Sustainable Farm Building Design with 2-Tuple House of Quality

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Abstract

Sustainability could be a good strategy or a path to follow for any industry to achieve a durable and adaptable system. In the construction sector, where a non-stop activity to build a new environment exists, sustainability is a massive necessity for continuity. Sustainable construction and design facilitate adaptable solutions with nature rather than producing solutions against it. Hence, this paper aims to propose a methodology for designing farm buildings for sustainable agriculture. The need for structures in the rural lands is a necessity for farming activities and stocking. Creating a sustainable building for farming practices is also an essential step to transition to sustainable agriculture. For this purpose, the House of Quality (HoQ) of the Quality Function Deployment (QFD) is suggested with the 2-tuple linguistic model integration. The group decision-making (GDM) approach is applied to simulate stakeholder inclusion for the design phase. The 2-tuple model helps to compute with multi-granular linguistic information. The use of multi-granular information augments the accuracy of computations and transforms the design phase closer to human thinking. To test the plausibility of the recommended methodology, a case study from Turkey is presented with the results and the analysis. Finally, the concluding remarques are provided at the end.

Keywords: Building design, sustainable farm building, HoQ, QFD, 2-tuple linguistic model, GDM

I. INTRODUCTION

Sustainability becomes one of the critical trending notions in our century with the rising awareness about the human effects on our earth. When it comes to sustainability, the idea is addressed in three dimensions: environmental, economic, and social. These three notions are the three main components of sustainability. The primary purpose of these components is to be stable or sustained in any situation. For this purpose, efficient usage of economic, environmental, and social sources is significant.

Sustainability could be a good strategy or a path to follow for any industry to achieve a durable and adaptable system. In the construction sector, where there is non-stop activity to build a new environment, sustainability is necessary to have continuity. In the building sector, the realization of sustainable building remains at a low rate, despite the increased need for it [13]. 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 [1]:

- 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. However, a prioritization of these principles could be done to achieve a sustainable building step by step. Different multi-criteria decision-making (MCDM) approaches could be used to handle the complications of this application. In this paper, the House of Quality (HoQ) of the Quality Function Deployment Method (QFD) is recommended to translate customer requests into building design requirements. The customer requests are treated as the sustainability requirements for operating a methodology that serves for sustainable design.

As an application area, the agricultural buildings are selected. The agricultural systems have immense impacts on their environments [30]. And the need for structures in the rural lands is a necessity for farming activities and stocking. Therefore, designing a sustainable building for farming practices is also an important step to transition to sustainable agriculture.

Consequently, this paper suggests an HoQ based framework for a sustainable farm building design. The HoQ technique is extended with the 2-tuple linguistic model to fortify its ability to deal with linguistic variables. Plus, the 2-tuple model facilitates the interpretation of outputs with linguistic variables, creating an assessment model closer to human thinking. A group decision-making (GDM) approach is followed to mimic the stakeholder or end-user inclusion in the designing phase. By integrating the end-user and the sustainability issues into the building design, this

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methodology aims to propose valuable guidance for farmers for their buildings.

The main contribution of this paper can be summarized as a first-time proposition of a linguistic model for a sustainable farm building design. The suggested linguistic-based design framework may guide farmers and policymakers to reach a sustainable agriculture environment. Plus, policymakers can use this methodology to create regulations for their rural areas.

The remaining parts are organized as follows: The following section gives the existing literature about HoQ and the building design area. Moreover, the same section provides a detected customer needs (CNs) and design requirements (DRs) for sustainable farm building design. Section III presents the preliminaries about the recommended methodology. Section IV gives the case study, and the results and analysis are presented followingly. Finally, in Section VI, the concluding remarques are provided.

II. LITERATURE REVIEW

This section gives the theoretical background about building design and QFD and the suggested 2-tuple HoQ framework components.

A. Building Design and QFD

Shigeru Mizuno and Yoji Akao first introduced QFD at the end of the '60s. Concerning transferring customer expectations, QFD is a robust approach with suitable applications[2]. Various studies discussed QFD and its applications in different areas. The main idea of the QFD approach is how to balance CNs. Prearranging CN is the leading and first step for QFD. In this paper, it is recommended to use for the design of a sustainable farm building. For this purpose, detailed research about sustainable building requirements and their design requirements is done.

In the literature, Uztürk et al. suggested a fuzzy linguistic-based approach for a hospital building design [24]. The healthcare sector is the one sector that a QFD model is suggested for the building design [8, 25]. Other studies commonly focus on building envelop design [21–23] or building design management [19, 26, 27] with QFD methodology.

As seen from the existing literature, the QFD and its HoQ are potent tools to handle building design decisions. Moreover, its extension with the fuzzy linguistic creates more accurate and unbiased findings for the designers and construction teams. So, by generating robust CNs and DRs, the recommended model may be convenient for the building designers and construction firms. The detected customer expectations and the technical requirements for a sustainable farm building will be given in the next section.

B. Sustainable Farm Building Design

Sustainable construction and design facilitate adaptable solutions with nature rather than producing solutions against it. In the long term, it also helps for energy-saving and cost-saving for farming activities [14]. The construction phase and the design phase are both proposing solutions for sustainable building. Among them, the design phase has a more critical role in the life cycle of the building [3, 21]. The initial decisions in the designing phase have an immense effect on the long-term of the construction site and the building's land use.

Consequently, a better analysis of the desired sustainability issues should be addressed in the design phase. Considering the value of the design components, in this paper, two groups of requirements are generated from a comprehensive academic literature review.

The first group covers the CNs in the HoQ, and the second one contains the DRs to reach the CNs. The CNs are assigned as the sustainability requirements that a farm building has for its future life. Table 1 and Table 2 present the detected CNs and the DRs for a sustainable farm building design.

Table 1. CNs for the farm building design [3–5, 10, 11].

CN#	CNs
CN1	Flexible interiors
CN2	Quick construction
CN3	Low cost
CN4	Less site preparation
CN5	Durability
CN6	Natural Ventilation
CN7	Natural Lighting
CN8	Less resource usage
CN9	Accessibility
CN10	Adaptability to the field

These ten requirements form the basis of sustainable design. According to these dimensions, technical requirements for a building will be evaluated. Their relations will be studied thanks to the HoQ technique, and the 2-Tuple linguistic model will help to better analyze the relations with linguistic variables.

As aforementioned, the GDM approach will be used to obtain an objective weighting of dimensions and relations. Forming a group will help to simulate a project group for the construction projects.

Table 2. DRs for sustainable farm building [5, 10, 14, 18, 29].

DR#	DRs
DR1	Sensor utilization
DR2	Types, sizes, and shapes of openings
DR3	Fixed light windows for skylights
DR4	Flexible building envelop design
DR5	Non-toxic, low VOC glues and paints
DR6	Rainwater storage
DR7	Local material use for construction
DR8	Recycled material use
DR9	Life-cycle cost analysis before the construction
DR10	Innovative architecture
DR11	Heat emitting windows
DR12	Proper building operations and maintenance

As Table 2 states, twelve technical attributes are derived from the literature. The main aim is to prioritize them according to the CNs. As a result, their prioritization will be obtained, and the results will serve the practitioners as a roadmap for their construction projects.

The following section will present the preliminaries for the suggested methodology and the detailed steps of the framework.

III. METHODOLOGY

As aforementioned, the selected primary tool for a farm building design is HoQ. This section will give the details of the HoQ technique and the 2-tuple linguistic model.

A. 2-Tuple Linguistic Model

Herrera and Martinez first represent this model in 2000 [15]. The 2-tuple linguistic model and its extensions have been applied to various topics, mainly decision-making and decision analysis problems [15, 17, 20]. Basic definitions are as follows [15]:

The 2-Tuple fuzzy linguistic representation model represents the linguistic information using a 2-Tuple (S, α) here; S is a linguistic label, and α is a numerical value representing the value of the symbolic translation. The function is defined as:

$$\Delta_s : [0, g] \rightarrow \bar{S}$$
$$\Delta_s(\beta) = (S_i, \alpha), with \begin{cases} i = round(\beta) \\ \alpha = \beta - i \end{cases} \quad (1)$$

The linguistic term set S could be converted into 2-Tuple form by adding zero value as in the following relation:

$$S_i \in S \Rightarrow (S_i, 0) \quad (2)$$

For further details, the readers can refer to [15]. The main benefits of the 2-tuple linguistic model are the augmented accuracy and interpretability of the results and the possibility to deal with variables closer to the human beings' cognitive processes. Regarding these benefits, to create a flexible environment for the DMs and better analysis and knowledge about the sustainable building design area, the suggested 2-Tuple methodology is integrated with the HoQ technique.

B. Aggregation Technique for GDM

The main benefit of the GDM approach is to create an unbiased, objective decision-making environment where the final solution is beneficial to each DM. The GDM approach is based on the aggregation of different opinions from multiple DMs [7]. GDM is a commonly adopted method preferred over a single DM due to its superiority in avoiding partiality and bias [6, 12].

Regarding all the benefits mentioned above, the 2-tuple linguistic model's *Linguistic Hierarchies (LH)* approach is selected as an aggregation technique for this GDM methodology. The methodology is based on the experts' knowledge; however, the level of experience and expertise may differ concerning the interest of DMs. So, providing different granulated linguistic evaluation sets to each DM may be a powerful solution to balance the knowledge difference rising from diverse backgrounds.

LH [15] approach is used to unify the multigranular linguistic input under the one unified linguistic set. A transformation equation exists to normalize label sets with different granularity. The following equation gives the relations:

$$TF_{t'}^{t}(S_i^{n(t)}, \alpha^{n(t)}) = \Delta\left(\frac{\Delta^{-1}(S_i^{n(t)}, \alpha^{n(t)}) \cdot (n(t') - 1)}{n(t) - 1}\right) \quad (5)$$

where *TF* is the transformation function for *LH*, and the transformation is from t^{th} level to t'^{th} level.

Furthermore, for aggregating normalized linguistic variables *Weighted Aggregation Operator (WAO)* of 2-Tuple model is recommended as well. The following equation gives the formulation:

$$\vec{x} = \left(\frac{\sum_{i=1}^{n} \Delta^{-1}(e_i, \alpha_i) \times \Delta^{-1}(w_i, \alpha_i)}{\sum_{i=1}^{n} \Delta^{-1}(w_i, \alpha_i)}\right) = \Delta\left(\frac{\sum_{i=1}^{n} \beta_i \times w_i}{\sum_{i=0}^{n} w_i}\right) \quad (6)$$

where, (e_i, α_i) is the assessments provided by each expert; (w_i, α_i) stands for the weights of experts and n represents the number of experts and β_i is the β values for ith criterion's importance.

C. 2-Tuple HoQ Framework for Sustainable Farm Building Design

The computational steps of 2-Tuple QFD are as follows [9, 16, 28]:

1. Assigning an objective of the study. Then defining a problem related to it. Afterward, detect requirements for this objective and form a decision-making group to solve the problem.

2. Selecting a linguistic comparison scale for each DM to represent their own opinion about the problem assigned. Different scales could be chosen according to the experience of experts in the case study. Tables 3 and 4 show the different scales for experts.

Table 3. Label Set for DMs [15]

Label Set for five scale	Abbreviation	S_i^5
VL	VL	S_0^5
Low	L	S_1^5
Medium	M	S_2^5
High	H	S_3^5
Perfect	P	S_4^5

Table 4. Label set for DMs

Label Set for nine scale	Abbreviation	S_i^9
Very Low	VL	S_0^9
Almost Low	AL	S_1^9
Low	L	S_2^9
Almost Medium	AM	S_3^9
Medium	M	S_4^9
Almost High	AH	S_5^9
High	H	S_6^9
Very High	VH	S_7^9
Perfect	P	S_8^9

3. Detecting the CNs about the problem and taking their related importance from the DM group. The importance taken from the DM group is in a Label Set form.
   3.1. Normalizing the multi-granulated assessments under the highest granularity (S_i^9**)** by Eq. (5).
   3.2. Aggregating DMs normalized assessments with Eq. (6).
4. Detecting DRs for QFD according to the CNs.
   At this step, DRs need to be well evaluated according to CNs to get logical relations between them during the relation matrix construction.
5. Constructing the relation matrix for HoQ to determine pairwise relations between CNs and DRs.
   This step is to determine the level of relations between CNs and DRs. The DMs can perform their evaluations again in the label set form, and the same steps as 3.1 and 3.2 are to follow to aggregate the DMs assessments.
6. Calculating the importance of DRs and ranking them in decreasing order.

Figure 1 represents the HoQ components and structure, and followingly, Figure 2 summarizes the suggested framework's steps.

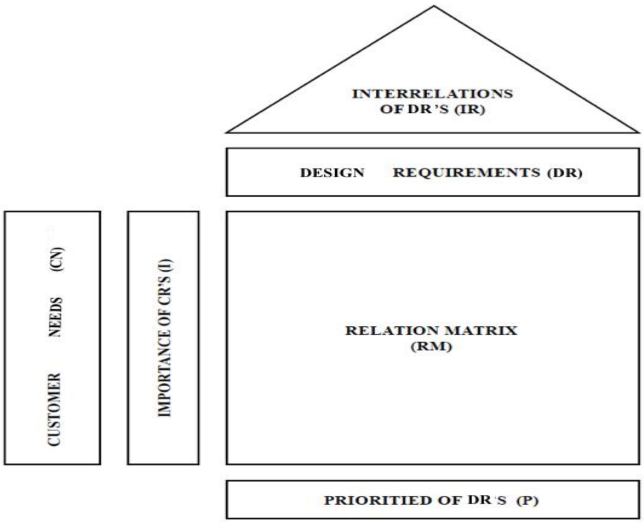

Figure 1. The HoQ structures[2].

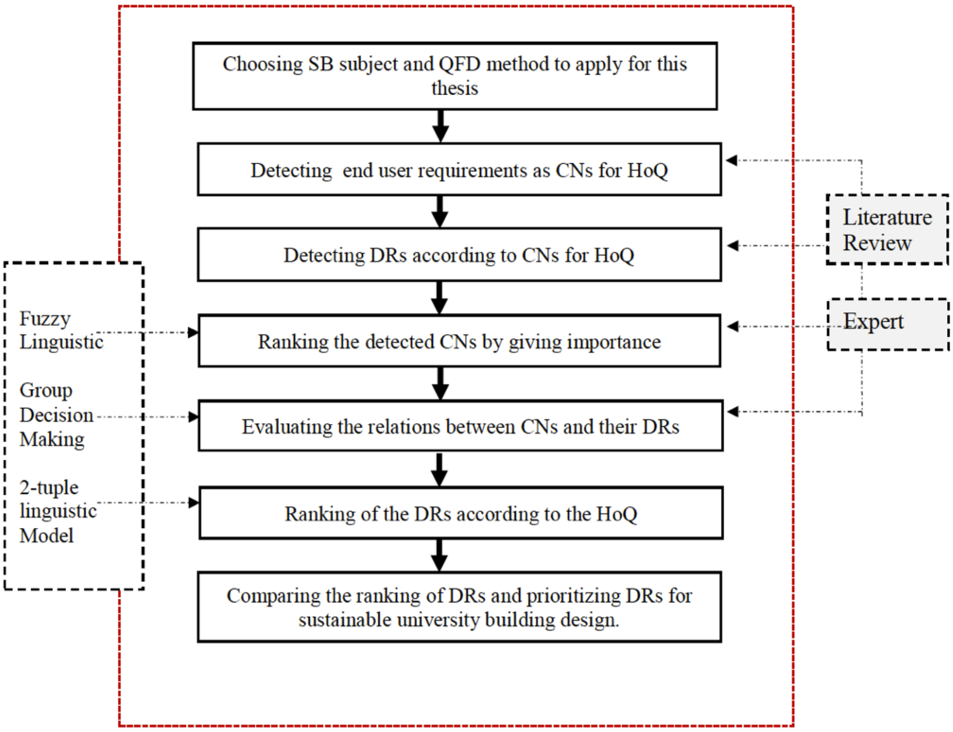

Figure 2. Summary of the suggested methodology

IV. CASE STUDY

In this section, a case study from Turkey is presented to test the plausibility of the recommended methodology.

An organic farm closer to Istanbul city is chosen as a case study. The selected farm also provides accommodation to its visitors in sustainable buildings. So, the farm's strategy is familiar with sustainability and sustainable design. Besides its accommodation areas, the farm also continues to produce organic food in the rural regions of Kandıra. They plan to design a farming building closer to their greenhouses and the production field. Therefore, we have proposed our methodology as guidance for their farm building project.

Consequently, a decision-making group is formed from two owners/managers of the farm and one academician. Two DMs from the farm had different experiences about the sustainable building and design area so that S_i^5 and S_i^9 are provided to them. The academician also made her assessments with S_i^9label set.

As stated in Section III, Step 4, the DMs are asked to evaluate CNs (Table 1) separately. Here Table 5 gives the individual assessments of each DM and their aggregated importance.

Table 5. DMs assessments and the aggregated importance of CNs

DM1	DM2	DM3	Aggregated	Beta values
M	AH	P	(H,-0.04)	5.96
H	AM	M	(M,0.04)	4.04
M	H	P	(H,0.35)	6.35
P	VH	AH	(H,-0.43)	6.43
P	P	P	(P,0)	8.00
P	P	P	(P,0)	8.00
P	VH	P	(P,-0.39)	7.61
H	H	H	(H,0)	6.00
M	AM	AM	(M,-0.39)	3.61
H	AH	P	(H,0.39)	6.39

As stated in Section III.C, Step 5, the relation matrix is constructed to investigate the relations between the CNs and DRs. The following Table 6 gives the aggregated ultimate relation matrix for the case study.

During the formation of aggregated relation matrix, each DMs' assessments were collected separately. The normalization and the aggregation steps in Section III are followed, and finally, the relation matrix is obtained. Afterward, using the CNs importance, prioritization for the DRs is obtained.

The details of the obtained results and the sensitivity analysis will be given in the next section.

V. RESULTS AND ANALYSIS

The obtained beta values for each DR are given in Figure 3. By using Eq. (1), the beta values can be presented in linguistic label set form.

When the DRs are ranked according to their final beta values, the most critical five technical requirements are detected as:

1. Innovative architecture
2. Local material use for construction
3. Flexible building envelop design

Table 6. Final aggregated relation matrix.

	DRs / CNs	CNs Importan	DR1 Sensor utilization	DR2 Types, sizes and shapes of openings	DR3 Fixed ligh windows for skylights	DR4 Flexible building envelop design	DR5 Non-toxic low VOC glues and paints	DR6 Rainwater storage	DR7 Local material use for construction	DR8 Recyled material use	DR9 Life-cycle cost analysis before the construction	DR10 Innovative architecture	DR11 Heat emitting windows	DR12 Proper building operations and maintenance
CN1	Flexible interiors	(H,-0.04)		(AM,0.22)		(P,0)		(M,-0.43)	2.78		(AM,-0.22)	(AH,-0.22)		(AH,-0.22)
CN2	Quick construction	(M,0.04)		(H,0)		(M,0)			(P,0)		(L,0)	(M,0)		(AH,-0.22)
CN3	Low cost	(H,0.35)	(L,0)		(AL,0.22)	(AL,0.22)		(AH,-0.22)	(H,0)	(P,0)	(VH,0.22)		(H,0)	(L,0.29)
CN4	Less site preperation	(H,-0.43)							(H,0.39)			(P,0)		(L,0.29)
CN5	Durability	(P,0)		(L,0)		(AH,0.22)	(AH,0.22)		(H,0.39)		(P,0)	(L,0)		(VH,-0.22)
CN6	Natural Ventilation	(P,0)	(M,0)	(VH,0.17)		(M,0)						(VH,-0.22)	(AH,-0.22)	
CN7	Natural Lighting	(P,-0.39)	(H,0)	(VH,0.17)	(P,0)	(AH,-0.22)						(VH,-0.22)		
CN8	Less resourse usage	(H,0)	(M,0)					(P,0)	(VH,0.17)	(VH,0.22)				(AH,-0.22)
CN9	Accessibility	(M,-0.39)									(L,0)	(M,0)		
CN10	Adaptability to the field	(H,0.39)				(AH,-0.22)	(AH,-0.22)					(M,0.39)		(L,-0.39)

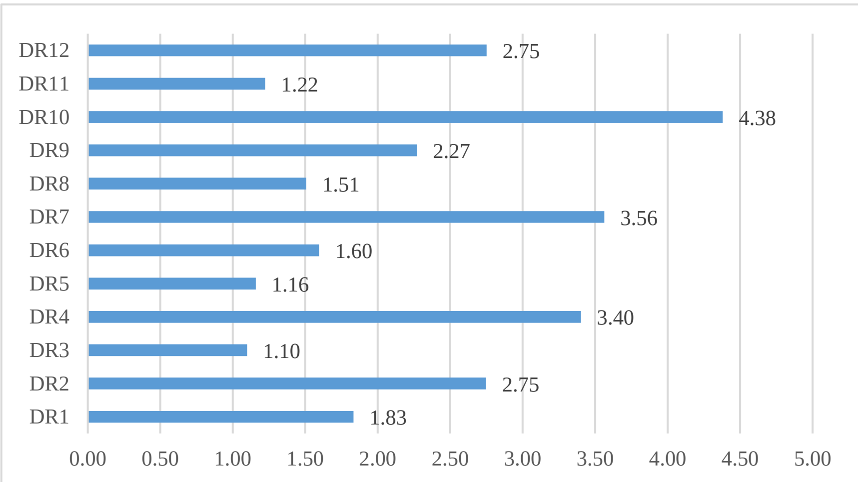

Figure 3. Obtained beta values for the final ranking of DRs.

4. Types, sizes, and shapes of openings
4. Proper building operations and maintenance
5. Fixed light windows for skylights

The ranking of DRs proposes a roadmap to follow to reach a sustainable farm building. By changing the CNs importance, each project can have its road for designing with their preferences. Accordingly, testing the robustness and the replicability of the model is essential. For that purpose, a sensitivity analysis is conducted. Figure 4 gives the results of the sensitivity analysis.

Ten different scenarios are created; each scenario emphasizes one CN. Ten different rankings are obtained, and the values show that the suggested model ranks the DRs according to CN weights.

The same sensitivity analysis also enables us to investigate DR-CN relations more carefully. The changing ranking of DR shows us which CN has a significant impact on which technical attributes. Accordingly, by analyzing these differences more comprehensive understanding of the sustainable farm building design can be obtained.

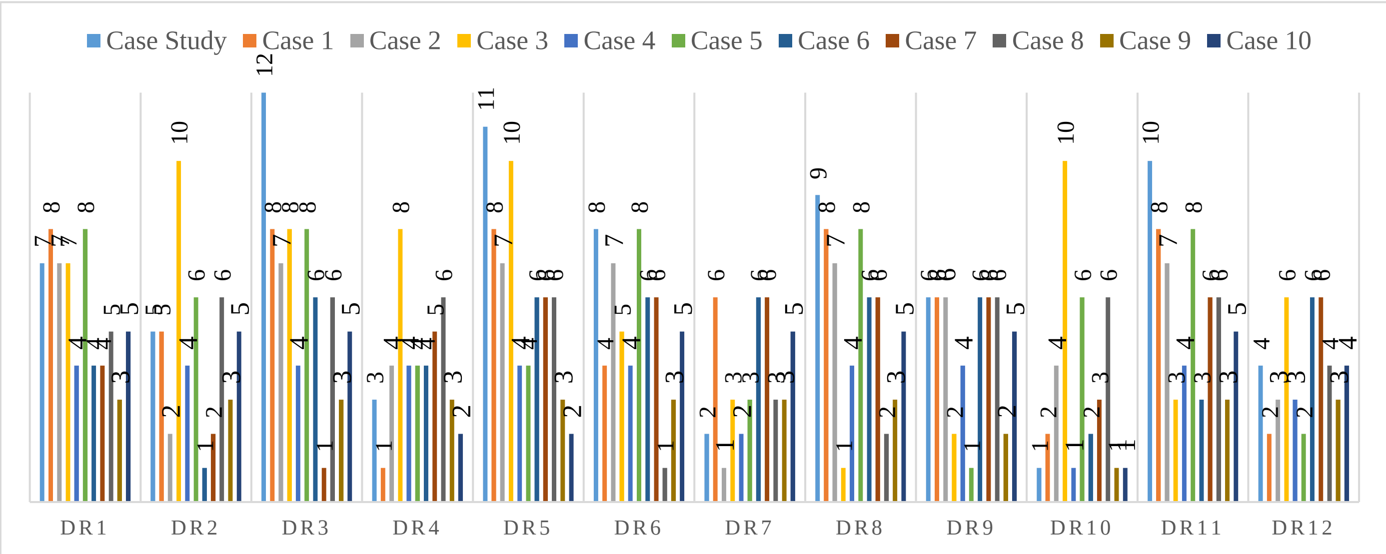

Figure 4. Sensitivity analysis

VI. CONCLUSIONS

Nowadays, where sustainability is a critical issue for creating more durable and flexible systems, this paper proposes a valuable framework for sustainable agriculture. Transition to sustainable agriculture is a process which is needed to be designed carefully. One of the agricultural system components is the farm buildings that are located in the farming fields. So, to reach a sustainable agricultural system, whole system components should design concerning the sustainability issues. Consequently, a comprehensive design approach is needed for environmentally friendly agriculture fields.

The well-known design tool, HoQ, is suggested for designing sustainable farm buildings. Moreover, the HoQ technique is extended with the 2-tuple linguistic model to create a model that can operate with the linguistic information. To test the applicability of the recommended framework, a real case study from Turkey is presented. The results from the case study showed that the innovative architecture, local material usage, and the envelop design are the primary first three steps to follow for a sustainable farm building.

This paper aims to present guidance for practitioners and construction companies to follow during their projects. The methodology is adaptable for different cases; by changing the CNs' weights, each project can obtain its roadmap for its projects.

As a limitation, the number of DMs can be stated. In this paper, the recommended methodology is tested with three DMs; however, the framework can work with DMs up to higher numbers.

Furthermore, for future studies, the same methodology can be followed for other industries as well. The same methodology can serve as valuable guidance for strategy and solution detection for various sectors by improving the CNs according to the sectors.

VII. ACKNOWLEDGMENTS

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