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Interval-Valued Pythagorean Fuzzy QFD Design Weighted by Best-Worst Method: An Application to E-Scooter Design

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Abstract. Quality Function Deployment (QFD) is a technique used to collect Customer Requirements (CRs) for the product to be designed before the start of the manufacturing processes, and also used to determine whether CRs will be met with correlated or uncorrelated Design Requirements (DRs). In QFD technique, customers tend to explain their expectations from the product by using linguistic expressions instead of using exact numbers. Vagueness and impreciseness in linguistic expressions can be captured perfectly using fuzzy set theory. Pythagorean fuzzy (PF) sets as one of the extensions of ordinary fuzzy sets offer the decision maker a larger membership and non-membership assignment region than ordinary intuitionistic fuzzy sets. In this paper, customer requirements in QFD analysis are prioritized by Best-Worst Method (BWM), which has become a very popular optimization-based weighting method in recent years. In the proposed BWM and QFD methodology, interval-valued Pythagorean fuzzy (IVPF) sets are used for the first time in order to handle the uncertainties in the linguistic judgments. In the application, the two-phase IVPF methodology is proposed to a real life e-scooter design problem addressing 12 customer & 12 design requirements. The proposed PF methodology could determine the weights of customer requirements, and identify which of the design requirements is stronger, and make a competitive analysis to reveal the position of our company in the market under fuzzy environment. Besides, the sensitivity and comparative analyses have demonstrated the dominance of our company over the other competitors.

Key words: interval-valued Pythagorean fuzzy sets, QFD, House of Quality, Best-Worst Method, Multi-Criteria Decision-Making (MCDM), Multi-Attribute Decision-Making (MADM), E-scooter design.

1. Introduction

An organized method for identifying client needs or requirements and converting them into detailed plans for producing goods that would satisfy those demands is known as

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Quality Function Deployment (QFD) which was introduced by Mizuno and Akao (1978). These explicit and implicit client needs or demands are referred to as the "voice of the customer". Several techniques are used to record the voice of the consumer, including direct conversation or interviews, surveys, focus groups, customer specifications, observation, warranty information, and field reports, etc. Hence, the "Voice of the Customer" is translated via QFD into the precise technical specifications and standards that the design must meet in order to be successful on the market. Especially in product planning and new product development, QFD is frequently utilized.

A product planning matrix, often known as a "house of quality", is then created to compile this understanding of the needs of the customers. These matrices are used to translate higher level "what's" into lower level "how's" – product specifications or technological features—that can be used to meet those needs (Song *et al.*, 2014).

Experts mostly prefer to use linguistic variables such as Certainly Low Importance (CLI) and Certainly High Importance (CHI) to explain the importance of the customer requirements. The relationships between whats and hows can also be evaluated by a different linguistic term set such as Certainly High Relation (CHR) and Certainly Low Relation (CLR). Apart from these, organizational difficulty explains the difficulty of technical requirements to be realized. Organizational difficulties are appraised by linguistic terms as well, and located at the bottom of the House of Quality. In this part, absolute importance values are also computed, which indicates the technical aspects of the considered product taking the most attention from the customers. Next, relative absolute importance values are calculated pointing out the relative importance degrees of the design requirements where the sum of these relative values equals to "1".

At the roof of the House of Quality, correlations between the hows are indicated by linguistic sets ranging from Certainly Low Positive Correlation (CLPC) to Certainly High Positive Correlation (CHPC). The wall on the very right side points out the customer ratings with respect to customer requirements using the terms such as Certainly Low Satisfactory (CLS), or Certainly High Satisfactory (CHS). Similarly, at the very bottom of the House of Quality, engineering assessments of the companies/organizations are performed with regard to design requirements using the terms such as Certainly Low Satisfactory (CLS), or Certainly High Satisfactory (CHS). Corresponding numerical values of linguistic terms can be assigned from linguistic scales generally including five to nine fuzzy levels.

Linguistic terms can be transformed to their corresponding numerical values by utilizing the fuzzy set theory developed by Zadeh (1965). Ordinary fuzzy sets have been expanded to several new extensions with the aim of defining more detailed membership functions including decision makers' hesitancies. These recent extensions can be listed as Intuitionistic Fuzzy Fets (IFS), Pythagorean Fuzzy Sets (PFS), Fermatean Fuzzy Sets (FFS), Neutrosophic Sets (NS), and Picture Fuzzy Sets (PiFS) etc. In this paper, we employ PFS in order to capture vagueness and ambiguities in the linguistic assessments with a larger domain to assign membership degrees (Akram *et al.*, 2024).

Generally, the importance degrees of customer requirements are different since a disparate linguistic assessment is made by the customers for each requirement. The weights

of customer requirements can be determined by various techniques such as Analytic Hierarchy Process (AHP) (Saaty, 1980), Analytic Network Process (ANP) (Saaty, 1996), the CRiteria Importance Through Intercriteria Correlation (CRITIC) (Diakoulaki *et al.*, 1995), Step-wise weight assessment ratio analysis (SWARA) (Kersuliene *et al.*, 2010) and Simple Multi-attribute Rating Technique (SMART) (Edwards and Barron, 1994).

One of the frequently used weighting method is Best-Worst Method (BWM) (Rezai, 2015) which is an optimization-based method differing from the above techniques with this feature (Gul *et al.*, 2024). BWM provides a list of advantages as comprehensive view of the evaluation range allowing researchers the ability of verifying the coherence of pairwise comparisons. In order to reduce potential bias in decision making, BWM uses a dual pairwise comparison model in a single optimization framework. It is also capable of producing multiple optimal solutions under the scenarios having at least three criteria or alternatives. In order to cope with uncertainties and ambiguity, there have been a number of versions of the classical BWM by utilizing different fuzzy set extensions such as intuitionistic fuzzy sets and spherical fuzzy sets. We employ Pythagorean fuzzy sets for the extensions of BWM and QFD methods. The advantage of Pythagorean fuzzy sets over intuitionistic fuzzy sets is that they allow membership degrees to be assigned from a broader domain. This allows the expert to be more comfortable and flexible in assigning membership degrees. The preference between Pythagorean Fuzzy Sets (PFS) and Spherical Fuzzy Sets (SFS) relies heavily on the type of uncertainty the experts deal with, mathematical flexibility, and interpretability in decision-making problems. PFS has been more widely adopted and studied compared to SFS. SFS allows more flexibility by including hesitancy, but this can also introduce ambiguity or overfitting in modelling if the hesitancy degree isn't well-defined.

In this paper, an interval-valued Pythagorean fuzzy (IVPF) BWM is introduced to determine the weights of the customer requirements. This process is applied for each of the multiple experts; and later the set of weights obtained from BWM are aggregated and used as an input for IVPF QFD analysis. According to the best knowledge of the authors, this is the first time to develop IVPF BWM and integrate it into IVPF QFD analysis for solving a real life product design problem.

E-scooters are one of the most common micro-mobility vehicles. Shared e-scooters are frequently preferred because of their affordable travel costs, easy availability, and easy progress in crowded traffic. There are several different e-scooters in the global market each having different features. In the literature, few studies conducted on e-scooter design through MCDM methods exist (Torrisi *et al.*, 2025; Sonawane *et al.*, 2025).

In this paper, a new scooter is aimed to be designed based on QFD analysis integrated with BWM including 12 customer and 12 design requirements. In this design, customer requirements such as "*Long lasting electric scooter charge*", "*fast charging*", "*Bluetooth Internet connection*", and "*Climbing ramps with ease*" are involved while design requirements such as "*Lithium ion* (*Li-Ion*) *batteries*", "*Charging rate*", "*Wi-Fi Bluetooth assembly*", and "*Stainless adjustable umbrella holder*" are handled to meet the customer requirements. Herein, linguistic assessments are employed for customer and design requirements, and then these assessments are converted to their corresponding IVPF numbers. House of

Fig. 1. Frequencies of fuzzy BWM papers by publication years.

Quality computations are realized based on these Pythagorean fuzzy numbers. Besides, competitive and sensitivity analyses are also implemented to illustrate the position of our company among the competitors and monitor how this position is affected based on the different values of a coefficient which is used to compile the Overall Performance Rating scores based on the DRs and CRs.

Organization of the study is as follows: Section 2 provides a detailed literature review on fuzzy BWM and QFD. Section 3 gives the preliminaries of IVPF sets while Section 4 displays the steps of the proposed IVPF BWM and QFD methodology. Section 5 demonstrates the application of the proposed IVPF methodology, sensitivity and comparative analyses. Finally, Section 6 presents conclusions and states the future remarks.

2. Literature Review on Fuzzy BWM & QFD

In this section, a comprehensive literature review on fuzzy BWM method and fuzzy QFD method is separately presented. The section focuses on MCDM methods integrated with BWM and QFD studies under fuzzy environment.

2.1. *Fuzzy BWM*

To deal with uncertainties and vagueness in humans' cognitive decision making processes, the fuzzy set theory is integrated into BWM. The literature review in article title, abstract, and keywords on fuzzy BWM in SCOPUS database provided 584 papers. The distribution of the published papers on fuzzy BWM is illustrated by Fig. 1.

Below, short summaries of the recent publications employing different extensions of the ordinary fuzzy sets are presented according to their chronological orders. In one of the early studies, Guo and Zhao (2017) proposed the integration of the fuzzy set theory into BWM enabling articulation of linguistic terms defined by triangular fuzzy numbers. In the paper, the authors applied The Graded Mean Integration Representation to appraise

the set of criteria and alternative options. Mou *et al.* (2017) initiated and integrated the Intuitionistic Fuzzy Preference Relation with BWM for a group decision making problem. In the study, the researchers compile individual preference relations to weighted individual preferences where they are used to determine the best and worst criteria. Majumder *et al.* (2021) proposed the integration of BWM and AHP utilizing intuitionistic fuzzy sets to identify the most essential alternative for a water treatment plant. Norouzi and Hajiagha (2021) proposed the usage of interval-valued type-2 fuzzy sets into fuzzy BWM. In the study, experts' hesitant opinions were also considered. The proposed approach was applied to various numerical cases. Alimohammadlou and Khoshsepehr (2022) implemented hesitant fuzzy BWM to a green-resilient supplier selection problem. In the study, the researchers suggested to consider four factors which were sequentially production, green quality, organizational aspects, and resilience. Liu *et al.* (2022) applied the QUALItative FLEXible multiple criteria (QUALIFLEX) approach which was combined with fuzzy BWM and fuzzy CRITIC method employing q-rung orthopair fuzzy sets to a green supplier evaluation problem. Tavana *et al.* (2022) preferred an integrated BWM and CoCoSo method by means of interval Type-2 trapezoidal fuzzy sets to assess engineering and ecological difficulties and evaluate eco-friendly packaging option. Alimohammadlou and Sharifian (2023) utilized BWM and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) method with Interval Type-2 Fuzzy Sets (IT2FSs) to cope with uncertainties that Small and Medium-sized Enterprises (SMEs) have faced during the transition to Industry 4.0. Chao *et al.* (2024) applied a single alone method-fuzzy BWM with hesitant fuzzy linguistic terms for evaluating industrial water resources security options. Chen *et al.* (2024) implemented fuzzy BWM, regret theory, and the Multi-Attributive Border Approximation area Comparison (MABAC) methods using interval-valued intuitionistic fuzzy sets in order to decide on an appropriate disposal mode for emergency medical waste. Deniz and Aydin (2024) incorporated fuzzy BWM and the Multi-Objective Optimization by Ratio Analysis (MULTIMOORA) method via spherical fuzzy sets to assist bus charging station location selection under smart and sustainable view point. Otay *et al.* (2024) proposed an integrated optimization based Pythagorean fuzzy BWM and TOPSIS methodology for prioritizing sustainable energy systems in smart cities. Seikh and Chatterjee (2024) applied SWARA, BWM, and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) by employing interval-valued Fermatean fuzzy sets for e-waste management strategy evaluation problem by taking into account various criteria such as environmental effects, waste disposal necessities, job potentials, and investment costs.

2.2. *Fuzzy QFD*

In several fuzzy QFD studies, different MCDM methods have been integrated into the QFD analysis such as AHP (Akbaş and Bilgen, 2014), Multi-Objective Optimization on the basis of a Ratio Analysis (MULTIMOORA) (Tavana *et al.*, 2021), TOPSIS (Dat *et al.*, 2015), VIKOR (Wu *et al.*, 2017), and Grey Relation Analysis (GRA) (Song *et al.*, 2014). Besides, QFD method was often integrated by other fuzzy set extensions. Hesitant fuzzy QFD (Onar *et al.*, 2016), Intuitionistic fuzzy QFD (Yu *et al.*, 2018), Neutrosophic

Fig. 2. Keywords network analysis on “product design”, “fuzzy” and “QFD”.

QFD (Van *et al.*, 2018), Interval-valued Pythagorean fuzzy QFD (Haktanir and Kahraman, 2019), Interval type-2 fuzzy QFD (Liu *et al.*, 2019), q-Rung orthopair fuzzy QFD (Liu *et al.*, 2021a), Fermatean fuzzy QFD (Sumrit and Keeratibhubordee, 2024), Spherical fuzzy QFD (Kutlu Gündoğdu and Kahraman, 2020), and Picture fuzzy QFD (Li *et al.*, 2022). Figure 2 presents the results of network analysis done by VOSviewer 1.6.20, based on the association strength of keywords, with a minimum cluster size of ten for the keywords of “product design”, “fuzzy” and “QFD”.

Our literature review in article title, abstract, and keywords on QFD using SCOPUS database gave 4,920 published papers. Among these, 894 papers use fuzzy QFD in their article titles, abstracts, and keywords while 265 papers utilize fuzzy QFD in their titles. The distribution of the papers on fuzzy QFD is given by Fig. 3.

Below, there are short summaries of some noteworthy studies on the fuzzy QFD method that have been published since 2015. Yazdani *et al.* (2019) integrated QFD and grey relational analysis to ease the decision process to determine main supply chain drivers. Haktanir (2020) developed an integrated Pythagorean fuzzy QFD & COPRAS methodology under fuzzy environment to prioritize competitive suppliers. Wang *et al.* (2020) developed an integrated collaborative quality design framework for large complex products supply chain by using fuzzy QFD and grey analysis. Liu *et al.* (2021b) proposed a hesitant fuzzy linguistic QFD method with prospect theory to overcome the limitations of the traditional QFD. Wu *et al.* (2021) proposed a Kano model and TOPSIS method integrated QFD model to measure the uncertainties and behavioural risk factors in e-

Fig. 3. Frequencies of QFD publications by years.

commerce service design under interval type-2 fuzzy linguistic environment. Efe and Efe (2022) developed a q-rung orthopair fuzzy QFD approach to adjust the weights of CRs. Haktanir and Kahraman (2022) developed an intuitionistic Z-fuzzy QFD method with Chebyshev's inequality and applied it for a new product design. Karasan *et al.* (2022) proposed a neutrosophic QFD methodology based on AHP & DEMATEL and applied it to the design of a car seat. Aydin *et al.* (2023) developed a sustainable linear programming based QFD methodology under interval-valued intuitionistic fuzzy environment. Seker and Aydin (2023) developed a Fermatean fuzzy based QFD methodology to satisfy passenger requirements. Wang *et al.* (2023) proposed an interval 2-tuple Pythagorean fuzzy QFD approach integrating the social network consensus reaching model, and CoCoSo method. Yang *et al.* (2024) extended a single-valued neutrosophic grey relational analysis to identify the interdependence priority of DRs.

3. Preliminaries of Pythagorean Fuzzy Sets

3.1. *Single-Valued Pythagorean Fuzzy Sets (SVPFSs)*

Intuitionistic type-2 fuzzy sets initiated by Atanassov (1999), were named as Pythagorean fuzzy sets in 2013 (Yager, 2013). In a Pythagorean fuzzy set (PFS), the sum of the squares of membership and non-membership degrees is less than or equal to "1" while their sums may be greater than "1" (Otay and Jaller, 2019).

Let X be a fixed set, then a PFS $\tilde{A}$ is defined as in Eq. (1) (Yager, 2016):

$$\tilde{A} \cong \left\{\left\langle x, \mu_{\tilde{A}}(x), v_{\tilde{A}}(x)\right\rangle; x \in X\right\} \quad \text{where } 0 \leqslant \mu_{\tilde{A}}(x)^2 + v_{\tilde{A}}(x)^2 \leqslant 1, \tag{1}$$

where $\mu_{\tilde{A}}(x) : X \to [0, 1]$ is a membership degree and $v_{\tilde{A}}(x) : X \to [0, 1]$ is a non-membership degree of the element $x \epsilon X$ to A.

A hesitancy degree of a PFS $\tilde{A}$ is stated as in Eq. (2):

$$\pi_{\tilde{A}}(x) = \sqrt{1 - \mu_{\tilde{A}}(x)^2 - v_{\tilde{A}}(x)^2}. \tag{2}$$

Assume that $\tilde{a} = \langle \mu_1, v_1 \rangle$, $\tilde{b} = \langle \mu_2, v_2 \rangle$, and $\tilde{c} = (\mu, v)$ are Pythagorean fuzzy Numbers (PFNs). Then, some arithmetic operations for these PFNs can be presented in Eqs. (3)–(5) (Pérez-Domínguez *et al.*, 2018).

$$\tilde{a} \oplus \tilde{b} = \left(\sqrt{\mu_1^2 + \mu_2^2 - \mu_1^2\mu_2^2}, v_1 v_2\right), \tag{3}$$

$$\tilde{a} \otimes \tilde{b} = \left(\mu_1\mu_2, \sqrt{v_1^2 + v_2^2 - v_1^2 v_2^2}\right), \tag{4}$$

$$\lambda\tilde{c} = \left(\sqrt{1 - \left(1 - \mu^2\right)^\lambda}, v^\lambda\right); \qquad \tilde{c}^\lambda = \left(\mu^\lambda, \sqrt{1 - \left(1 - v^2\right)^\lambda}\right) \quad (\lambda > 0). \tag{5}$$

3.2. *Interval-Valued Pythagorean Fuzzy Sets (IVPFSs)*

Let $\tilde{A} = \langle [\mu_L, \ \mu_U], [v_L, v_U] \rangle$ be an Interval-Valued Pythagorean Fuzzy Number (IVPFN), then upper and lower hesitancy degrees (π_L and π_U) can be given as in Eq. (6):

$$\pi_L^2 = 1 - \left(\mu_U^2 + v_U^2\right); \qquad \pi_U^2 = 1 - \left(\mu_L^2 + v_L^2\right). \tag{6}$$

Assuming that $\tilde{A} = \langle [\mu_{\tilde{A}}^-, \mu_{\tilde{A}}^+], [v_{\tilde{A}}^-, v_{\tilde{A}}^+] \rangle$ and $\tilde{B} = \langle [\mu_{\tilde{B}}^-, \mu_{\tilde{B}}^+], [v_{\tilde{B}}^-, v_{\tilde{B}}^+] \rangle$ are IVPFNs, and, then some arithmetic operations are as in Eqs. (7)–(10) (Peng and Yang, 2015):

$$\begin{aligned}\tilde{A} \oplus \tilde{B} &= \left(\left[\sqrt{(\mu_A^L)^2 + (\mu_B^L)^2 - (\mu_A^L)^2(\mu_B^L)^2}, \sqrt{(\mu_A^U)^2 + (\mu_B^U)^2 - (\mu_A^U)^2(\mu_B^U)^2}\right], \left[v_A^L v_B^L, v_A^U v_B^U\right]\right),\end{aligned} \tag{7}$$

$$\begin{aligned}\tilde{A} \otimes \tilde{B} &= \left(\left[\mu_A^L\mu_B^L, \mu_A^U\mu_B^U\right], \left[\sqrt{(v_A^L)^2 + (v_B^L)^2 - (v_A^L)^2(v_B^L)^2}, \sqrt{(v_A^U)^2 + (v_B^U)^2 - (v_A^U)^2(v_B^U)^2}\right]\right),\end{aligned} \tag{8}$$

$$\lambda\tilde{A} = \left[\sqrt{(1 - (1 - (\mu_A^L)^2)^\lambda}, \sqrt{(1 - (1 - (\mu_A^U)^2)^\lambda}\right], \left[(v_A^L)^\lambda, (v_A^U)^\lambda\right]), \quad (\lambda > 0), \tag{9}$$

$$(\tilde{A})^\lambda = \left(\left[(\mu_A^L)^\lambda, (\mu_A^U)^\lambda\right], \left[\sqrt{(1 - (1 - (v_A^L)^2)^\lambda}, \sqrt{(1 - (1 - (v_A^U)^2)^\lambda}\right]\right), \quad (\lambda > 0). \tag{10}$$

Definition 1. Assume that $\tilde{A}_j = \langle [\mu_{Lj}, \ \mu_{Uj}], [v_{Lj}, v_{Uj}] \rangle$ is an IVPFN and $w = (w_1, w_2, \ldots, w_n)^T$, $(w_j \geqslant 0, \sum_{j=1}^n w_j = 1)$ is the weight vector of $\tilde{A}_j$. Then, Interval-valued Pythagorean Fuzzy Weighted Average (IVPFWA) and Geometric (IVPFWG) operators

can be computed as in Eqs. (11)–(12) (Garg, 2018):

$$\begin{aligned}&\mathrm{IVPFWA}(\tilde{A}_1, \tilde{A}_2, \ldots \tilde{A}_n)\\&= \left\langle \left[\left(1 - \prod_{j=1}^{n} (1-\mu_{Lj}^2)^{w_j}\right)^{1/2}, \left(1 - \prod_{j=1}^{n} (1-\mu_{Uj}^2)^{w_j}\right)^{1/2} \right], \left[\prod_{j=1}^{n} v_{Lj}^{w_j}, \prod_{j=1}^{n} v_{Uj}^{w_j} \right] \right\rangle,\end{aligned} \tag{11}$$

$$\begin{aligned}&\mathrm{IVPFWG}(\tilde{A}_1, \tilde{A}_2, \ldots \tilde{A}_n)\\&= \left\langle \left[\prod_{j=1}^{n} \mu_{Lj}^{w_j}, \prod_{j=1}^{n} \mu_{Uj}^{w_j} \right], \left[\left(1 - \prod_{j=1}^{n} (1-v_{Lj}^2)^{w_j}\right)^{1/2}, \left(1 - \prod_{j=1}^{n} (1-v_{Uj}^2)^{w_j}\right)^{1/2} \right] \right\rangle.\end{aligned} \tag{12}$$

Definition 2. An IVPFN $\tilde{A} = \langle [\mu_L, \mu_U], [v_L, v_U] \rangle$ can be defuzzified utilizing Eq. (13) (Haktanir and Kahraman, 2019).

$$P_D(\tilde{A}) = \frac{\left(\begin{array}{c} \mu_L^2 + \mu_U^2 + (1 - v_L^2 - \pi_U^2) + (1 - v_U^2 - \pi_L^2) + \mu_L \mu_U \\ + \sqrt[4]{(1 - v_L^2 - \pi_U^2) \times (1 - v_U^2 - \pi_L^2)} \end{array} \right)}{6}. \tag{13}$$

Definition 3. The score function for an IVPFN $\tilde{A} = \{\langle x, [\mu_{\tilde{A}}^-, \mu_{\tilde{A}}^+], [v_{\tilde{A}}^-, v_{\tilde{A}}^+] \rangle | x \in X\}$ can be obtained via Eq. (14) (Otay *et al.*, 2024).

$$Sc(\tilde{A}) = \frac{1}{2}\left((\mu_{\tilde{A}}^-)^2 + (\mu_{\tilde{A}}^+)^2 - (v_{\tilde{A}}^-)^2 - (v_{\tilde{A}}^+)^2 \right), \quad \left(Sc(\tilde{A}) \in [-1, 1] \right). \tag{14}$$

4. Proposed IVPF BWM Based IVPF QFD

In this section, an IVPF BWM & QFD methodology is presented step by step. In Fig. 4, the proposed two-phase IVPF BWM & QFD methodology is demonstrated.

- **Phase 1: IVPF BWM**

In this sub-section, the steps of IVPF BWM are briefly presented by modifying the intuitionistic fuzzy Best-Worst Method methodology in the study of Alkan and Kahraman (2022).

Step 1. Decision makers ($DM_k = \{DM_1, DM_2, \ldots, DM_K\}$) and a criteria set ($C_i = \{C_1, C_2, \ldots, C_n\}$) are identified.

Step 2. Decision makers determines the most important (MI) criterion and the most unimportant (MU) criterion as denoted by C_{MI} and C_{MU}, respectively. Table 1 lists the linguistic scale for determining the C_{MI} and C_{MU} values.

Step 3. *IVPF MI to Others* vector ($\tilde{S}_{MI}^{Pk}$) is identified by Pythagorean fuzzy evaluations of other criteria compared to the most important one for the kth decision maker utilizing Table 1.

Fig. 4. The proposed IVPF BWM & QFD methodology.

Table 1
Interval-valued Pythagorean fuzzy linguistic scale (Bolturk and Kahraman, 2019).

Linguistic terms	IVPF numbers
Certainly Low Importance (CLI)	([0.05, 0.15], [0.80, 0.95])
Very Low Importance (VLI)	([0.10, 0.25], [0.70, 0.85])
Low Importance (LI)	([0.20, 0.35], [0.60, 0.75])
Below Average Importance (BAI)	([0.30, 0.45], [0.55, 0.70])
Equal Importance (EI)	([0.50, 0.50], [0.50, 0.50])
Above Average Importance (AAI)	([0.55, 0.70], [0.30, 0.45])
High Importance (HI)	([0.60, 0.75], [0.20, 0.35])
Very High Importance (VHI)	([0.70, 0.85], [0.10, 0.25])
Certainly High Importance (CHI)	([0.80, 0.95], [0.05, 0.15])

The $\tilde{S}_{MI}^{Pk}$ vector is illustrated as in Eq. (15):

$$\tilde{S}_{MI}^{Pk} = \left(\tilde{s}_{MI1}^{Pk}, \tilde{s}_{MI2}^{Pk}, \ldots, \tilde{s}_{MIn}^{Pk}\right), \tag{15}$$

where $\tilde{s}_{MIi}^{Pk} = ([\mu_{MIi}^{PL}, \mu_{MIi}^{PU}], [v_{MIi}^{PL}, v_{MIi}^{PU}])$ is the preference of C_{MI} over C_i based on $\mathrm{DM_k}$'s judgment.

Step 4. *IVPF MU to Others* vector ($\tilde{S}_{MU}^{Pk}$) is identified by Pythagorean fuzzy evaluations of other criteria compared to the most unimportant one utilizing Table 1. The $\tilde{S}_{MU}^{Pk}$ vector is presented in Eq. (16):

$$\tilde{S}_{MU}^{Pk} = \left(\tilde{s}_{MU1}^{Pk}, \tilde{s}_{MU2}^{Pk}, \ldots, \tilde{s}_{MUn}^{Pk}\right), \tag{16}$$

where $\tilde{s}_{MUi}^{Pk} = ([\mu_{MUi}^{PL}, \mu_{MUi}^{PU}], [v_{MUi}^{PL}, v_{MUi}^{PU}])$ is the preference of C_{MU} over C_i based on $\mathrm{DM_k}$'s judgment.

Step 5. In this step, based on DMs' judgments, the optimal IVPF weight of each criterion is computed. The weights of the most important and the most unimportant criteria are shown in Eqs. (17)–(18), respectively.

$$\widetilde{w}_{MI}^{Pk} = \left(\left[\mu_{MI}^{PL}, \mu_{MI}^{PU}\right], \left[v_{MI}^{PL}, v_{MI}^{PU}\right]\right), \tag{17}$$

$$\widetilde{w}_{MU}^{Pk} = \left(\left[\mu_{MU}^{PL}, \mu_{MU}^{PU}\right], \left[v_{MU}^{PL}, v_{MU}^{PU}\right]\right). \tag{18}$$

The optimal weights of the criteria should satisfy the following conditions: $deff(\widetilde{w}_{MI}^{Pk})/deff(\widetilde{w}_{i}^{Pk}) = a_{MIi}$ and $deff(\widetilde{w}_{i}^{Pk})/deff(\widetilde{w}_{MU}^{Pk}) = a_{MUi}$. In order to obtain the best possible solution, the maximum absolute differences of $|\widetilde{w}_{MI}^{Pk}/\widetilde{w}_{i}^{Pk} - \tilde{r}_{MIi}^{Pk}|$ and $|\widetilde{w}_{i}^{Pk}/\widetilde{w}_{MU}^{Pk} - \tilde{r}_{MUi}^{Pk}|$ for all is' are minimized. The optimization problem in Eq. (19) provides the optimal weights $\widetilde{w}_{i}^{Pk} = (\widetilde{w}_{1}^{*}, \widetilde{w}_{2}^{*}, \ldots, \widetilde{w}_{n}^{*})^{k}$ for each DM and for each criterion analysed. In Eq. (19), the minimum ε points out the consistency of the comparison matrices. The closer values of ε to "0" demonstrate a more consistent matrix.

$$
\begin{aligned}
&\min \varepsilon \\
&\text{s.t.} \\
&\left|\mu_{MI}^{PL(k)} + v_i^{PL(k)} - \mu_{MI}^{PL(k)}.v_i^{PL(k)} - \mu_{MIi}^{PL(k)}\right| \leqslant \varepsilon, \quad \text{for all } i \\
&\left|\mu_{MI}^{PU(k)} + v_i^{PU(k)} - \mu_{MI}^{PU(k)}.v_i^{PU(k)} - \mu_{MIi}^{PU(k)}\right| \leqslant \varepsilon, \quad \text{for all } i, \\
&\left|\mu_{i}^{PL(k)} + v_{MU}^{PL(k)} - \mu_{i}^{PL(k)}.v_{MU}^{PL(k)} - \mu_{MUi}^{PL(k)}\right| \leqslant \varepsilon, \quad \text{for all } i, \\
&\left|\mu_{i}^{PU(k)} + v_{MU}^{PU(k)} - \mu_{i}^{PU(k)}.v_{MU}^{PU(k)} - \mu_{MUi}^{PU(k)}\right| \leqslant \varepsilon, \quad \text{for all } i, \\
&\left|\mu_{i}^{PL(k)} + v_{MI}^{PL(k)} - v_{MIi}^{PL(k)}\right| \leqslant \varepsilon, \quad \text{for all } i, \\
&\left|\mu_{i}^{PU(k)} + v_{MI}^{PU(k)} - v_{MIi}^{PU(k)}\right| \leqslant \varepsilon, \quad \text{for all } i, \\
&\left|\mu_{MU}^{PL(k)} + v_{i}^{PL(k)} - v_{MUi}^{PL(k)}\right| \leqslant \varepsilon, \quad \text{for all } i, \\
&\left|\mu_{MU}^{PU(k)} + v_{i}^{PU(k)} - v_{MUi}^{PU(k)}\right| \leqslant \varepsilon, \quad \text{for all } i, \\
&0 \leqslant \left(\mu_i^{PU(k)}\right)^2 + \left(v_i^{PU(k)}\right)^2 \leqslant 1, \\
&\sum_{i=1}^{n} Sc\left(\widetilde{w}_i^{Pk}\right) = 1, \\
&Sc\left(\widetilde{w}_i^{Pk}\right) \geqslant 0, \quad \text{for all } i.
\end{aligned}
\tag{19}
$$

Step 6. IVPFWG operator (Eq. (12)) aggregates the DMs judgments. Thus, the optimal weights of criteria $\widetilde{w}_i^P$ are calculated.

Step 7. Finally, the IVPF weights of criteria are defuzzified through Eq. (13). Then, the weights are normalized by Eq. (20).

$$
w_i^N = \frac{w_i}{\sum_{i=1}^{n} w_i}. \tag{20}
$$

- **Phase 2: IVPF QFD**

In the following, we present the IVPF QFD model based on the evaluations of three DMs. In the analysis, when any of the decision makers has no opinion about the considered CRs or DRs, the other decision makers' opinions are processed only (Haktanir and Kahraman, 2019).

CR&DR Relation Analysis

Step 8: Linguistic CRs are defined and customer importance ratings are assigned by means of Pythagorean fuzzy scale presented in Table 2. This linguistic scale satisfies the following conditions: systematic behaviour, intersection between intervals, and replacement of membership and non-membership intervals for reciprocal terms. Herein, CRs are rated by three DMs as in Fig. 5 by using Table 2 (Haktanir and Kahraman, 2019). Figure 5 is designed for n customer requirements together with their Importance Evaluations (IE). In this step, the solutions of IVPF BWM are used as the importance evaluations (IE_i, $i = 1, 2, \ldots, n$).

Table 2
Linguistic terms and their corresponding IVPF numbers (Haktanir and Kahraman, 2019).

Linguistic term	IVPF number
Certainly Low Importance (CLI) / Certainly Low Satisfactory (CLS) / Certainly Low Relation (CLR) / Certainly Low Difficulty (CLD)	([0.10, 0.30], [0.70, 0.90])
Very Low Importance (VLI) / Very Low Satisfactory (VLS) / Very Low Relation (VLR) / Very Low Difficulty (VLD)	([0.20, 0.40], [0.60, 0.80])
Low Importance (LI) / Low Satisfactory (LS) / Low Relation (LR) / Low Difficulty (LD)	([0.30, 0.50], [0.50, 0.70])
Medium Level Importance (MLI) / Medium Level Satisfactory (MLS) / Medium Level Relation (MLR) / Medium Level Difficulty (MLD)	([0.40, 0.60], [0.40, 0.60])
High Importance (HI) / High Satisfactory (HS) / High Relation (HR) / High Difficulty (HD)	([0.50, 0.70], [0.30, 0.50])
Very High Importance (VHI) / Very High Satisfactory (VHS) / Very High Relation (VHR) / Very High Difficulty (VHD)	([0.60, 0.80], [0.20, 0.40])
Certainly High Importance (CHI) / Certainly High Satisfactory (CHS) / Certainly High Relation (CHR) / Certainly High Difficulty (CHD)	([0.70, 0.90], [0.10, 0.30])

Customer Requirements (Whats)	Design Requirement / Importance Evaluation (IE)
CR1	IE_1
CR2	IE_2
⋮	⋮
CRn	IE_n

Fig. 5. Linguistic customer importance ratings for CRs.

Direction of Improvement		↑	↓	↑	...	↓
Customer Requirements (Whats)	Design Requirement / Importance Evaluation (IE)	DR1	DR2	DR3	...	DRm
CR1	IE_1	MLR, HR, HR		MLR, LR, HR		
CR2	IE_2		VHR, HR, HR		⋱	LR, LR, MLR
⋮	⋮	⋮	⋮	⋮		⋮
CRn	IE_n	MLR, MLR, HR				

Fig. 6. Improvement directions of DRs and the relationship matrix.

Step 9: In this step, the DRs (Hows) are defined and the direction of improvement of DRs are determined. Next, the relationship matrix for m design requirements and n customer requirements, is constructed as presented in Fig. 6.

Step 10: The levels of organizational difficulty of the hows are identified at the bottom part of Fig. 7. Organizational Difficulty ($\widetilde{OD}$) means how difficult to achieve a certain DR for an organization. Afterwards, target values of DRs utilizing classical numbers as denoted with Greek letters α, β, . . . , and η are given in the same figure.

Direction of Improvement		↑	↓	↑	...	↓
Customer Requirements (Whats)	Design Requirement / Importance Evaluation (IE)	DR1	DR2	DR3	...	DRm
CR1	IE_1	MLR, HR, HR		MLR, LR, HR		
CR2	IE_2		VHR, HR, HR			LR, LR, MLR
⋮	⋮	⋮	⋮	⋮		⋮
CRn	IE_n	MLR, MLR, HR				
Organizational Difficulty		CLD,VLD,LD	CLD,VLD,VLD	LD, HD, MLD	...	VLD, CLD, LD
Target values		α	β	...	...	η

Fig. 7. Organizational difficulty of the hows and target values.

Table 3
Linguistic correlation scale with IVPF numbers (Haktanir and Kahraman, 2019).

Linguistic term for positive correlation	Linguistic term for negative correlation	IVPF number
Certainly Low Positive Correlation (CLPC)	Certainly Low Negative Correlation (CLNC)	([0.10, 0.30], [0.70, 0.90])
Very Low Positive Correlation (VLPC)	Very Low Negative Correlation (VLNC)	([0.20, 0.40], [0.60, 0.80])
Low Positive Correlation (LPC)	Low Negative Correlation (LNC)	([0.30, 0.50], [0.50, 0.70])
Medium Level Positive Correlation (MPC)	Medium Level Negative Correlation (MNC)	([0.40, 0.60], [0.40, 0.60])
High Positive Correlation (HPC)	High Negative Correlation (HNC)	([0.50, 0.70], [0.30, 0.50])
Very High Positive Correlation (VHPC)	Very High Negative Correlation (VHNC)	([0.60, 0.80], [0.20, 0.40])
Certainly High Positive Correlation (CHPC)	Certainly High Negative Correlation (CHNC)	([0.70, 0.90], [0.10, 0.30])

Step 11: The correlation matrix among DRs (at the roof of HoQ) is designed as in Fig. 8. The correlations are evaluated based on the judgments of three DMs by using the IVPF scale shown in Table 3. In Figs. 7 and 8, positive and negative correlations are shown by blue and red colour arrows, respectively. In Fig. 8, empty cells point out no correlation among DR pairs. The cells with only two linguistic terms indicate that only two experts state their opinions.

Step 12: In this step, Absolute Importance ($\tilde{AI}$) value of each DR is computed by Eq. (21):

$$\tilde{AI}_j = \left\{ \left(\bigoplus_{i=1}^{n} IE_i \otimes \tilde{R}_j \right) \otimes (1 + \widetilde{CI}_j) \right\} \oslash (1 + \widetilde{ROD}_j), \quad j = 1, 2, \ldots, m, \tag{21}$$

where $\tilde{R}$ is the aggregated linguistic terms in the relationship matrix; $\widetilde{CI}$ is the aggregated Correlation Impact factor (see Eq. (22)), and $\widetilde{ROD}$ is Relative Organizational Difficulty (see Eq. (23)).

In Eq. (21), the aggregated values of $\tilde{R}$ are calculated by means of aggregation operator in Eq. (12), while the values of IE are the crisp importance weights of CRs obtained from Pythagorean fuzzy BWM in Phase 1. The $\widetilde{OD}$ linguistic assessments for each DR are aggregated using Eq. (12) in order to calculate $\widetilde{ROD}$ later. Herein, also Relative Abso-

Fig. 8. Correlation matrix of the hows.

Direction of Improvement							
Customer Requirements (Whats)	Design Requirements / Importance Evaluation (IE)		DR1	DR2	DR3	...	DRn
CR1	IE1		MLR, HR, HR		MLR, LR, HR		
CR2	IE2			VHR, HR, HR			LR, LR, MLR
⋮	⋮		⋮	⋮	⋮	⋱	⋮
CRn	IEn		MLR, MLR, HR				
Organizational Difficulty			CLD, VLD, LD	CLD, VLD, VLD	LD, HD, MLD	...	VLD, CLD, LD
Target values			α	β	...	...	η
Engineering Assessment	O: Our Company φ1: Company 1 φ2: Company 2	CLS				...	
		VLS				...	
		LS				...	
		MLS				...	
		HS				...	
		VHS				...	
		CHS				...	
Absolute Importance $(\widetilde{AI})$			$\widetilde{AI}_1$	$\widetilde{AI}_2$	...	...	$\widetilde{AI}_m$
Relative Absolute Importance (%) $(\widetilde{RAI})$			$\widetilde{RAI}_1$	$\widetilde{RAI}_2$	...	...	$\widetilde{RAI}_m$

Fig. 9. Values of $\widetilde{AI}$ and $\widetilde{RAI}$.

lute Importance ($\widetilde{RAI}$) is derived through Eq. (24). Since IVPFS division and subtraction operations have not been explicitly defined in the literature, defuzzification formula is employed as given in Eq. (13). Absolute Importance ($\widetilde{AI}$) and Relative Absolute Importance ($\widetilde{RAI}$) values are shown in Fig. 9.

$$\widetilde{CI}_j = \left(n_{c_j}/(j-1)\right) * (\widetilde{\overline{pc}}_j \ominus \widetilde{\overline{nc}}_j), \quad \widetilde{-1} \leqslant \widetilde{CI}_j \leqslant \widetilde{+1}, \tag{22}$$

$$\widetilde{ROD}_j = \left(\frac{\widetilde{OD}_{ij}}{\bigoplus_{i=1}^{n} \widetilde{OD}_{ij}}\right), \quad j = 1, 2, \ldots, m, \tag{23}$$

$$\widetilde{RAI}_j = \widetilde{AI}_j \oslash \left(\bigoplus_{j=1}^{m} \widetilde{AI}_j\right), \quad j = 1, 2, \ldots, m, \tag{24}$$

Customer Requirements (Whats)	Design Requirement / Importance Evaluation (IE)	DR1	DR2	DR3	...	DRm	Customer Rating						
							O: Our Company, φ1: Company 1, φ2: Company 2						
							CLS	VLS	LS	MLS	HS	VHS	CHS
CR1	IE_1	MLR, HR, HR		MLR, LR, HR	⋱			φ1, φ1	φ1, O	O, φ2	φ2, O, φ2		
CR2	IE_2		VHR, HR, HR			LR, LR, MLR			O, φ1, φ2	O, φ2, φ1	φ1, φ2	O	
⋮	⋮	⋮	⋮	⋮		⋮				φ2, φ2	φ1, φ2, O, O	φ1, φ1, O	
CRn	IE_n	MLR, MLR, HR							φ1, φ1	φ2, φ2, φ1	O, φ2	O, O	

Fig. 10. Linguistic ratings for competition with respect to CRs.

where n_{c_j}: the number of correlations of DR_j with the other DRs; $\widetilde{\overline{pc}}_j$: average of the positive correlations of DR_j, and $\widetilde{\overline{nc}}_j$: average of the negative correlations of DR_j.

Step 13: The DRs are ranked with respect to $\widetilde{RAI}_j$ where $\widetilde{RAI}_j = \langle[\mu^L_{\widetilde{RA}_j}, \mu^U_{\widetilde{RA}_j}], [v^L_{\widetilde{RA}_j}, v^U_{\widetilde{RA}_j}]\rangle$ values with the hesitancy interval $[\pi^L_{\widetilde{RA}_j}, \pi^U_{\widetilde{RA}_j}]$. The highest RAI_j value indicates the most important DRs that should be focused on during the design phase of a new product.

Competitive Analysis

Step 14: The linguistic ratings for competition with respect to CRs, as shown in Fig. 10, are evaluated by multiple decision makers using the IVPF scale in Table 2.

In this step, linguistic ratings with regard to the corresponding CRs are aggregated through Eq. (12). Then, the weighted comparison score ($\mathfrak{I}^{CR}_{O-\phi}$) between our company O and company ϕ with regard to CRs are computed by Eq. (25).

$$\mathfrak{I}^{CR}_{O-\phi} = \sum_{i=1}^{n}\left(\xi^{CR}_{O-\phi} \times d^{CR}_i(O,\phi) \times IE_i\right), \quad \phi = \varphi_1, \ldots, \varphi\mathfrak{y}, \tag{25}$$

where

$$\xi^{CR}_{O-\phi} = \begin{cases} +1, & \text{if } O \text{ is better than } \phi, \\ -1, & \text{if } \phi \text{ is better than } O, \\ 0, & \text{if } O \text{ is equal to } \phi \end{cases} \tag{26}$$

and

$$d^{CR}_i(O,\phi) = \frac{\sqrt{2}}{4}\Big(\sqrt{\left(\mu^L_O - \mu^L_\phi\right)^2 + \left(v^L_O - v^L_\phi\right)^2} + \sqrt{\left(\mu^U_O - \mu^U_\phi\right)^2 + \left(v^U_O - v^U_\phi\right)^2}\Big), \quad i = 1, 2, \ldots, n. \tag{27}$$

Step 15: Next, competitive analysis is conducted this time with respect to the DRs employing Table 2, as illustrated in Fig. 11.

Linguistic ratings with regard to the corresponding DRs are integrated via Eq. (12). Afterwards, the weighted comparison score ($\tilde{\mathfrak{I}}^{DR}_{O-\phi}$) between our company O and com-

Direction of Improvement			↑	↓	↑	...	↓
Customer Requirements (Whats)	**Design Requirements** / **Importance Evaluation** (IE)		DR1	DR2	DR3	...	DRm
CR1	IE_1		MLR, HR, HR		MLR, LR, HR	⋱	
CR2	IE_2			VHR, HR, HR			LR, LR, MLR
⋮	⋮		⋮	⋮	⋮		⋮
CRn	IE_n		MLR, MLR, HR				
Organizational Difficulty			CLD, VLD, LD	CLD, VLD, VLD	LD, HD, MLD	...	VLD, CLD, LD
Target values			α	β	...	...	η
Engineering Assessment	**O: Our Company φ1: Company 1 φ2: Company 2**	**CLS**				...	
		VLS				...	
		LS	O, φ1, φ2	φ1, φ2		...	
		MLS	O, O, φ2	φ2, φ2, φ1,	φ2, φ1, O	...	φ2
		HS	φ1, φ2, φ1,	O	O, O, φ2, φ1	...	φ1, φ2
		VHS		O, O, φ1	φ2, φ1	...	O, O, φ1
		CHS				...	O, φ1, φ2
Absolute Importance $(\widetilde{AI})$			$\widetilde{AI}_1$	$\widetilde{AI}_2$	...	...	$\widetilde{AI}_m$
Relative Absolute Importance (%) $(\widetilde{RAI})$			$\widetilde{RAI}_1$	$\widetilde{RAI}_2$	...	...	$\widetilde{RAI}_m$

Fig. 11. Linguistic ratings of the competition with respect to DRs.

pany ϕ with regard to DRs are computed via Eq. (28).

$$\tilde{\mathfrak{I}}_{O-\phi}^{DR} = \bigoplus_{j=1}^{m} \left(\xi_{O-\phi}^{DR} \times d_j^{DR}(O,\phi) \times \widetilde{AI}_j\right), \quad \phi = \varphi 1, \ldots, \varphi \mathfrak{y} \tag{28}$$

where

$$\xi_{O-\phi}^{DR} = \begin{cases} +1, & \text{if } O \text{ is better than } \phi, \\ -1, & \text{if } \phi \text{ is better than } O, \\ 0, & \text{if } O \text{ is equal to } \phi \end{cases} \tag{29}$$

and

$$d_j^{DR}(O,\phi) = \frac{\sqrt{2}}{4}\left(\sqrt{\left(\mu_O^L - \mu_\phi^L\right)^2 + \left(v_O^L - v_\phi^L\right)^2} + \sqrt{\left(\mu_O^U - \mu_\phi^U\right)^2 + \left(v_O^U - v_\phi^U\right)^2}\right), \quad j = 1, 2, \ldots, m \tag{30}$$

Step 16: To see our position among the competitors, Overall Performance Rating ($\widetilde{OPR}$) score of our company is obtained utilizing Eq. (31) by considering weighted comparison score assessments of both CRs and DRs.

$$\widetilde{OPR} = \kappa \mathfrak{I}_{O-\phi}^{CR} \oplus (1-\kappa)\tilde{\mathfrak{I}}_{O-\phi}^{DR}, \tag{31}$$

where κ and $(1-\kappa)$ are the importance coefficients of CRs and DRs, respectively.

Step 17: As conclusion, the relative position of our company with respect to competitive companies is determined through the value of $\widetilde{OPR}$. Larger positive $\widetilde{OPR}$ value points out that our company performs much better than Company ϕ while larger absolute negative

Table 4
List of CRs and DRs.

Customer requirements (CRs)	Design requirements (DRs)
CR1: Long lasting smart electric scooter charge	DR1: Lithium ion (Li-Ion) batteries
CR2: Fast charging	DR2: Low C-rate (charging rate)
CR3: Bluetooth Internet connection	DR3: Wi-Fi Bluetooth assembly
CR4: Climbing ramps with ease	DR4: High motor power at least 2 × 800W brushless motor
CR5: Increased and longer footboard	DR5: Light aluminium alloy material
CR6: Mitigating the Risk of Theft	DR6: Hidden several scooter GPS trackers
CR7: User-friendly interface of scooter application	DR7: An easy updatable and reliable software with more informative features on the scooter
CR8: No risk of getting wet in the rain	DR8: Stainless adjustable umbrella holder
CR9: High maneuverability	DR9: Centered orientable wheels at the front and at the rear
CR10: Adequate lighting and being noticed in traffic in the dark	DR10: Embedded colourful LED strip lights
CR11: Sudden stop feature with brake	DR11: Adding more than one brake system such as disk brakes, drum brakes, or regenerative brakes.
CR12: Anti-slip pedal foot mat	DR12: Non slip sole sticker

$\widetilde{OPR}$ value indicates that our company performs much worse than Company ϕ. If defuzzified OPR value equals to "0", equal performances of our company and the competitive companies are observed.

5. An Application to E-Scooter Product Design Problem

Scooters are one of the most used micromobility vehicles in all over the world. An electric scooter (motor scooter) is a motorcycle with a seat, a platform for the rider's feet, and an underbone or step-through frame, with an emphasis on comfort and fuel efficiency. Electric scooters (ESs), often known as e-scooters, are environmentally beneficial; can easily avoid traffic; and are space and money-saving devices. Nowadays, ESs are available for a pursuit of short-term rentals through a scooter-sharing system, which is a shared transportation service. E-scooters are picked up and dropped off at certain points within the service area, rather than having a permanent home address. Scooter-sharing programs aim to give the general population a quick and practical means of transportation for last-mile mobility in cities. In this case study, an e-scooter design is tried to be optimized by a QFD analysis under Pythagorean fuzzy environment. This e-scooter design will be used in a scooter-sharing system.

A manufacturer of micromobility vehicles in Istanbul is designing an e-scooter that they plan to manufacture. As a result of the interviews with the customers, the following 12 CRs were determined as listed in Table 4. During the technical meetings held with engineers and product development experts in the company on how to meet these customer needs, the following DRs were determined for each customer requirement. Table 4 presents the CRs and the corresponding DRs.

Table 5
Judgments for BWM.

CR	The best to the others			CR	Others to the worst		
	DM1	DM2	DM3		DM1	DM2	DM3
CR1	AAI	HI	AAI	CR1	VHI	VHI	VHI
CR2	AAI	HI	AAI	CR2	VHI	HI	VHI
CR3	CHI	CHI	CHI	CR3	AAI	EI	AAI
CR4	HI	AAI	HI	CR4	VHI	VHI	HI
CR5	CHI	CHI	CHI	CR5	EI	AAI	EI
CR6	HI	HI	VHI	CR6	HI	HI	HI
CR7	VHI	HI	HI	CR7	AAI	HI	HI
CR8	VHI	VHI	VHI	CR8	AAI	AAI	AAI
CR9	AAI	AAI	EI	CR9	CHI	CHI	CHI
CR10	HI	VHI	VHI	CR10	HI	AAI	AAI
CR11	EI	EI	AAI	CR11	CHI	CHI	CHI
CR12	AAI	AAI	HI	CR12	CHI	CHI	VHI

5.1. *Problem Data and Solutions*

This sub-section demonstrates the dataset collected from the managers and experts in the production department of the firm, and the calculation steps of the proposed two-phase fuzzy methodology with tabular and graphical illustrations.

5.1.1. *Results of IVPF Best-Worst Method*

According to the DMs, the most important (best) and least important (worst) Customer Requirement are determined as given in Table 5 by using linguistic terms listed in Table 2. When the steps of the proposed methodology are followed, first of all the non-linear IVPF BWM optimization model is constructed using Eq. (19). The model is run for Table 5. The weights of the DMs are set to $\gamma_1 = \gamma_2 = \gamma_3 = 1/3$.

By running the proposed IVPF BWM (Eq. (19)) in General Algebraic Modelling System (GAMS) 24.02 software, the defuzzified IVPF weights of the CRs for each DM are obtained as given together with their aggregated defuzzified weights in Table 6.

5.1.2. *Results of IVPF QFD Using BWM Weights*

In this sub-section, IVPF QFD method is employed to design an E-scooter under consideration of 12 customer & 12 technical requirements. Based on the three DMs' judgments, the Relationship matrix between CRs and DRs and Correlation matrix between DRs (Roof of HoQ) are constructed as in Figs. 12 and 13, respectively. In Fig. 13, the linguistic scale in Table 3 is used for determining correlations. In this figure, yellow coloured linguistic terms indicate negative correlations between the DR pairs. Directions of the improvements are indicated with blue and red colours in which red colour is used for the design requirements whose larger values are preferred and blue colour is used for the opposite cases. As seen in the same figure, 10 out of 12 DRs' direction of the improvements are pointed out with blue colour. In Fig. 12, linguistic evaluations of organizational difficulties for the DRs which are collected from three DMs, are represented at the bottom of the HoQ. Be-

Table 6
Weights of the CRs.

CR	DM1	DM2	DM3	Aggregated defuzzified weights (IE_i)
CR1	0.091	0.088	0.093	0.091
CR2	0.091	0.084	0.093	0.089
CR3	0.065	0.074	0.067	0.069
CR4	0.086	0.093	0.084	0.087
CR5	0.054	0.072	0.056	0.061
CR6	0.082	0.084	0.079	0.082
CR7	0.073	0.084	0.084	0.080
CR8	0.073	0.076	0.068	0.072
CR9	0.098	0.097	0.111	0.102
CR10	0.082	0.076	0.076	0.078
CR11	0.108	0.100	0.100	0.103
CR12	0.098	0.073	0.088	0.086

sides, the weights of CRs obtained from the Pythagorean Fuzzy BWM in Phase 1 are also shown in the same figure.

In Figs. 14 and 15, aggregated IVPF numbers of linguistic evaluations in correlation matrix and aggregated IVPF numbers of linguistic evaluations in relation matrix ($\widetilde{R}$) are presented. Aggregation of individual IVPF evaluations is realized through Eq. (12). Afterwards, the absolute importance ($\widetilde{AI}$) value of each DR is calculated by means of Eq. (21). The $\tilde{R}$, *CI* and *ROD* values are computed in the computation of $\widetilde{AI}$ as given in Table 7. As seen in this table, the design requirement that is the most difficult to realize is DR8 (Stainless adjustable umbrella holder). This is then followed by DR7 and DR10 which are "an easy updatable and reliable software with more informative features on the scooter" and "embedded colorful LED strip lights ", respectively. Relative absolute importance (*RAI*) value of each DR is also given in the last column of the same table. According to *RAI* values, DR12 (Non slip sole sticker) and DR11 (More than one brake system) are the top two most important DRs compared to the others based on Eq. (21).

Competition among the companies with respect to CRs is shown in Fig. 16. There are three customer requirements met at the CHS level. These CRs are "Increased and longer footboard", "Sudden stop feature with brake", and "Anti-slip pedal foot mat" which are satisfied by our company and Company φ 2. On the contrary, the CR of "No risk of getting wet in the rain" is certainly low satisfied by Company $\varphi 1$.

On the other hand, competition among the companies with respect to the DRs is represented in Fig. 17. Linguistic evaluations of the target levels for the DRs are also collected from the DMs as given in Fig. 17. As it is seen from the figure, there is no company having Certainly Low Satisfactory (CLS) and Very Low Satisfactory (VLS) degrees for the DRs. The DRs "Adding more than one brake system" and "An easy updatable and reliable software" are not satisfied at the CHS level. On the other hand, the DR of "Light aluminium alloy material" is only met by our company at the CHS level.

In Table 8, the computation of weighted comparison scores with regard to the CRs are displayed. Using Eq. (25), the weighted comparison scores for $O - \varphi 1$ and $O - \varphi 2$ are computed as $\Im^{CR}_{O-\varphi 1} = 0.059$ and $\Im^{CR}_{O-\varphi 2} = 0.030$. The defuzzified weighted comparison

HOWS / WHATS	Design Requirements	Lithium ion (Li-Ion) batteries	Stainless adjustable umbrella holder	Low C-rate (charging rate)	Wi-fi Bluetooth assembly	Embedded Colorful LED Strips Lights	Light Aluminium alloy material	Adding more than one brake system	An easy updatable and reliable software	High Motor power	Centered orientable wheel	Hidden scooter gps trackers	Non slip sole sticker
Customer requirements	**Importance Evaluations**	$\tilde{R}_1$	$\tilde{R}_2$	$\tilde{R}_3$	$\tilde{R}_4$	$\tilde{R}_5$	$\tilde{R}_6$	$\tilde{R}_7$	$\tilde{R}_8$	$\tilde{R}_9$	$\tilde{R}_{10}$	$\tilde{R}_{11}$	$\tilde{R}_{12}$
Long lasting smart electric scooter charge	0.091	VHR, CHR, CHR											
Fast charging	0.089			VHR, VHR, CHR									
Bluetooth Internet connection	0.069				VHR, VHR, CHR								
Climbing ramps with ease	0.087									VHR, CHR, CHR			
Increased and longer footboard	0.061						CHR, CHR, CHR						
Mitigating the Risk of Theft	0.082											VHR, VHR, VHR	
User-friendly interface of scooter application	0.08								VHR, VHR, CHR				
No risk of getting wet in the rain	0.072		CHR, CHR, CHR										
High maneuverability	0.102										VHR,CHR, VHR		
Adequate lighting and being noticed in traffic in the dark	0.078					CHR,CHR,CHR							
Sudden stop feature with brake	0.103							CHR, VHR, CHR					
Anti-slip Pedal Foot Mat	0.086												VHR, VHR, HR
Organizational Difficulty		CLD,VLD,LD	CLD,CLD,VLD	CLD,VLD,VLD	VLD,LD,MLD	VLD,CLD,VLD	CLD,VLD,CLD	LD,MLD,MLD	HD,MLD,MLD	VLD,LD,VLD	MLD,LD,MLD	VLD,LD,LD	CLD,CLD,CLD

Fig. 12. Relationship matrix between CRs and DRs.

Fig. 13. Correlation matrix between DRs (Roof of HoQ).

Fig. 14. Aggregated IVPF numbers of linguistic evaluations in correlation matrix.

| HOWS / WHATS | | Importance Evaluations | Design Requirements | | |

Table 7
IE, $\tilde{R}$, CI and ROD values for computation of $\widetilde{AI}$ for each DR.

DRs	Weights of related CRs	$\tilde{R}_j$				CI_j	ROD_j	Defuzzified $\widetilde{AI}_j$	RAI_j
		μ_L	μ_U	v_L	v_U				
DR1	0.091	0.665	0.865	0.142	0.338	0.04	0.16	0.1044	0.026
DR2	0.089	0.700	0.900	0.100	0.300	0.00	0.11	0.1883	0.047
DR3	0.069	0.632	0.832	0.174	0.371	0.06	0.13	0.2370	0.059
DR4	0.087	0.632	0.832	0.174	0.371	0.05	0.26	0.2559	0.064
DR5	0.061	0.700	0.900	0.100	0.300	0.03	0.13	0.3211	0.080
DR6	0.082	0.700	0.900	0.100	0.300	−0.06	0.11	0.3457	0.086
DR7	0.080	0.665	0.865	0.142	0.338	−0.02	0.34	0.3300	0.082
DR8	0.072	0.632	0.832	0.174	0.371	0.05	0.43	0.3522	0.088
DR9	0.102	0.665	0.865	0.142	0.338	−0.05	0.19	0.4181	0.104
DR10	0.078	0.632	0.832	0.174	0.371	0.01	0.34	0.4179	0.104
DR11	0.103	0.600	0.800	0.200	0.400	0.05	0.23	0.4981	0.124
DR12	0.086	0.565	0.765	0.239	0.437	0.00	0.09	0.5521	0.137

			Customer Rating						
			O: Our Company , φ1: Company 1, φ2: Company 2						
Customer Requirements	**Importance Evaluations**	**Design Requirements**	**CLS**	**VLS**	**LS**	**MLS**	**HS**	**VHS**	**CHS**
Long lasting smart electric scooter charge	0.091	...			φ1	φ1, O, φ2	φ1, O, φ2	O, φ2	
Fast charging	0.089	...				φ1, O, φ2, φ1	φ1, φ2	O, O, φ2	
Bluetooth Internet connection	0.069	...			φ1, φ1	φ2, φ2, O, O	φ1, φ2, O		
Climbing ramps with ease	0.087	...			φ1, φ1	O, φ2, φ2	O, φ1, φ2	O	
Increased and longer footboard	0.061	...					O, φ1, φ2	O, φ1, φ1	O, φ2, φ2
Mitigating the Risk of Theft	0.082	...				O, φ2, φ2	O, φ1, φ1	O, φ2, φ1	
User-friendly interface of scooter application	0.08	...			φ1, φ2	φ2, φ2, O	φ1, O, φ1	O	
No risk of getting wet in the rain	0.072	...	φ1, φ1	φ2, φ2, O	O, φ2, φ1	O			
High maneuverability	0.102	...			O, φ2, φ2	O, O, φ1, φ2	φ1, φ1		
Adequate lighting and being noticed in traffic in the dark	0.078	...			O, φ1, φ1	φ2, O, O, φ1	φ2, φ2		
Sudden stop feature with brake	0.103	...				φ1, φ2	O, O, φ2, φ1	φ1	O, φ2
Anti-slip Pedal Foot Mat	0.086	...				φ1	φ2, φ1, φ2	φ1, O, O	O, φ2

Fig. 16. Comparison analysis with respect to CRs.

scores with regard to the DRs are shown in Table 9. Using Eq. (28), the weighted comparison scores for $O-\varphi 1$ and $O-\varphi 2$ are calculated as $\Im^{DR}_{O-\varphi 1} = 0.327$ and $\Im^{DR}_{O-\varphi 2} = 0.304$.

Afterwards, the Overall Performance Rating (OPR) scores of our company and the competitors are derived using Eq. (31). The defuzzified solutions ($OPR_{O-\varphi 1} = 0.193$ and $OPR_{O-\varphi 2} = 0.167$) indicate that our company is superior to the competitors ($\varphi 1$ and $\varphi 2$) for the value of κ set to "0.50". Additionally, our company outperforms $\varphi 2$ more than $\varphi 1$.

Organizational Difficulty			CLD,VLD,LD	CLD,CLD,VLD	CLD,VLD,VLD	VLD,LD,MLD	VLD,CLD,VLD	CLD,VLD,CLD	LD,MLD,MLD	HD,MLD,MLD	VLD,LD,VLD	MLD,LD,MLD	VLD,LD,LD	CLD,CLD,CLD
Target Values			Operating between 2.5 to 4.0 V	904L stainless steel	A C-rate of 1C or 2C	Long Range bluetooth adapter	Waterproof LED Strips Lights with four lighting modes	6061 aluminum alloy material	Two-wheeler Braking System	Android-based, iOS-compatible, Wi-Fi and Bluetooth-enabled	Brushless DC motors with 350 Watts	E-scooter wheel size with 8.5″	Waterproof Spy real time tracking system	Waterproof Sunscreen Carbon Fiber PVC Non-Slip Scooter Protective Film
Engineering Assessment	O: Our Company C1: Company 1 C2: Company 2	CLS												
		VLS												
		LS							φ1, φ1	φ2, φ1, φ2				
		MLS	φ1			φ2, φ2			φ1	φ1, O, φ2		φ1, φ1, φ1	φ1, φ2, φ2	
		HS	φ1, φ2	φ1, φ2, φ2	φ1, φ1, φ2	φ2, O	φ2, φ1, O	φ1, φ1, φ2	φ2, O, φ2	O, φ1, O	φ1, φ2, φ2	φ2, O, φ2	φ2, φ1, O	
		VHS	φ2, φ1, φ2, O	O, O, φ2	φ1, φ2, O	O, φ1, φ1	φ2, φ2, O	φ1, φ2, φ2	φ2, O, O		O, φ1, φ2	O, O	O, φ1, O	φ1, φ2, O, O, φ1
		CHS	O, O	φ1, φ1, O	O, φ2, O	O, φ1	O, φ1, φ1	O, O, O			O, O, φ1	φ2		φ2, φ1, O, φ2

Fig. 17. Comparison analysis with respect to DRs.

Table 8
Computation of weighted comparison scores with regard to CRs.

CRs	O	$\varphi 1$	$\varphi 2$	$d_i^{CR}(O,\varphi 1)$	$d_i^{CR}(O,\varphi 2)$	$\xi_{O-\varphi 1}^{CR}$	$\xi_{O-\varphi 2}^{CR}$	$(\xi_{O-\varphi 1}^{CR} \times d_i^{CR}(O,\varphi 1) \times IE_i)$, $i = 1, 2, \ldots, 12$	$(\xi_{O-\varphi 2}^{CR} \times d_i^{CR}(O,\varphi 2) \times IE_i)$, $i = 1, 2, \ldots, 12$
CR1	0.3969	0.2880	0.3969	0.1004	0.0000	1	0	0.0091	0.0000
CR2	0.4340	0.3272	0.3969	0.0903	0.0296	1	1	0.0080	0.0026
CR3	0.3272	0.2540	0.3272	0.0755	0.0000	1	0	0.0052	0.0000
CR4	0.3969	0.2540	0.3272	0.1362	0.0607	1	1	0.0118	0.0053
CR5	0.5223	0.4830	0.5651	0.0271	0.0290	1	−1	0.0017	−0.0018
CR6	0.3969	0.4414	0.3573	0.0394	0.0355	−1	1	−0.0032	0.0029
CR7	0.3969	0.3194	0.2600	0.0709	0.1278	1	1	0.0057	0.0102
CR8	0.1954	0.0954	0.1481	0.1406	0.0597	1	1	0.0101	0.0043
CR9	0.2600	0.3632	0.2295	0.1003	0.0332	−1	1	−0.0102	0.0034
CR10	0.2600	0.2295	0.3632	0.0332	0.1003	1	−1	0.0026	−0.0078
CR11	0.4771	0.3969	0.4288	0.0640	0.0418	1	1	0.0066	0.0043
CR12	0.5722	0.3969	0.4771	0.1389	0.0750	1	1	0.0119	0.0064

Table 9
Computation of weighted comparison scores with regard to DRs.

DRs	O	$\varphi 1$	$\varphi 2$	$d_j^{DR}(O,\varphi 1)$	$d_j^{DR}(O,\varphi 2)$	$\xi_{O-\varphi 1}^{DR}$	$\xi_{O-\varphi 2}^{DR}$	$\xi_{O-\varphi 1}^{DR} \times d_j^{DR}(O,\varphi 1) \times AI_j$, $j = 1, 2, \ldots, 12$	$\xi_{O-\varphi 2}^{DR} \times d_j^{DR}(O,\varphi 2) \times AI_j$, $j = 1, 2, \ldots, 12$
DR1	0.6193	0.3969	0.483	0.1717	0.099	1	1	0.0179	0.0104
DR2	0.5722	0.5651	0.4414	0.0121	0.100	1	1	0.0021	0.0173
DR3	0.6193	0.4414	0.5223	0.1323	0.072	1	1	0.0311	0.0170
DR4	0.5223	0.5722	0.3272	0.0397	0.160	−1	1	−0.0097	0.0393
DR5	0.5223	0.5651	0.483	0.029	0.027	−1	1	−0.0093	0.0087
DR6	0.6706	0.4414	0.483	0.1696	0.137	1	1	0.0568	0.0457
DR7	0.483	0.2295	0.4414	0.2333	0.033	1	1	0.0770	0.0109
DR8	0.3632	0.288	0.2295	0.073	0.133	1	1	0.0259	0.0473
DR9	0.6193	0.5223	0.4414	0.0724	0.132	1	1	0.0301	0.0550
DR10	0.483	0.295	0.4771	0.1635	0.009	1	1	0.0689	0.0039
DR11	0.483	0.3969	0.3272	0.0724	0.133	1	1	0.0360	0.0661
DR12	0.5722	0.5722	0.6193	0.00	0.033	0	−1	0.0000	−0.0181

5.2. *Sensitivity Analysis*

In this sub-section, we examine the effects of κ on the Overall Performance Rating scores. As the values of κ increases from "0" to "1.0", it is observed that the *OPR* values have declined for both of the comparisons ($O - \varphi 1$ and $O - \varphi 2$). The results of the sensitivity analysis have presented in Table 10 and illustrated in Fig. 18. As shown in Fig. 18, there is no intersection of the *OPR* lines which means our company is always much more superior to $\varphi 2$ than how we are to $\varphi 1$.

In this sub-section, we also perform sensitivity analysis by changing the weights of each CR individually from "0.1" to "1.0" while distributing the weights of remaining CRs equally and satisfying the condition that the sum of the weights equals to "1.0". Table 11 lists the results of $OPR_{O-\varphi 1}$ and $OPR_{O-\varphi 2}$ based on the different weights of CRs while setting κ equals to "0.50" as illustrated in Fig. 19.

In Fig. 19 (a), when Overall Performance Rating (*OPR*) scores of $O-\varphi 1$ are examined, CR1 and CR2 are the customer requirements where our company has the best overall performance rating scores compared to Company $\varphi 1$. In Fig. 19 (b), CR2 and CR1 are the CRs in which our company is the best when compared to Company $\varphi 2$.

Table 10
Results of sensitivity analysis for different κ values.

κ	$OPR_{O-\varphi 1}$	$OPR_{O-\varphi 2}$
0.1	0.300	0.276
0.2	0.273	0.249
0.3	0.247	0.221
0.4	0.220	0.194
0.5	0.193	0.167
0.6	0.166	0.139
0.7	0.140	0.112
0.8	0.113	0.085
0.9	0.086	0.057
1.0	0.059	0.030

Fig. 18. Sensitivity analysis for changing values of κ.

Fig. 19. Effects of CR weights on $OPR_{O-\varphi 1}$ and $OPR_{O-\varphi 2}$.

5.3. *Comparative Analysis*

In this sub-section, the proposed IVPF BWM and QFD methodology is compared with crisp QFD method by keeping the same weights for the CRs obtained through fuzzy BWM. The values ranging from "1" to "7" are assigned sequentially in Table 2 for the corresponding judgments. For instance, "CLI/CLS/CLR/CLD" takes "1" while

Table 11
Results of $OPR_{O-\varphi 1}$ and $OPR_{O-\varphi 2}$ based on the weights of CRs.

The weights	$OPR_{O-\varphi 1}$											
	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9	CR10	CR11	CR12
0.1	0.2000	0.1990	0.1980	0.1980	0.1980	0.1970	0.1970	0.1970	0.1950	0.1960	0.1950	0.196
0.2	0.2160	0.2110	0.2030	0.2020	0.2010	0.1980	0.1970	0.1950	0.1790	0.1860	0.1850	0.188
0.3	0.2310	0.2210	0.2070	0.2060	0.2040	0.1980	0.1970	0.1930	0.1630	0.1750	0.1730	0.180
0.4	0.2450	0.2310	0.2110	0.2090	0.2060	0.1980	0.1960	0.1900	0.1470	0.1640	0.1610	0.170
0.5	0.2580	0.2400	0.2150	0.2130	0.2080	0.1970	0.1950	0.1870	0.1300	0.1520	0.1470	0.159
0.6	0.2700	0.2480	0.2190	0.2160	0.2090	0.1960	0.1940	0.1840	0.1120	0.1390	0.1320	0.147
0.7	0.2810	0.2560	0.2230	0.2190	0.2110	0.1940	0.1920	0.1790	0.0940	0.1260	0.1160	0.133
0.8	0.2910	0.2630	0.2260	0.2220	0.2110	0.1920	0.1890	0.1740	0.0740	0.1110	0.0980	0.117
0.9	0.3010	0.2700	0.2290	0.2250	0.2110	0.1890	0.1860	0.1670	0.0530	0.0940	0.0780	0.099
1	0.3100	0.2750	0.2310	0.2260	0.2100	0.1850	0.1800	0.1550	0.0250	0.0700	0.0480	0.069
The weights	$OPR_{O-\varphi 2}$											
	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9	CR10	CR11	CR12
0.1	0.1720	0.1720	0.1700	0.1730	0.1690	0.1700	0.1700	0.1690	0.1680	0.1670	0.1680	0.168
0.2	0.1860	0.1870	0.1740	0.1750	0.1680	0.1710	0.1710	0.1650	0.1620	0.1500	0.1590	0.159
0.3	0.1990	0.2010	0.1770	0.1790	0.1670	0.1720	0.1720	0.1610	0.1540	0.1330	0.1490	0.149
0.4	0.2100	0.2130	0.1800	0.1830	0.1650	0.1730	0.1730	0.1570	0.1470	0.1140	0.1380	0.137
0.5	0.2200	0.2240	0.1820	0.1870	0.1620	0.1730	0.1740	0.1520	0.1380	0.0960	0.1260	0.125
0.6	0.2300	0.2340	0.1840	0.1910	0.1590	0.1730	0.1740	0.1470	0.1290	0.0760	0.1140	0.112
0.7	0.2380	0.2430	0.1860	0.1940	0.1560	0.1720	0.1730	0.1410	0.1190	0.0550	0.1000	0.097
0.8	0.2460	0.2520	0.1880	0.1970	0.1520	0.1710	0.1720	0.1340	0.1080	0.0330	0.0850	0.080
0.9	0.2530	0.2590	0.1890	0.1990	0.1470	0.1690	0.1690	0.1260	0.0960	0.0080	0.0680	0.060
1	0.2600	0.2660	0.1890	0.2000	0.1390	0.1630	0.1620	0.1140	0.0770	-0.0240	0.0430	0.030

Table 12
Results of the comparative analysis with classical QFD method with regard to CRs.

CRs	O	$\varphi 1$	$\varphi 2$	$d_i^{CR}(O,\varphi 1)$	$d_i^{CR}(O,\varphi 2)$	$\xi_{O-\varphi 1}^{CR}$	$\xi_{O-\varphi 2}^{CR}$	$(\xi_{O-\varphi 1}^{CR} \times d_i^{CR}(O,\varphi 1) \times IE_i)$, $i = 1, 2, \ldots, 12$	$(\xi_{O-\varphi 2}^{CR} \times d_i^{CR}(O,\varphi 2) \times IE_i)$, $i = 1, 2, \ldots, 12$
CR1	5.0000	4.0000	5.0000	1.0000	0.0000	1	0	0.0910	0.0000
CR2	5.3333	4.3333	5.0000	1.0000	0.3333	1	1	0.0890	0.0297
CR3	4.3333	3.6667	4.3333	0.6667	0.0000	1	0	0.0460	0.0000
CR4	5.0000	3.6667	4.3333	1.3333	0.6667	1	1	0.1160	0.0580
CR5	6.0000	5.6667	6.3333	0.3333	0.3333	1	−1	0.0203	−0.0203
CR6	5.0000	5.3333	4.6667	0.3333	0.3333	−1	1	−0.0273	0.0273
CR7	5.0000	4.3333	3.6667	0.6667	1.3333	1	1	0.0533	0.1067
CR8	3.0000	1.6667	2.3333	1.3333	0.6667	1	1	0.0960	0.0480
CR9	3.6667	4.6667	3.3333	1.0000	0.3333	−1	1	−0.1020	0.0340
CR10	3.6667	3.3333	4.6667	0.3333	1.0000	1	−1	0.0260	−0.0780
CR11	5.6667	5.0000	5.3333	0.6667	0.3333	1	1	0.0687	0.0343
CR12	6.3333	5.0000	5.6667	1.3333	0.6667	1	1	0.1147	0.0573

"CHI/CHS/CHR/CHD" is set to "7". Tables 12 and 13 list the solutions of the crisp QFD method. In Table 12, the computation of weighted comparison scores with regard to the CRs using the crisp numbers are presented.

Utilizing Eq. (25), the weighted comparison scores for $O - \varphi 1$ and $O - \varphi 2$ are as follows: $\mathfrak{I}_{O-\varphi 1}^{CR} = 0.592$ and $\mathfrak{I}_{O-\varphi 2}^{CR} = 0.297$. The defuzzified weighted comparison scores with regard to the DRs using the crisp numbers are as given in Table 13. By Eq. (28),

Table 13
Results of the comparative analysis with classical QFD method with regard to DRs.

DRs	O	$\varphi 1$	$\varphi 2$	$d_j^{DR}(O,\varphi 1)$	$d_j^{DR}(O,\varphi 2)$	$\xi_{O-\varphi 1}^{DR}$	$\xi_{O-\varphi 2}^{DR}$	$\xi_{O-\varphi 1}^{DR} \times d_j^{DR}(O,\varphi 1) \times AI_j$, $j=1,2,\ldots,12$	$\xi_{O-\varphi 2}^{DR} \times d_j^{DR}(O,\varphi 2) \times AI_j$, $j=1,2,\ldots,12$
DR1	6.6667	5.0000	5.6667	1.6667	1.0000	1	1	0.0402	0.0241
DR2	6.3333	6.3333	5.3333	0.0000	1.0000	0	1	0.0000	0.0241
DR3	6.6667	5.3333	6.0000	1.3333	0.6667	1	1	0.0693	0.0346
DR4	6.0000	6.3333	4.3333	−0.3333	1.6667	−1	1	−0.0246	0.1228
DR5	6.0000	6.3333	5.6667	−0.3333	0.3333	−1	1	−0.0241	0.0241
DR6	7.0000	5.3333	5.6667	1.6667	1.3333	1	1	−0.0447	−0.0357
DR7	5.6667	3.3333	5.3333	2.3333	0.3333	1	1	0.1674	0.0239
DR8	4.6667	4.0000	3.3333	0.6667	1.3333	1	1	0.0894	0.1789
DR9	6.6667	6.0000	5.3333	0.6667	1.3333	1	1	0.0694	0.1387
DR10	5.6667	4.0000	5.6667	1.6667	0.0000	1	0	0.2226	0.0000
DR11	5.6667	5.0000	4.3333	0.6667	1.3333	1	1	0.1389	0.2778
DR12	6.3333	6.3333	6.6667	0.0000	−0.3333	0	−1	0.0000	−0.0429

the weighted comparison scores for $O-\varphi 1$ and $O-\varphi 2$ are found as $\Im_{O-\varphi 1}^{DR} = 0.704$ and $\Im_{O-\varphi 2}^{DR} = 0.770$. Lastly, the OPR scores of our company and the competitors are obtained via Eq. (31). The solutions ($OPR_{O-\varphi 1} = 0.648$ and $OPR_{O-\varphi 2} = 0.534$) highlight that our company is superior to the competitors ($\varphi 1$ and $\varphi 2$) for the value of κ set to "0.50" in the crisp version. The findings of the comparative section are found relatively higher than the solutions of the proposed methodology.

6. Conclusion and Future Remarks

Quality function deployment is an essential tool to determine what you need on your products to satisfy the customers. The House of Quality is a product planning matrix built to show how customer requirements relate directly to the technical requirements using competitive benchmarking data to achieve customer satisfaction and loyalty. However, the required data for HoQ are generally vague and imprecise rather than exact and sharp values. To cope with ambiguity and lack of information, weighted evaluation of customer requirements has been realized by the newly proposed interval-valued Pythagorean fuzzy BWM method in this study. According to the best knowledge of the authors, it is the first study proposing interval-valued Pythagorean fuzzy BWM method and integrating it to Pythagorean fuzzy QFD method.

The relationships and correlation matrices between CRs and DRs and technical and competitive benchmarking analyses in QFD have been made by incorporating IVPF sets into the analysis. The results have shown that the CRs "*sudden stop feature with brake*", "*anti-slip pedal foot mat*", "*high maneuverability*", "*fast charging*" and "*long lasting smart electric scooter charge*" have been identified as the most important customer requirements, respectively. In the competitive benchmarking analyses based on the CRs and DRs, it is explicitly found out that our company outperforms companies $\varphi 1$ and $\varphi 2$ considering $OPR_{O-\varphi 1}(0.193)$ and $OPR_{O-\varphi 2}(0.167)$ values. Apart from these, sensitivity analysis based on the integrating coefficient(κ) has shown that our company dominates the competitors $\varphi 1$ and $\varphi 2$ for the considered CRs and DRs. The developed fuzzy model has

successfully realized the relations among the CRs and DRs and the processes of competitive analyses. Additionally, sensitivity analysis for the changing weights of the CRs points out that CR1 and CR2 are the leading CRs where our company has the best overall performance rating scores ($OPR_{O-\varphi 1}$, $OPR_{O-\varphi 2}$) compared to the competitors.

The proposed methodology can be used as a sub-system of a decision support system which could be used during product design and production processes in real life applications. This study presents a two-phase fuzzy decision making framework which enables decision makers to direct investments towards the most essential sources through optimized resource allocations, and prioritizing the CRs and DRs and points out the position of the company in the competitive environment. Moreover, the proposed fuzzy framework can provide a base for collaboration among stakeholders, producers, and technology developers.

For further research, we recommend aggregated correlation impact factor to be processed with positive and negative correlations separately instead of the net average correlation impact concept used in this study. However, this may cause larger complexity in the calculations but will bring a different point of view to the proposed approach. Besides, we also suggest IVPF AHP method to be employed for computing the weights of the customer requirements to compare the results of IVPF BWM.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Author 1: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Validation, Visualization.
Author 2: Conceptualization, Methodology, Supervision, Validation, Data curation, Writing – original draft, and Investigation.

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