32 \times 3)}{0.85 + 0.69 + 0.32 + 0.42} = 1.71 = \beta$$

β value is transformed into 2-Tuple form by applying Eq. (3.10).

$$round(\beta) = 2 = i$$
$$\alpha = \beta - i = 1.71 - 2 = -0.28$$

The 2-Tuple representation of S_1^7 in S_9 is equal to;

$$(S_2, -0.28)$$

Third expert's evaluation is already in S_9 and there is no need for ant transformation process. The evaluation of the third expert for CN1 is $(S_4, 0)$ on S_9.

After unifying the granularity of the data, next step is to aggregate them to obtain collective importance for CN1. During this process, the importance of experts must be conceived. Their importance is given in Table 4.41. The aggregation will be done with weighted aggregation operator as in Eq. (3.8).

$$\Delta\left(\frac{\sum_{i=1}^{n} \beta_i \times w_i}{\sum_{i=0}^{n} w_i}\right) = \Delta\left(\frac{(1.92 \times 6.07) + (2.61 \times 1.72) + (3.46 \times 4)}{1.92 + 2.61 + 3.46}\right) = \Delta(3.75)$$

$$\Delta(3.75) = (S_4, -0.25)$$

$(S_4, -0.25)$ is the aggregated collective importance value for CN1. Other CNs' importance is calculated with the same computational steps as CN1 and the aggregated collective importance values are shown in the Table 5.3 and 5.4.

Detecting DRs for a sustainable university building according to CNs obtained from the previous step. Table 5.5 shows the DRs and their related CNs together. The detailed explanation for each CN and DR is given in the previous section.

All DRs are generated according to the CNs and requirements are developed according to detailed literature research and experts' opinion.

4.

Table 5.5a Customer needs and their design requirement pairings

Customer Needs		Design Requirements
SUSTAINABLE SITES	Location	Climate of the site Transportation through the site Water resources of the site Local infrastructure
	Habitat of the site	Affected species by the building in the site Nature of life in that area
	Community of the site	Contributing the community on that site Nature of street life in that area
	Development of the site	Local infrastructure Predevelopment of the site
CONSTRUCTION and DESIGN	Energy management	Fixed Light windows for skylight LED lightings Sensor Utilization Building forms and dimensions Window Typologies Types, sizes and shapes of openings Low flow plumbing fixing Rainwater storage Native plants for landscaping Waste generation areas Natural conditioning in building
	Thermal comfort	Building forms and dimensions Building Envelop Quality Fixed Light Windows for skylight Types, shapes and forms of the openings Window typologies Natural conditioning in building Climate of the site
	Building orientation	Building forms and dimensions Fixed light windows for skylight Window typologies Natural conditioning in building Transportation through the site

Table 5.5b Customer needs and their design requirement pairings

Category	Customer Needs	Design Requirements
CONSTRUCTION and DESIGN	Acoustic	Building Envelope Quality Absorptive and reflective surfaces and materials into the space Blocking the noisy places Transportation through the site Nature of the street life on that site Predevelopment of the site
	Occupant's productivity	Heat-emitting windows Window typologies Building forms and dimensions Absorptive and reflective surfaces and materials into the space Blocking the noisy places Non-toxic low-VOC glues and paints Environmentally friendly material use
SOCIAL	Eco-friendly and unique design	Building forms and dimensions Environmentally friendly material use Innovative architecture
	Safety	Perform proper building operations and maintenance Environmentally friendly material use Non-toxic low-VOC glues and paints
	Social security and rights	Make social security for all workers of sustainable building
	Equal opportunity in employment	Give equal opportunity to everyone to work for sustainable building Give equal opportunity to everyone to access to sustainable building
	Awareness for sustainable strategies for buildings' occupants and public	Access for everyone to behaviour changing awareness about sustainable strategies through internet Publish real time on internet about energy and water consumption, temperature and humidity readings
ECONOMIC	Reducing life-cycle costs	Life-cycle cost analysis before the investment Minimize LCL
	Reducing investment cost	Minimize investment cost Minimize operation and maintenance cost
	Flexibility and adaptability	Be adaptable to any different demand for sustainability Be flexible to any different demand for sustainability
	Business continuity	Be a safeguard for the interests of stakeholders of the building

5. Constructing the relation matrix according the relations between each CN and DR.

Each expert evaluated relations between each CN and DR in their scale and their evaluations are given with the requirements in the previous section. In this step, the aggregated collective relation matrix is obtained. Table 5.8 shows the aggregated 2-Tuple values for each CN and DR.

Here in Table 5.6 is given as an example for DR1 for the evaluations by each expert.

Table 5.6 Evaluations of DR1 by each expert

		Evaluations of DR1					
		1st expert in S_5		**2nd expert in S_7**		**3rd expert in S_9**	
		Linguistic	*2-tuple*	*Linguistic*	*2-tuple*	*Linguistic*	*2-tuple*
CN1	**CN1.1**	P	$(S_4^5, 0)$	P	$(S_6^7, 0)$	P	$(S_8^9, 0)$
	CN1.2	P	$(S_4^5, 0)$	VH	$(S_5^7, 0)$	VH	$(S_7^9, 0)$
	CN1.3	L	$(S_1^5, 0)$	VL	$(S_1^7, 0)$	VL	$(S_1^9, 0)$
	CN1.4	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
CN2	**CN2.1**	P	$(S_4^5, 0)$	P	$(S_6^7, 0)$	P	$(S_8^9, 0)$
	CN2.2	P	$(S_4^5, 0)$	VH	$(S_5^7, 0)$	VH	$(S_7^9, 0)$
	CN2.3	P	$(S_4^5, 0)$	P	$(S_6^7, 0)$	P	$(S_8^9, 0)$
	CN2.4	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
	CN2.5	H	$(S_3^5, 0)$	H	$(S_4^7, 0)$	H	$(S_6^9, 0)$
CN3	**CN3.1**	L	$(S_1^5, 0)$	L	$(S_2^7, 0)$	L	$(S_2^9, 0)$
	CN3.2	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
	CN3.3	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
	CN3.4	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
	CN3.5	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
CN4	**CN4.1**	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
	CN4.2	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$
	CN4.3	M	$(S_2^5, 0)$	M	$(S_0^7, 0)$	AM	$(S_3^9, 0)$
	CN4.4	N	$(S_0^5, 0)$	N	$(S_0^7, 0)$	N	$(S_0^9, 0)$

The aggregation process is done with Eq.(3.10) and (3.11).First the linguistic label sets are transformed into fuzzy triangular form in graphs as in Figure 5.3. Then their intersection values are obtained from graph to calculate the transformed label set. As an example, transformation of S_5 to S_9 is calculated.

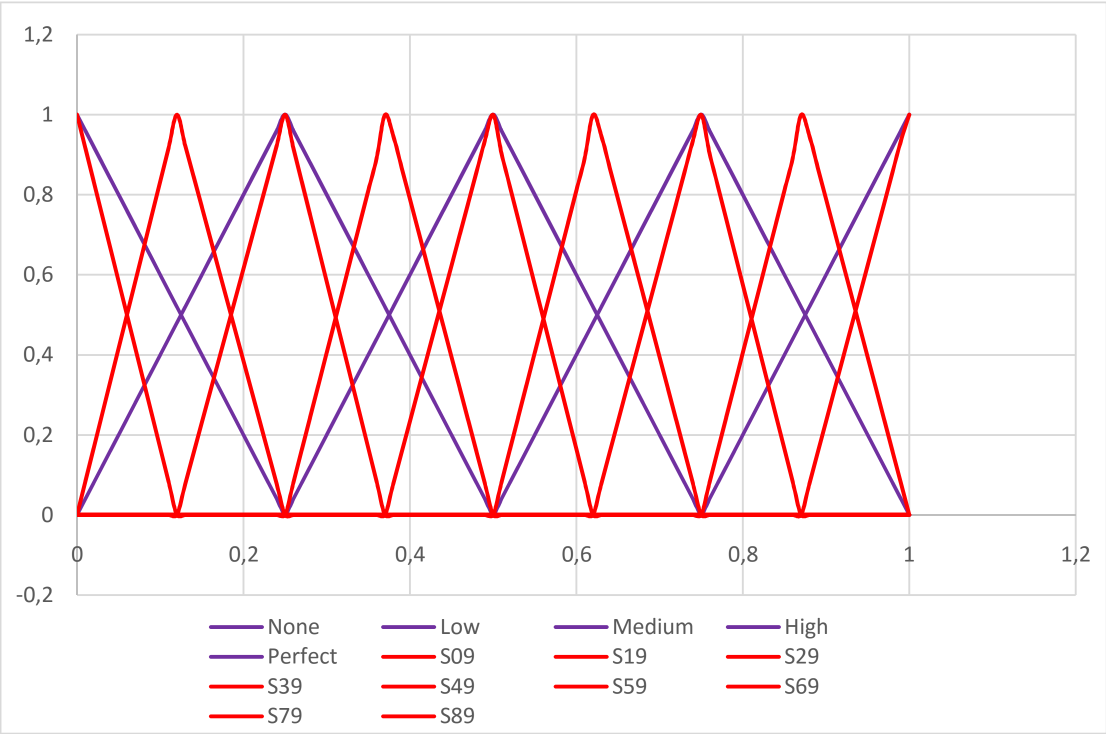

Figure 5.3 Intersection of S_5 with S_9

The intersection of label sets are as follows:

- For $S_0^5(None\ in\ purpe\ on\ the\ Figure\ 5.3)$:

It intersects with S_1^9 on (0.08, 0.67) and with S_2^9 on (0.17, 0.38).

Intersected label set for S_0^5 in S_9 is shown as follow;

$$S = \{(S_0^9, 0); (S_1^9, 0.67); (S_2^9, 0.38); (S_3^9, 0); (S_4^9, 0), (S_5^9, 0); (S_6^9, 0); (S_7^9, 0); (S_8^9, 0)\}$$

The Eq. (3.10) and (3.11) are used to transform the label set in into 2-Tuple. The application of the equation is as follow;

$$\frac{(0.67 \times 1) + (2 \times 0.38)}{0.67 + 0.38} = 1.43 = \beta$$

β value is transformed into 2-Tuple form by applying Eq. (3.3).

$$round(\beta) = 1 = i$$
$$\alpha = \beta - i = 1.43 - 1 = 0.43$$

The 2-Tuple representation of S_0^5 in S_9 is equal to;

$$(S_1, 0.43)$$

- For S_1^5 $(Low\ in\ purple\ on\ the\ Figure\ 5.3)$

It intersects with S_0^9 on (0.08,0.33), S_1^9 on (0.17,0.62) and (0.25,1), S_3^9 on (0.33,0.65), S_4^9 on (0.42,0.39).

Intersected label set for S_1^5 in S_9 is shown as follow;

$$S = \begin{Bmatrix} (S_0^9, 0.33); (S_1^9, 0.62); (S_1^9, 1); (S_2^9, 0); (S_3^9, 0.65); \\ (S_4^9, 0.39), (S_5^9, 0); (S_6^9, 0); (S_7^9, 0); (S_8^9, 0) \end{Bmatrix}$$

The Eq. (3.10) and (3.11) are used to transform the label set into 2-Tuple. The application is as follow;

$$\frac{(0.33 \times 0) + (0.62 \times 1) + (1 \times 1) + (0.65 \times 3) + (0.39 \times 4)}{0.33 + 0.62 + 1 + 0.65 + 0.39} = 1.76 = \beta$$

β value is transformed into 2-Tuple form by applying Eq. (3.3).

$$round(\beta) = 2 = i$$
$$\alpha = \beta - i = 1.76 - 2 = -0.24$$

The 2-Tuple representation of S_1^5 in S_9 is equal to;

$$(S_2, -0.24)$$

- For $S_2^5 (Medium\ in\ purpe\ on\ the\ Figure\ 5.3)$

It intersects with S_2^9 on (0.33,0.33), S_3^9 on (0.42,0.63), S_4^9 on (0.5,1), S_5^9 on (0.58,0.65) and S_6^9 on (0.67,0.39).
Intersected label set for S_2^5 in S_9 is shown as follow;

$$S = \begin{Bmatrix} (S_0^9, 0); (S_1^9, 0); (S_2^9, 0.33); (S_3^9, 0.63); (S_4^9, 1); \\ (S_5^9, 0.65); (S_6^9, 0.39); (S_7^9, 0); (S_8^9, 0) \end{Bmatrix}$$

The Eq. (3.10) and (3.11) is used to transform the label set into 2-Tuple. The application is as follow;

$$\frac{(0.33 \times 2) + (0.63 \times 3) + (1 \times 4) + (0.65 \times 5) + (0.39 \times 6)}{0.33 + 0.63 + 1 + 0.65 + 0.39} = 4.04 = \beta$$

β value is transformed into 2-Tuple form by applying Eq. (3.3).

$$round(\beta) = 4 = i$$
$$\alpha = \beta - i = 4.04 - 4 = 0.04$$

The 2-Tuple representation of S_2^5 in S_9 is equal to;

$$(S_4, 0.04)$$

- For $S_3^5(High\ in\ purpe\ on\ the\ Figure\ 5.3)$

It intersects with S_4^9 on (0.58,0.33), S_5^9 on (0.67,0.63), S_6^9 on (0.75,1), S_7^9 on (0.84,0.73) and S_8^9 on (0.92,0.39).
Intersected label set for S_3^5 in S_9 is shown as follow;

$$S = \begin{Bmatrix} (S_0^9, 0); (S_1^9, 0); (S_2^9, 0); (S_3^9, 0); (S_4^9, 0.33); \\ (S_5^9, 0.63); (S_6^9, 1); (S_7^9, 0.73); (S_8^9, 0.39) \end{Bmatrix}$$

The Eq. (3.10) and (3.11) are used to transform the label set into 2-Tuple. The application is as follow;

$$\frac{(0.33 \times 4) + (0.63 \times 5) + (6 \times 1) + (0.73 \times 7) + (0.39 \times 8)}{0.33 + 0.63 + 1 + 0.73 + 0.39} = 6.07 = \beta$$

β value is transformed into 2-Tuple form by applying Eq. (3.3).

$$round(\beta) = 6 = i$$
$$\alpha = \beta - i = 6.07 - 6 = 0.07$$

The 2-Tuple representation of S_3^5 in S_9 is equal to;

$$(S_6, 0.07)$$

- For $S_4^5(Perfect\ in\ purpe\ on\ the\ Figure\ 5.3)$

It intersects with S_6^9 on (0.83,0.33), S_7^9 on (0.92,0.63) and S_8^9 on (1,1).
Intersected label set for S_2^5 in S_9 is shown as follow;

$$S = \begin{Bmatrix} (S_0^9, 0); (S_1^9, 0); (S_2^9, 0); (S_3^9, 0); (S_4^9, 0); \\ (S_5^9, 0); (S_6^9, 0.33); (S_7^9, 0.63); (S_8^9, 1) \end{Bmatrix}$$

The Eq. (3.10) and (3.11) are used to transform the label set into 2-Tuple. The application is as follow;

$$\frac{(0.33 \times 6) + (0.63 \times 7) + (1 \times 8)}{0.33 + 0.63 + 1} = 7.34 = \beta$$

β value is transformed into 2-Tuple form by applying Eq. (3.3).

$$round(\beta) = 7 = i$$
$$\alpha = \beta - i = 7.34 - 7 = 0.34$$

The 2-Tuple representation of S_4^5 in S_9 is equal to;

$$(S_7, 0.34)$$

The same computational steps are applied for the S_7 to transform it into S_9.

Then the weighted aggregation operator is used to aggregate the three different evaluations from three different experts under the same label set of S_9. The computational steps of weighted aggregation operator of DR1 for CN1.1 is shown as example as follows. First the evaluations of experts and their importance are given in the Table 5.7 then the calculations will be given.

Table 5.7 Evaluations of DR1 inS_9 for CN1.1

DRs	**DR1**		
Experts	**EX1**	**EX2**	**EX3**
Importance	$(\boldsymbol{S_2, -0,08})$	$(\boldsymbol{S_3, -0.39})$	$(\boldsymbol{S_3, 0.46})$
CN1.1	$(S_7, 0.34)$	$(S_8, -0.43)$	$(S_8, 0)$

The Eq.(3.8) is applied for weighted aggregation operator.

$$\Delta\left(\frac{\sum_{i=1}^{n}\beta_i \times w_i}{\sum_{i=0}^{n} w_i}\right) = \Delta\left(\frac{(1.92 \times 7.34) + (2.61 \times 7.57) + (3.46 \times 8)}{(1.92 + 3.46 + 2.61)}\right) = \Delta(7.70)$$

$$\Delta(7.70) = (S_8, -0.30)$$

$(S_8, -0.30)$ is the aggregated 2-Tuple value for the CN1.1 and DR1 in the relation matrix. The same calculations are done for the rest of the requirements detected for the sustainable university building. Aggregated relationship matrix is obtained at the end and it is shown in the Table 5.8.

6. Next step is to calculate the importance of each DR according to the evaluations and CNs. At the end of this step ranking of the DRs will be obtained.

Eq.(12) will be applied to calculate the importance of each DR. At this step, the importance of 1st level CNs and 2nd level CNs will be involved to obtain the importance of DR according to end-user preferences.
The importance of first level CNs and second level CNs are given in the previous section. At this step, they will be used. The calculations of importance for first three DR is given as an example at this step.

Table 5.8a Aggregated Collective Relation Matrix

	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15
CN1.1	(S8, -0.3)	(S8, -0.3)	(S3,0.46)	(S7,-0.02)	(S8,-0.3)	(S7,-0.02)	(S6,-0.18)	(S3,0.46)	(S1,-0.26)	(S1,-0.26)	(S6,-0.18)	(S6,-0.18)	(S1,-0.26)	(S4,-0.10)	(S5,0.39)
CN1.2	(S7, -0.02)	(S7,-0.02)	(S6,-0.18)	(S6,-0.18)	(S7,0.27)	(S8,-0.3)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S3,0.46)	(S1,-0.26)	(S1,-0.26)	(S5,0.39)	(S4,-0.10)
CN1.3	(S1,0.42)	(S1,0.42)	(S2,0.06)	(S3,0.46)	(S1,-0.26)	(S1,0.42)	(S3,0.46)	(S2,0.06)	(S2,0.06)	(S2,0.06)	(S4,-0.10)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN1.4	(S1,-0.26)	(S7,0.27)	(S7,-0.02)	(S7,-0.02)	(S4,-0.10)	(S6,-0.18)	(S8,-0.3)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S8,-0.3)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN2.1	(S8,-0.3)	(S2,0.06)	(S1,0.42)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S5,0.39)	(S7,-0.02)	(S7,0.27)	(S8,-0.3)	(S7,-0.02)	(S6,-0.18)	(S4,-0.10)	(S2,0.06)
CN2.2	(S7,-0.02)	(S1,-0.26)	(S5,0.39)	(S5,0.39)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S6,-0.18)	(S6,-0.18)	(S8,-0.3)	(S8,-0.3)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN2.3	(S8,-0.3)	(S1,-0.26)	(S1,0.42)	(S3,0.46)	(S1,-0.26)	(S1,-0.26)	(S7,-0.02)	(S7,0.27)	(S7,-0.02)	(S7,-0.02)	(S8,-0.3)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S3,0.46)
CN2.4	(S1, -0.26)	(S7,-0.02)	(S1,-0.26)	(S2,0.06)	(S1, -0.26)	(S3,0.46)	(S6,-0.18)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S7,-0.02)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN2.5	(S6,-0.18)	(S2,0.06)	(S1,-0.26)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S7,-0.02)	(S6,-0.18)	(S6,-0.18)	(S7,-0.02)	(S8,-0.3)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S5,0.39)
CN3.1	(S2,0.06)	(S2,0.06)	(S1,0.42)	(S2,0.06)	(S6,-0.18)	(S6,-0.18)	(S5,0.39)	(S4,-0.10)	(S6,-0.18)	(S6,-0.18)	(S7,-0.02)	(S7,-0.02)	(S7,-0.02)	(S7,-0.02)	(S4,-0.10)
CN3.2	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S4,-0.10)	(S1,-0.26)	(S1,0.42)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S6,-0.18)	(S6,-0.18)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN3.3	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,0.42)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN3.4	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,0.42)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN3.5	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,0.42)
CN4.1	(S1,-0.26)	(S4,-0.10)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S7,-0.02)	(S4,-0.10)	(S4,-0.10)	(S4,-0.10)	(S7,-0.02)	(S4,-0.10)	(S2,0.06)	(S1,0.42)	(S1,0.42)
CN4.2	(S1,-0.26)	(S6,-0.18)	(S1,-0.26)	(S4,-0.10)	(S1,-0.26)	(S1,-0.26)	(S4,-0.10)	(S2,0.06)	(S4,-0.10)	(S6,-0.18)	(S7,-0.02)	(S1,0.42)	(S1,0.42)	(S1,0.42)	(S1,0.42)
CN4.3	(S3,0.46)	(S3,0.46)	(S1,-0.26)	(S6,-0.18)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,0.42)	(S5,0.39)	(S2,0.06)
CN4.4	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S8,-0.3)	(S1,-0.26)	(S1,-0.26)	(S5,0.39)	(S1,-0.26)	(S1,-0.26)	(S5,0.39)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)

Table 5.8bAggregated Collective Relation Matrix

	DR16	DR17	DR18	DR19	DR20	DR21	DR22	DR23	DR24	DR25	DR26	DR27	DR28	DR29	DR30	DR31
CN1.1	(S1,-0.26)	(S4,-0.10)	(S1,-0.26)	(S5,0.39)	(S1,-0.26)	(S7,-0.02)	(S2,0.06)	(S2,0.06)	(S2,0.06)	(S2,0.06)	(S2,0.06)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S7,-0.02)	(S8,-0.3)
CN1.2	(S4,-0.10)	(S1,0.42)	(S2,0.06)	(S1,0.42)	(S3,0.46)	(S4,-0.10)	(S1,-0.26)	(S1,-0.26)	(S6,-0.18)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S7,0.27)
CN1.3	(S2,0.06)	(S1,-0.26)	(S5,0.39)	(S1,0.42)	(S1,0.42)	(S7,-0.02)	(S6,-0.18)	(S3,0.46)	(S6,-0.18)	(S7,-0.02)	(S7,-0.02)	(S7,-0.02)	(S5,0.39)	(S5,0.39)	(S8,-0.3)	(S8,-0.3)
CN1.4	(S7,-0.02)	(S1,-0.26)	(S7,-0.02)	(S7,0.27)	(S2,0.06)	(S5,0.39)	(S5,0.39)	(S5,0.39)	(S7,-0.02)	(S6,-0.18)	(S5,0.39)	(S1,-0.26)	(S2,0.06)	(S2,0.06)	(S3,0.46)	(S4,-0.10)
CN2.1	(S1,-0.26)	(S8,-0.3)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S7,-0.02)	(S8,-0.3)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN2.2	(S1,-0.26)	(S7,-0.02)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S6,-0.18)	(S8,-0.3)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN2.3	(S1,0.42)	(S7,-0.02)	(S5,0.39)	(S2,0.06)	(S1,-0.26)	(S6,-0.18)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,0.42)
CN2.4	(S3,0.46)	(S6,-0.18)	(S6,-0.18)	(S8,-0.3)	(S1,-0.26)	(S7,-0.02)	(S6,-0.18)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S4,-0.10)
CN2.5	(S1,-0.26)	(S6,-0.18)	(S3,0.46)	(S6,-0.18)	(S1,-0.26)	(S7,-0.02)	(S7,0.27)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S4,-0.10)	(S3,0.46)
CN3.1	(S7,-0.02)	(S2,0.06)	(S6,-0.18)	(S1,-0.26)	(S6,-0.18)	(S8,-0.3)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN3.2	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S1,0.42)	(S1,0.42)	(S1,0.42)	(S8,-0.3)	(S1,0.42)	(S6,-0.18)	(S4,-0.10)	(S4,-0.10)	(S4,-0.10)	(S2,0.06)	(S1,0.42)	(S2,0.06)	(S1,-0.26)
CN3.3	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S7,0.27)	(S1,0.42)	(S7,-0.02)	(S7,-0.02)	(S7,-0.02)	(S4,-0.10)	(S2,0.06)	(S2,0.06)	(S1,-0.26)
CN3.4	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S8,-0.3)	(S1,0.42)	(S7,-0.02)	(S8,-0.3)	(S8,-0.3)	(S4,-0.10)	(S2,0.06)	(S2,0.06)	(S1,-0.26)
CN3.5	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)	(S1,-0.26)	(S6,-0.18)	(S1,0.42)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)	(S7,-0.02)	(S7,0.27)	(S8,-0.3)	(S7,-0.02)	(S2,0.06)
CN4.1	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,0.42)	(S1,-0.26)	(S2,0.06)	(S5,0.39)	(S4,-0.10)	(S4,-0.10)	(S4,-0.10)	(S4,-0.10)	(S1,0.42)	(S1,-0.26)	(S1,-0.26)	(S2,0.06)	(S1,-0.26)
CN4.2	(S1,0.42)	(S2,0.06)	(S6,-0.18)	(S1,0.42)	(S1,0.42)	(S6,-0.18)	(S1,-0.26)	(S1,-0.26)	(S4,-0.10)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)
CN4.3	(S1,0.42)	(S6,-0.18)	(S5,0.39)	(S1,0.42)	(S1,-0.26)	(S7,-0.02)	(S7,-0.02)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S1,-0.26)	(S5,0.39)	(S1,-0.26)
CN4.4	(S1,-0.26)	(S5,0.39)	(S1,0.42)	(S1,-0.26)	(S1,-0.26)	(S5,0.39)	(S7,-0.02)	(S2,0.06)	(S4,-0.10)	(S3,0.46)	(S3,0.46)	(S2,0.06)	(S2,0.06)	(S2,0.06)	(S7,-0.02)	(S1,-0.26)

Table 5.9 β values for CNs' importance and DR1 from aggregated matrix

β values for 1st level CNs	β values for 2nd level CNs	β values for DR1's evaluations	β values for DR2's evaluations	β values for DR3's evaluations
3.75	7.70	7.70	7.70	3.46
3.75	1.42	6.98	6.98	5.82
3.75	1.42	1.42	1.42	2.06
3.75	6.68	0.74	7.27	6.98
5.19	2.61	7.70	2.06	1.42
5.19	3.46	6.98	0.74	5.39
5.19	5.26	7.70	0.74	1.42
5.19	2.06	0.74	6.98	0.74
5.19	7.70	5.82	2.06	0.74
3.03	2.06	2.06	2.06	1.42
3.03	3.90	0.74	0.74	0.74
3.03	3.46	0.74	0.74	0.74
3.03	2.06	0.74	0.74	0.74
3.03	1.42	0.74	0.74	0.74
3.48	7.70	0.74	3.90	0.74
3.48	2.06	0.74	5.82	0.74
3.48	3.46	3.46	3.46	0.74
3.48	3.90	0.74	0.74	0.74

β values are obtained from Eq. (3.3). The β values for DR1,DR2 and DR3 and the importance of CNs are given in the Table 5.9.

First the relation matrix should be aggregated with the importance of first and second level CNs.

$$\frac{\sum_{i=1,j=0,k=0}^{18} \beta_i \times \beta_j \times \beta_k}{\sum \beta_j \times \sum \beta_k}$$

Where, β_i is the β values for DRs, β_j is the β values for first level CNs and β_k is the β values for second level CNs. The weighted value for DR1 is 0.047. This is the weighting part of Eq. (3.12) Then the division part Eq. (3.12), which is $\frac{1}{m}$ (m is the number of CNs), is applied to get the importance of DR1.

$$\frac{0.047}{18} = 0.019$$

0.019 is the β value for DR1's importance. It is retranslated into 2-Tuple form with Eq. (3.3):

$$i = round(\beta) = round(0.019) = 0$$
$$\alpha = \beta - i = 0.019 - 0 = 0.019$$

The 2-Tuple representation of DR1's importance in $S^9$is:

$$(S_0, 0.019)$$

For DR2, same calculations are done to obtained weighted CNs in Eq. (3.12) and 0.047 is gained. As in DR1 0.047 is retransformed into 2- Tuple version by using Eq. (3.3).and $(S_0, 0.018)$ is obtained.

Also for DR3, weighting operation is done and 0.021 is obtained. When it is divided into number of CNs 0.012 is gained. Eq. (3.3). is used to retransform it into 2-Tuple form:

$$i = round(\beta) = round(0.012) = 0$$
$$\alpha = \beta - i = 0.012 - 0 = 0.012$$

The 2-Tuple representation of DR3's importance in $S^9$is:

$$(S_0, 0.012)$$

When these three requirements are compared according to the Eq. (3.5) their ranking is as follows. The importance and the ranking of all other DRs are given in the Table 4.61.

$$(S_0, 0.019) > (S_0, 0.018) > (S_0, 0.012)$$

As mentioned before, the comparison of 2-Tuple is done according to Eq. (3.5).

5.2 Obtained Results and Discussion

Integrated 2-Tuple with QFD methodology is applied for a sustainable university building design and according to the end-user preferences the ranking of the DRs are obtained from this case study. The results of the rankings are given in the Table 5.10

Table 5.10 Importance and ranking of DRs

DRs	2-tuple Importance	Ranking	DRs	2-Tuple Importance	Ranking
DR1	$(S_0, 0.019)$	10	**DR16**	$(S_0, 0.012)$	24
DR2	$(S_0, 0.018)$	11	**DR17**	$(S_0, 0.020)$	8
DR3	$(S_0, 0.012)$	26	**DR18**	$(S_0, 0.023)$	6
DR4	$(S_0, 0.024)$	5	**DR19**	$(S_0, 0.014)$	20
DR5	$(S_0, 0.012)$	27	**DR20**	$(S_0, 0.008)$	31”
DR6	$(S_0, 0.014)$	21	**DR21**	$(S_0, 0.031)$	1
DR7	$(S_0, 0.025)$	3	**DR22**	$(S_0, 0.025)$	4
DR8	$(S_0, 0.016)$	17	**DR23**	$(S_0, 0.014)$	22
DR9	$(S_0, 0.016)$	15	**DR24**	$(S_0, 0.017)$	13
DR10	$(S_0, 0.020)$	9	**DR25**	$(S_0, 0.016)$	14
DR11	$(S_0, 0.030)$	2	**DR26**	$(S_0, 0.016)$	16
DR12	$(S_0, 0.022)$	7	**DR27**	$(S_0, 0.015)$	18
DR13	$(S_0, 0.009)$	30	**DR28**	$(S_0, 0.012)$	28
DR14	$(S_0, 0.013)$	23	**DR29**	$(S_0, 0.010)$	29
DR15	$(S_0, 0.012)$	25	**DR30**	$(S_0, 0.018)$	12
			DR31	$(S_0, 0.015)$	19

As it is seen from the values, the comparison is made according to 2-Tuple comparison rules and the ranking is as it is in the Table 5.10. DR with the highest β value is the most important requirement to evaluate during the designing of the sustainable university building.

DR21 which is “absorptive and reflective surfaces and materials into the space” is the most important criteria to conceive during designing phase of the sustainable university building. Later, it must be followed by DR11 which is “LED lightings” and DR7 which is “contributing the community on that site”.

To be able to reflect the user preferences to the sustainable university building design it is better to prioritize the planning phase according to the ranking on the Table 5.10.

6 CONCLUSION AND PERSPECTIVES

As a conclusion, in thesis for Master of Science, sustainable university building design subject has been studied. To reflect the end-user preferences to the sustainable university building design QFD which is a MCDM tool is used with 2-Tuple based information.
The main reason for utilizing the QFD method is its ability and easy computational steps to transform customer needs into design requirements for a service or product. Additionally, to that, this method has never been used for such intent to design a sustainable building in the literature before.

When, it exists end-user preferences as an input for the method, there is too much linguistic information and their importance to handle during the calculations. Further, more than one decision maker creates multi-granularity in the information for the decision-making process. To eliminate these negative effects on the calculations 2-tuple method has been used as a supplementary technique with QFD in this thesis. Also, this QFD technic could be developed to benchmark and compare sustainable university buildings later to evaluate this study. This is a very advantageous property for QFD method.

First part of this study, the problem was assigned for MCDM. Then the decision makers or experts are detected to solve this problem. The problem is to prioritize the end-user preferences to design a sustainable university building design. Three experts were chosen to work during this process. Different experts had different back grounds about the subject and that has created a multi-granular environment for decision making.

In the first phase for the study, with a detailed literature review and experts' opinion CNs are detected as an end-user preference for a sustainable university building. In the second phase, experts have evaluated CNs relatively by giving their importance in linguistic forms. Later, the DRs have been detected according to the CNs, detailed literature review and experts' opinion. As a last phase, DRs and CNs are evaluated mutually to construct their relation matrix in order to apply QFD.

During all the evaluation phases, linguistic data have been used and later to eliminate the impreciseness and multi-granularity they have been transformed into 2-Tuple form.

As a last step, QFD is applied to the detected CNs and DRs to get the ranking of DRs to create a meaningful ranking according to end-user preferences.

Furthermore, in this thesis, we provide an integrated 2-Tuple with QFD methodology to plan a sustainable university building design.

In this Master of Science thesis, all the requirements have been detected according to literature review and experts' opinion. For a real case application, a detailed survey could be done to detect the end-user preferences of stakeholders of the real university building to create more accurate results if it is needed.

Also, this proposed methodology for sustainable university building design could be applied different building where various groups of stakeholders exist. Furthermore, other different MCDM methods such as VIKOR or TOPSIS could be add to integrated 2-Tuple with QFD method to evaluate and select the best university with detected DRs.

When this method is applied in far-reaching environments, it could be used to create and retrofit sustainable neighbourhoods in further studies.

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BIOGRAPHICAL SKETCH

Deniz UZTÜRK was born in Izmit on July 16, 1989. In 2002, she obtained the chance to study in Saint Joseph French High School in Istanbul. Later between years 2008 and 2014 she obtained her B.S. degree in Mining Engineering in Istanbul Technical University. Since September 2014, she is a student at Galatasaray University in M.S of Industrial Engineering. Also since March 2017 she works in Mavi Consulting in sustainability subject. Her areas of interest include quality function deployment, multi-criteria decision making, 2-Tuple linguistic representation, sustainability, and logistics. Her publications are given in the next section.

PUBLICATIONS

- Gülçin Büyüközkan, Deniz Uztürk "A QFD Based Sustainable Building Framework: Application for University Buildings" SBE 2016 Istanbul, October 2016
- Deniz Uztürk, Gülçin Büyüközkan "A QFD Approach for Sustainable Warehouse Design" LM-SCM 2016 Izmir, December 2016
- Gülçin Büyüközkan, Merve Güler, Deniz Uztürk "Selection of Wearable Glasses in the Logistics Sector"LM-SCM 2016 Izmir, December 2016
- Gülçin Büyüközkan, Deniz Uztürk "Combined QFD TOPSIS Approach with 2-Tuple Linguistic Information for Warehouse Selection" FUZIEEE 2017 Naples, July 2017 *(Paper Accepted)*