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New Product Design Using Chebyshev's Inequality Based Interval-Valued Intuitionistic Z-Fuzzy QFD Method

Elif HAKTANIR[1,2,*], Cengiz KAHRAMAN[1]

[1] *Department of Industrial Engineering, Istanbul Technical University, 34367, Besiktas, Istanbul, Turkey*
[2] *Department of Industrial Engineering, Altinbas University, 34217, Bagcilar, Istanbul, Turkey*
e-mail: elif.haktanir@altinbas.edu.tr, kahramanc@itu.edu.tr

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Abstract. In Quality function deployment (QFD) approach, customers tend to express their needs in linguistic terms rather than exact numerical values and these needs generally contain vague and imprecise information. To overcome this challenge and to use the method more effectively for complex customer-oriented design problems, this paper introduces a novel intuitionistic Z-fuzzy QFD method based on Chebyshev's inequality (CI) and applies it for a new product design. CI provides the assignment of a more objective reliability function. The reliability value is based on the maximum probability obtained from CI. Then, the expected values of lower and upper bounds of interval-valued intuitionistic fuzzy (IVIF) numbers are determined. A competitive analysis among our firm and competitor firms and an integrative analysis for the different functions of QFD is presented. The proposed Z-fuzzy QFD method is applied to the design and development of a hand sanitizer for struggling with COVID-19.

Key words: quality function deployment, interval-valued intuitionistic fuzzy sets, Z-fuzzy numbers, Chebyshev's inequality, new product design.

1. Introduction

With each passing day, customers' expectations of the product that they are planning to purchase are increasing. Today, manufacturers and service providers must meet customer demands at the maximum level in order to be successful and maintain their continuity. Their competitive advantage depends on the aesthetic success of the product they offer for sale as well as the technical features. Customers generally expect the product to be affordable, durable, easy to use and appealing to the eye. However, it is difficult, even impossible sometimes, for the producers to meet all these demands at the same time due to economical and timewise limitations. Companies must first prioritize customer needs in order to determine the best product they can produce using their competencies and the

*Corresponding author.

maximum customer demands they can respond to. One of the most used methods for this purpose is Quality Function Deployment (QFD).

House of Quality (HOQ) is a special and mostly used part of QFD which is named for its shape that reminds of a house with a roof on top. A classical HOQ consists of some parts in matrix form such as customer demands (CDs), customer evaluations (CEs) of those demands, technical descriptors (TDs), relationship matrix between CDs and TDs, and correlation matrix among TDs. In some recent studies, new matrices are added eligibly to the common parts such as technical difficulty and direction of improvement of TDs, and competitive analysis for both CDs and TDs. The HOQ matrices are generally constructed by an effort of a team of experts and multiple customers. Since humans tend to express their thoughts and ideas linguistically rather than exact and precise numbers, this brings vagueness and impreciseness to the design and development process. To overcome this obstacle and deal with complex problems more realistically, the fuzzy set theory has been applied successfully for decades.

The fuzzy set theory was introduced in the literature by Zadeh (1965) as ordinary fuzzy sets which are represented by an x value and its membership degree. Later, in 1986, intuitionistic fuzzy sets (IFSs) have been developed as a generalization of Zadeh's ordinary fuzzy sets by Atanassov (1986) which involve the degrees of membership and non-membership together with experts' hesitancies for an x value. Later, neutrosophic sets are introduced in the literature by Smarandache (1998) which consist of three components *truthiness, indeterminacy*, and *falsity* where these components can be assigned independently. Pythagorean fuzzy sets are developed by Yager (2013) and allowed the squared sum of the membership and non-membership degrees to be at most one. Picture fuzzy sets (PiFS) have been developed by Cuong (2015) in order to define a fuzzy set by *membership, non-membership*, and *hesitancy* degrees so that their squared sum is at most equal to one. As an extension of PiFs, Kutlu Gündoğdu and Kahraman (2019) developed the spherical fuzzy sets that the squared sum of three components (*membership, non-membership*, and *hesitancy* degrees) to be between zero and one. One of the latest extensions of intuitionistic fuzzy sets is circular intuitionistic fuzzy sets developed by Atanassov (2020). They add the uncertainty of the membership and non-membership degrees by defining a circle with radius "r" for these values.

In this paper IVIFSs are employed in the proposed QFD method taking into consideration the reliability of the assigned IVIF numbers. The reliability in this method is handled by Z-fuzzy numbers developed by Zadeh (2011). Z-fuzzy number is an ordered pair of fuzzy numbers where the first component is a real-valued uncertain variable as a restriction on the values. The second component is a measure of reliability for the first component. Z- fuzzy numbers are used to make computations with fuzzy numbers which are not totally reliable. A Z-fuzzy number can represent the information about an uncertain variable, whose first component represents a value of the variable, and the second component represents an idea of uncertainty or probability. In other words, the second component shows how sure the decision maker is with the first component (Yaakob and Gegov, 2015). Chebyshev's inequality is employed to calculate the maximum probability to determine the expected values of lower and upper bounds of the IVIF number in the first compo-

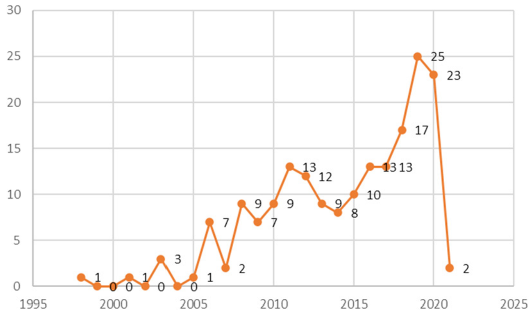

Fig. 1. Distribution of the F-QFD publications with respect to years.

nent. Thus, we obtain more realistic and objective results compared to classical Z-fuzzy approaches.

The advantage of our study and its contribution to the literature can be explained as follows. In most of the Z-fuzzy number studies, sufficient details on how to construct the reliability function are not presented. This study scientifically explains how to create the reliability function and integrate it into the restriction function with the help of Chebyshev's theory. Obtaining the extreme values in IVIF numbers through the integration of reliability factor is realized by using probability theory. Therefore, this paper offers a very different Z-fuzzy number idea from Zadeh's classical Z-fuzzy proposal. The advantage of our method is that it presents the QFD approach under intuitionistic fuzziness with all its aspects such as technical difficulty, competitive analysis through CDs and TDs.

The rest of this study is organized as follows. Section 2 presents a literature review on fuzzy QFD (F-QFD). Section 3 gives the preliminaries for intuitionistic Z-fuzzy numbers based on Chebyshev's inequality. Section 4 develops the intuitionistic Z-fuzzy QFD method based on Chebyshev's inequality. Section 5 illustrates the application of the proposed model on a new hand sanitizer design and development. Section 6 concludes the paper with discussions and future directions.

2. Literature Review

A literature review on F-QFD based on Scopus database gives a list of 185 publications. Figure 1 shows the distribution of the F-QFD publications with respect to years.

After the first study on F-QFD was published in 1998, the highest publication rate was attained in 2019 with 25 studies.

As given in Fig. 2, most of the F-QFD studies are in article form which is followed by conference papers and book chapters.

F-QFD has been applied to many subject areas. Figure 3 shows the frequencies of these publications. *Engineering, computer science*, and *business, management and accounting* are the most frequently applied subjects, respectively.

Some representative F-QFD studies are presented in Table 1 together with the type of fuzzy sets used, integrated methods, and application areas.

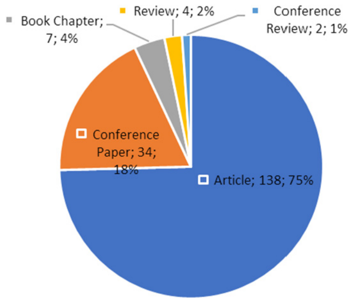

Fig. 2. Document type distributions of F-QFD publications.

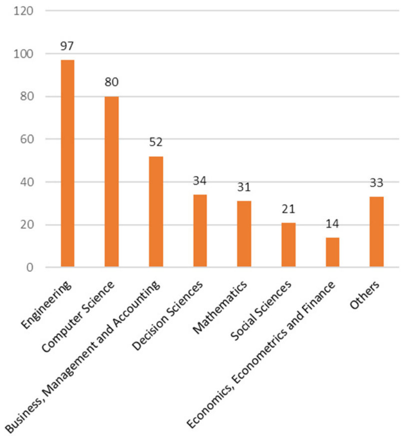

Fig. 3. Document type distributions of F-QFD publications.

We can conclude at the end of the literature review that TFNs are used more than other types of fuzzy numbers. The most integrated methods with F-QFD are AHP, ANP, TOPSIS, FMEA, and DM, respectively. The most used extensions of ordinary fuzzy sets with F-QFD are IFNs, HFNs, T2FNs and SFNs, respectively. The application areas of F-QFD are quite different from delivery drone design to choosing the ideal gas fuel at wastewater treatment plants. A focused application area of F-QFD is not observed in this comprehensive literature review.

3. Chebyshev's Inequality Based IV-Intuitionistic Z-Fuzzy Numbers

In this section, we first present the preliminaries of single-valued intuitionistic fuzzy (SVIF) and IVIF sets with some of their arithmetic operations. Then, ordinary Z-fuzzy numbers are introduced. And finally, Chebyshev's inequality-based interval-valued intuitionistic Z-fuzzy numbers are developed.

Table 1
Some representative F-QFD studies.

	Authors (year)	Type of fuzzy sets	Integrated methods	Application area
1	Haktanır *et al.* (2021)	SFNs	–	Delivery drone design
2	Lee and Park (2021)	TFNs	–	Prioritization of work activities of construction for safety
3	Efe *et al.* (2020)	IT2FNs	TOPSIS	Mobile phone selection
4	Baskar *et al.* (2020)	TFNs	DM, ISM, ANP, VIKOR, FMEA	Sesame seed separator development
5	Kang (2020)	TFNs	RST	Aesthetic product design
6	Bhuvanesh Kumar and Parameshwaran (2020)	TFNs	FMEA, AHP	Prioritizing lean tools for manufacturing industries
7	Ocampo *et al.* (2020)	TFNs	AHP, DEMATEL, ANP	Sustainable product design
8	Wang *et al.* (2020)	TFNs	GDM	Supply chain collaborative quality design of large complex products
9	Aouag *et al.* (2020)	TFNs	DEMATEL	Enhancement of value stream mapping application process
10	Büyüközkan *et al.* (2020)	TFNs	AHP	Customer oriented multifunctional power bank design
11	Kutlu Gündoğdu and Kahraman (2020)	SFNs	–	Linear delta robot technology development
12	Seker (2020a)	TFNs	AHP	Retail chain
13	Li *et al.* (2020)	TFNs	GOA, DM, ML	Analysis and extraction of consumer information for the evaluation of design requirement
14	Büyüközkan and Uztürk (2020)	IVIFNs	MCDM	Smart fridge design
15	Seker (2020b)	TFNs	–	Smart phone product design
16	Fan *et al.* (2020)	IFNs	ANP	Optimal selection of design scheme in cloud environment
17	Haktanır (2020)	IVPFSs	COPRAS	Prioritization of competitive suppliers
18	Deveci *et al.* (2019)	IVIFNs	PCA	Evaluation of service quality in public bus transportation
19	Kayapınar and Erginel (2019)	TFNs	SERVQUAL, MODM	Designing the airport service
20	Haktanır and Kahraman (2019)	IVPFSs	–	Solar photovoltaic technology development
21	Beheshtinia and Farzaneh Azad (2019)	TFNs	SERVQUAL, KANO	Budget constraint for hotel services
22	Lu *et al.* (2019)	TFNs	AHP, ANP	Design of brand revitalisation
23	Bilişik *et al.* (2019)	TFNs	–	Passenger satisfaction evaluation of public transportation in Istanbul
24	Ma *et al.* (2019a)	TFNs	FMEA	Identification of to-be-improved components for redesign of complex products and systems
25	Wang *et al.* (2019)	TFNs	AHP, MAM	Design and implementation of a hand training device
26	Wang (2019)	IFNs	AHP	Product design: case study on touch panels
27	Senthilkannan and Parameshwaran (2019)	TFNs	DM, AHP, FMEA, TOPSIS	Performance analysis and quality improvement in paper industry
28	Piengang *et al.* (2019)	TFNs	AHP, VIKOR	An APS software selection methodology
29	Ma *et al.* (2019b)	TFNs	FMEA	Identifying function components for product redesign
30	Fitriana *et al.* (2019)	TpFNs	DMM	Measurement and proposal of improving marketing process to improve the quality of aftersales in OV agency

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Table 1
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	Authors (year)	Type of fuzzy sets	Integrated methods	Application area
31	Yazdani *et al.* (2019)	IVTFNs	GRA	Multi attribute decision support model in a supply chain
32	Jafarzadeh *et al.* (2018)	TFNs	DEA	Project portfolio selection
33	Shuofang *et al.* (2018)	TFNs	EGM	Study methods of design elements
34	Osorio-Gómez and Manotas-Duque (2018)	TFNs	TOPSIS	Dispatching prioritization in maritime transportation considering operational risk
35	Osiro *et al.* (2018)	HFNs	–	Selecting supply chain sustainability metrics
36	De Almeida *et al.* (2018)	TFNs	ANP	New defense product development
37	Bhuvanesh Kumar and Parameshwaran (2018)	TFNs	FMEA	Selection of lean tools in a manufacturing organization
38	Milunovic Koprivica and Filipovic (2018)	TFNs	–	Improvement of boiler (house electric water heater)
39	Yu *et al.* (2018)	IVIFNs	CIM	Process of designing steering wheel for electric vehicles
40	Babbar and Amin (2018)	TpFNs	–	Supplier selection and order allocation in beverages industry
41	Liu *et al.* (2018)	TFNs	EGM, AHP	The importance of customer requirements and design elements and the correlation among various design elements
42	Amaladhasan *et al.* (2018)	TFNs	TOPSIS	Analysis and prioritisation of eco drivers in supply chain
43	Kang *et al.* (2018)	TFNs	EGM, KANO, AHP	New product development
44	Vongvit *et al.* (2017)	TFNs	TRIZ	Methodology for product development involving design of a 5-axis CNC machine from a 3-axis CNC machine
45	Liu *et al.* (2017)	TFNs	DSM	Process optimization of customer collaborative design
46	Chiadamrong and Tham (2017)	TFNs	SEM, MOLPM	Supply chain management strategy development
47	Akbaş and Bilgen (2017)	TFNs	TOPSIS, ANP, AHP	Choosing the ideal gas fuel at wastewater treatment plants
48	Keshteli and Davoodvandi (2017)	TFNs	AHP, TOPSIS	Ceramic and tile industry of Iran
49	Haq and Boddu (2017)	TFNs	AHP, TOPSIS	Analysis of enablers for the implementation of leagile supply chain management
50	Vinodh *et al.* (2017)	TFNs	–	Sustainable design of consumer electronics products
51	Çevik Onar *et al.* (2016)	HFNs	AHP, TOPSIS	Computer workstation selection
52	Rattawut (2016)	TFNs	AHP	Mini-CNC milling machine retrofit
53	Hakim *et al.* (2016)	TFNs	MOGP	Selecting processes in business process reengineering
54	Chowdhury and Quaddus (2016)	TFNs	MPOM	Sustainable service design
55	Chen (2016)	TFNs	DT	Green design quality management in industrial chain

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Table 1
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	Authors (year)	Type of fuzzy sets	Integrated methods	Application area
56	Büyüközkan and Güleryüz (2015)	TFNs	GDM	IT planning in collaborative product development
57	Dat *et al.* (2015)	TFNs	TOPSIS	Market segment evaluation and selection
58	Xiao *et al.* (2015)	TpFNs	–	Identification of software non-functional requirement
59	Mohanraj *et al.* (2015)	TFNs	VSM	Framework for value stream mapping in an Indian camshaft manufacturing organization
60	Raut and Mahajan (2015)	TFNs	AHP	Construction industry
61	Noorul Haq and Boddu (2015)	TFNs	TOPSIS	Leanness in supply chain
62	Roghanian and Alipour (2014)	TFNs	AHP, PROMETHEE	Achieving lean attributes for competitive advantages development
63	Zaim *et al.* (2014)	TFNs	ANP	Product development
64	Jamalnia *et al.* (2014)	TpFNs	MOGP	Global facility location-allocation problem
65	Palanisamy and Zubar (2013)	TFNs	MM, ANP	Vendor ranking
66	Taylan (2013)	TFNs	GRA, FIS	Determining multi attribute customer preferences of edible oil
67	Yang *et al.* (2013)	TFNs	–	Design for remanufacturing
68	Tavana *et al.* (2013)	TFNs	ANP	Balanced scorecard
69	Nejatian and Zarei (2013)	TFNs	TOPSIS	Improving organizational agility
70	Bevilacqua *et al.* (2012)	TFNs	–	Characterizing customers rating of extra virgin olive oil
71	Chang (2012)	TFNs	TRIZ	Teaching quality improvement
72	Lee *et al.* (2012)	TFNs	FDM	Customer needs and technology analysis in new product development
73	Vinodh and Chintha (2011)	TFNs	–	Enabling sustainability
74	Chen and Huang (2011)	TFNs	–	Knowledge management
75	Kavosi and Mavi (2011)	TFNs	TOPSIS, AHP	Product design and development (pen company in Iran)
76	Khademi-Zare *et al.* (2010)	TFNs	TOPSIS, AHP	Ranking the strategic actions of Iran mobile cellular telecommunication
77	Yang *et al.* (2010)	TFNs	DMAIC, FMEA	Problem selection in the 6σ definition stage
78	Liu (2009)	TFNs	FMEA	Extension fuzzy QFD from product planning to part deployment
79	Juan *et al.* (2009)	TFNs	PROMETHEE	Housing refurbishment contractor selection
80	Celik *et al.* (2009)	TFNs	AHP, FAD	Routing of shipping investment decisions in crude oil tanker market
81	Mousavi *et al.* (2008)	TFNs	TOPSIS	Bridge scheme selection
82	Su and Lin (2008)	TFNs	TRIZ	Service quality improvement
83	Wang *et al.* (2007)	TFNs	–	Customizing positioning of logistics service products of 3PLS
84	Kahraman *et al.* (2006)	TFNs	ANP, AHP	Improving product design and quality in a Turkish company producing PVC window and door systems
85	Hong and Wang (2005)	TFNs	–	Developing an integrated service strategy
86	Tsai *et al.* (2003)	TFNs	–	Enhancing manufacturing strategic planning

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Table 1
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	Authors (year)	Type of fuzzy sets	Integrated methods	Application area
87	Sohn and Choi (2001)	TFNs	–	Supply chain management with reliability consideration
88	Verma *et al.* (1998)	TFNs	–	Facilitating strategic product planning, early design decision-making and parameter target setting

Type of fuzzy sets abbreviations: Triangular Fuzzy Numbers (TFNs), Interval-Valued Triangular Fuzzy Numbers (IVTFNs), Trapezoidal Fuzzy Numbers (TpFNs), Interval Type-2 Fuzzy Numbers (IT2FNs), Intuitionistic Fuzzy Numbers (IFNs), Interval-Valued Intuitionistic Fuzzy Numbers (IVIFNs), Hesitant Fuzzy Numbers (HFNs), Interval-Valued Pythagorean Fuzzy Numbers (IVPFNs), Spherical Fuzzy Numbers (SFNs).
Integrated methods abbreviations: Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Choquet Integral Method (CIM), COmplex PRoportional ASsessment (COPRAS), Data Envelopment Analysis (DEA), Data Mining Methods (DMM), Decision Making Trial and Evaluation Laboratory (DEMATEL), Decision Tree (DT), Define-Measure-Analyze-Improve-Control (DMAIC), Delphi Method (DM), Design Structure Matrix (DSM), Evaluation Grid Method (EGM), Failure Mode and Effects Analysis (FMEA), Fuzzy Axiomatic Design (FAD), Fuzzy Delphi Method (FDM), Fuzzy Inference System (FIS), Grey Decision-Making Approach (GDM), Grey Relational Analysis (GRA), Group Decision Making Approach (GDM), Group-Organization Approach (GOA), Interpretive Structural Modelling (ISM), KANO, Machine Learning (ML), Mathematical Modelling (MM), Morphological Analysis Method (MAM), Multi-Objective Decision Model (MODM), Multi-Objective Goal Programming (MOGP), Multi-Objective Linear Programming Model (MOLPM), Multi-Phased 0-1 Optimization Model (MPOM), Multiple-Criteria Decision-Making (MCDM), Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE), Principal Component Analysis (PCA), Rough Set Theory (RST), Service Quality (SERVQUAL), Structural Equation Modelling (SEM), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Theory of Inventive Problem Solving (TRIZ), Value Stream Mapping (VSM), VIekriterijumsko KOmpromisno Rangiranje (VIKOR).

3.1. *Preliminaries*

Definition 1. Ordinary fuzzy sets are defined as in Eq. (1) (Zadeh, 1965):

$$\tilde{A} = \{(x, \mu(x)) | x \in X\}, \tag{1}$$

where the universe is X, and $0 \leqslant \mu(x) \leqslant 1$.

Definition 2. Intuitionistic fuzzy sets (IFSs) are defined as in Eq. (2) (Atanassov, 1986):

$$\tilde{A} = \{\langle u, (\mu_A(u), v_A(u)\rangle | u \in U\}, \tag{2}$$

where $\mu_A : U \to [0, 1]$, $v_p : U \to [0, 1]$ and $0 \leqslant \mu_A(u) + v_A(u) \leqslant 1$. For any IFS $\tilde{A}$ and $u \in U$, $\pi_A = 1 - \mu_A(u) - v_A(u)$ gives the hesitancy degree.

Definition 3. The addition, multiplication of two SVIF numbers, multiplication by a scalar, and power operations on SVIF numbers are presented as in Eqs. (3)–(6), respectively (Atanassov, 1994):

$$\tilde{A} \oplus \tilde{B} = (\mu_A + \mu_B - \mu_A\mu_B, v_A v_B), \tag{3}$$

$$\tilde{A} \otimes \tilde{B} = (\mu_A\mu_B, v_A + v_B - v_A v_B), \tag{4}$$

$$\alpha\tilde{A} = \left(1 - (1 - \mu_A)^\alpha, v_A^\alpha\right), \tag{5}$$

$$\tilde{A}^\alpha = \left(\mu_A^\alpha, 1 - (1 - v_A)^\alpha\right), \tag{6}$$

where α is a real value and $\alpha > 0$.

Definition 4. The score function of SVIF numbers is presented in Eq. (7) (Zhang *et al.*, 2012):

$$S_A(x) = \frac{1 - v_A(x)}{2 - \mu_A(x) - v_A(x)}. \tag{7}$$

Definition 5. Let closed subintervals be represented by $D \subseteq [0, 1]$. An IVIFS $\tilde{A}$ over X is defined as in Eq. (8) (Büyüközkan and Uztürk, 2020):

$$\tilde{A} = \left\{\left\langle x, \mu_A(x), v_A(x)\right\rangle \middle| x \in X\right\}, \tag{8}$$

where

$$\mu_{\tilde{A}} \to D \subseteq [0, 1], \qquad v_{\tilde{A}}(x) \to D \subseteq [0, 1]$$

with the condition $0 \leqslant \sup \mu_{\tilde{A}}(x) + \sup v_{\tilde{A}}(x) \leqslant 1, \forall x \in X$.

The lower and upper end points are represented by the symbols $\mu_{\tilde{A}}^L(x)$, $\mu_{\tilde{A}}^U(x)$, $v_{\tilde{A}}^L(x)$, and $v_{\tilde{A}}^U(x)$, respectively. Then, an IVIFS $\tilde{A}$ is given by Eq. (9) (Büyüközkan and Uztürk, 2020):

$$\tilde{A} = \left\{\left\langle x, \left[\mu_{\tilde{A}}^L(x), \mu_{\tilde{A}}^U(x)\right], \left[v_{\tilde{A}}^L(x), v_{\tilde{A}}^U(x)\right]\right\rangle \middle| x \in X\right\}, \tag{9}$$

where $0 \leqslant \mu_{\tilde{A}}^U(x) + v_{\tilde{A}}^U(x) \leqslant 1$, $\mu_{\tilde{A}}^L(x) \geqslant 0$, $v_{\tilde{A}}^L(x) \geqslant 0$.

For any x, the hesitancy degree can be computed by Eq. (10):

$$\pi_{\tilde{A}(x)} = 1 - \mu_{\tilde{A}}(x) - v_{\tilde{A}}(x) = \left(\left[1 - \mu_{\tilde{A}}^U(x) - v_{\tilde{A}}^U(x)\right], \left[1 - \mu_{\tilde{A}}^L(x) - v_{\tilde{A}}^L(x)\right]\right). \tag{10}$$

For convenience, let $\mu_{\tilde{A}}(x) = [\mu^L, \mu^U]$, $v_{\tilde{A}}(x) = [v^L, v^U]$, so $\tilde{A} = ([\mu^L, \mu^U], [v^L, v^U])$.

Definition 6. Let $\tilde{A} = ([\mu^L, \mu^U], [v^L, v^U])$ be an IVIF number. The following score function is proposed for defuzzifying $\tilde{A}$ (Karasan and Kahraman, 2019):

$$I(\tilde{A}) = \frac{\mu^L + \mu^U + (1 - v^L) + (1 - v^U) + \mu^L \times \mu^U - \sqrt{(1 - v^L) \times (1 - v^U)}}{4}. \tag{11}$$

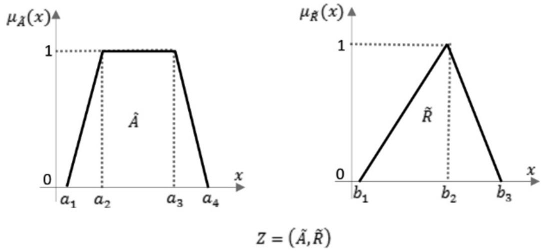


Fig. 4. A Z-fuzzy number.

3.2. *Classical Z-Fuzzy Numbers*

A Z-fuzzy number is defined by Zadeh (2011) as an ordered pair of fuzzy numbers, $(\tilde{A}, \tilde{R})$ which includes a restriction function $\tilde{A}$ and a reliability function $\tilde{R}$ representing the reliability level of the restriction function. If a fuzzy number is not totally reliable, Z-fuzzy numbers can provide a systematic approach to increase the reliability of that fuzzy number.

A Z-fuzzy number can be defined as in Fig. 4.

Definition 7. The expected value of a fuzzy set is calculated as in Eq. (12) (Zadeh, 2011):

$$E_{\tilde{A}}(x) = \int_x x\mu_{\tilde{A}}(x)dx, \tag{12}$$

where $\tilde{A}$ is defined as $\tilde{A} = \{\langle x, \mu_{\tilde{A}}(x)\rangle | x \in X\}$, and $\mu_{\tilde{A}} : X \to [0, 1]$.

Definition 8. Consider a Z-fuzzy number $Z = (\tilde{A}, \tilde{R})$, which is described as in Fig. 4. Let $\tilde{A} = \{\langle x, \mu_{\tilde{A}}(x)\rangle | \mu(x) \in [0, 1]\}$ and $\tilde{R} = \{\langle x, \mu_{\tilde{R}}(x)\rangle | \mu(x) \in [0, 1]\}$ (Zadeh, 2011).

The triangular fuzzy reliability function can be converted into a classical number by Eq. (13):

$$\alpha = \frac{\int x\mu_{\tilde{R}}(x)dx}{\int \mu_{\tilde{R}}(x)dx}. \tag{13}$$

Then, the result of Eq. (13) is integrated with the trapezoidal fuzzy restriction function as in Eq. (14):

$$\tilde{Z}^{\alpha} = \{\langle x, \mu_{\tilde{A}^{\alpha}}(x)\rangle | \mu_{\tilde{A}^{\alpha}}(x) = \alpha\mu_{\tilde{A}}(x), \mu(x) \in [0, 1]\}. \tag{14}$$

After applying Eq. (14), the Z-fuzzy number becomes a single ordinary fuzzy number as in Fig. 5.

In the next section, ordinary Z-fuzzy numbers will be extended by a new approach using Chebyshev's inequality. In this approach, reliability component of the Z-fuzzy number is calculated more objectively based on Chebyshev's probability terms.

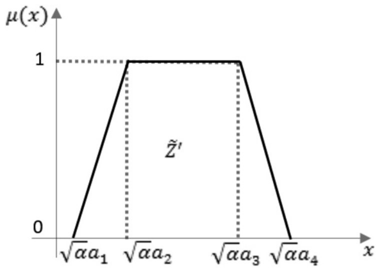


Fig. 5. Z-fuzzy number converted into a single ordinary fuzzy number.

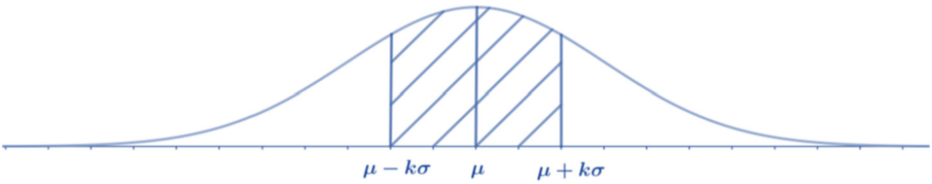


Fig. 6. Chebyshev's inequality.

3.3. *Chebyshev's Inequality Based IV-Intuitionistic Z-Fuzzy Numbers*

Chebyshev's inequality provides the maximum probability between two points with a given mean and variance as illustrated in Fig. 6 when the distribution of the considered data is not known. Let's assume that $\mu = \mathbb{E}(X) \in \mathbb{R}$ and $\sigma = sd(X) \in (0, \infty)$, where X is a random variable.

Chebyshev's inequality is given in Eq. (15):

$$\mathbb{P}\big(|X - \mu| \geqslant k\sigma\big) \leqslant \frac{1}{k^2}, \quad k > 0, \tag{15}$$

where k determines the distance from the population mean as in Fig. 6.

Assume that n number of linguistic evaluations is given as $\tilde{A} = \{E_1, E_2, \dots, E_n\}$, each is represented by an interval-valued intuitionistic fuzzy number. Let the arithmetic mean of the lower and upper values of the membership degrees be $\mu^L_{\overline{x}}$ and $\mu^U_{\overline{x}}$, respectively. Similarly, let the lower and upper values of non-membership degrees be $\upsilon^L_{\overline{x}}$, and $\upsilon^U_{\overline{x}}$, respectively. Then let the standard deviation of the lower and upper values of the membership degrees be μ^L_{σ} and μ^U_{σ}, respectively, whereas let the lower and upper values of non-membership degrees be υ^L_{σ}, and υ^U_{σ}, respectively.

Next operation is to find k value in Eq. (15) in a way that the maximum reliability $R_{\max}$ of the lower and upper values of membership and non-membership degrees is obtained. In this operation the k value must satisfy that $\overline{x} - kS = 0$ and/or $\overline{x} + kS = 1$. Then maximum reliability is calculated by $R_{\max} = 1 - 1/k^2$ for each lower and upper values of membership and non-membership degrees to be $R^{\mu_L}_{\max}$, $R^{\mu_U}_{\max}$, $R^{\upsilon_L}_{\max}$, and $R^{\upsilon_U}_{\max}$, respectively. Thus, the maximum reliability level becomes maximum between $R^{\mu_L}_{\max}$ and $R^{\mu_U}_{\max}$

and between $R_{\max}^{v_L}$ and $R_{\max}^{v_U}$. Then the expected value of the IVIF number is obtained by Eqs. (16)–(19):

$$E[\mu_L] = \left[(\overline{x}_{\mu_L} - k_{\mu_L} S_{\mu_L}) \times R_{\max}^{\mu_L}, (\overline{x}_{\mu_L} + k_{\mu_L} S_{\mu_L}) \times R_{\max}^{\mu_L}\right] = [\mu_{LL}, \mu_{LU}], \tag{16}$$

$$E[\mu_U] = \left[(\overline{x}_{\mu_U} - k_{\mu_U} S_{\mu_U}) \times R_{\max}^{\mu_L}, (\overline{x}_{\mu_U} + k_{\mu_U} S_{\mu_U}) \times R_{\max}^{\mu_L}\right] = [\mu_{UL}, \mu_{UU}], \tag{17}$$

$$E[v_L] = \left[(\overline{x}_{v_L} - k_{v_L} S_{v_L}) \times R_{\max}^{v_L}, (\overline{x}_{v_L} + k_{v_L} S_{\mu_L}) \times R_{\max}^{v_L}\right] = [v_{LL}, v_{LU}], \tag{18}$$

$$E[v_U] = \left[(\overline{x}_{v_U} - k_{v_U} S_{v_U}) \times R_{\max}^{v_L}, (\overline{x}_{v_U} + k_{v_U} S_{v_U}) \times R_{\max}^{v_L}\right] = [v_{UL}, v_{UU}]. \tag{19}$$

The IVIF number $([E[\mu_L], E[\mu_U]], [E[v_L], E[v_U]])$ is converted to a SVIF number by Eq. (20) for membership interval and Eq. (21) for non-membership interval, respectively.

$$D\left(\left[E[\mu_L], E[\mu_U]\right]\right) = \frac{E[\mu_{LL}] + E[\mu_{LU}] + (1 - E[v_{LL}]) + (1 - E[v_{LU}]) + E[\mu_{LL}] \times E[\mu_{LU}] - \sqrt{(1 - E[v_{LL}]) \times (1 - E[v_{LU}])}}{4}, \tag{20}$$

$$D\left(\left[E[v_L], E[v_U]\right]\right) = \frac{E[\mu_{UL}] + E[\mu_{UU}] + (1 - E[v_{UL}]) + (1 - E[v_{UU}]) + E[\mu_{UL}] \times E[\mu_{UU}] - \sqrt{(1 - E[v_{UL}]) \times (1 - E[v_{UU}])}}{4}. \tag{21}$$

Thus, SVIF number $(D(E[\mu]), D(E[v]))$ is obtained.

4. Intuitionistic Z-Fuzzy QFD Based on Chebyshev's Inequality

In this section, we present our novel Chebyshev's inequality based intuitionistic Z-fuzzy QFD approach. The proposed approach requires the number of experts to be n_e and the number of customers to be n_c that we interviewed. The steps of the proposed approach are composed of two phases and 10 steps in total, each is presented in detail below. The phase of customer demands (CDs) and technical descriptors (TDs) relation analysis and the phase of competitive analysis are the two main phases of the approach.

Phase 1 – CD&TD Relation Analysis

Step 1: Let n_c number of customers define the linguistic CDs and assign the linguistic customer evaluations using the scale in Table 2. The total number of CDs is T. Then, translate the linguistic customer evaluations into IVIF values by using Table 2 and aggregate by using Eqs. (20)–(21). Here, customers' weights (w_c) can be assigned differently. This is realized by Eqs. (22)–(25) which require the weighted mean and the weighted standard deviation of the assigned customer evaluations, respectively. This is applied for each element of T number of CDs. Please note that after the aggregation operations, the IVIF

Table 2
Linguistic and corresponding numerical scale for the weights of criteria.

Linguistic term	IVIF number
Absolutely Low Importance (ALI) / Absolutely Low Satisfactory (ALS) / Absolutely Low Relation (ALR) / Absolutely Low Difficulty (SLD)	([0.0, 0.1], [0.8, 0.9])
Very Low Importance (VLI) / Very Low Satisfactory (VLS) / Very Low Relation (VLR) / Very Low Difficulty (VLD)	([0.1, 0.2], [0.7, 0.8])
Low Importance (LI) / Low Satisfactory (LS) / Low Relation (LR) / Low Difficulty (LD)	([0.2, 0.3], [0.6, 0.7])
Medium Low Importance (MLI) / Medium Low Satisfactory (MLS) / Medium Low Relation (MLR) / Medium Low Difficulty (MLD)	([0.3, 0.4], [0.5, 0.6])
Approximately Equal Importance (AEI) / Approximately Equal Satisfactory (AES) / Approximately Equal Relation (AER) / Approximately Equal Difficulty (AED)	([0.4, 0.5], [0.4, 0.5])
Medium High Importance (MHI) / Medium High Satisfactory (MHS) / Medium High Relation (MHR) / Medium High Difficulty (MHD)	([0.5, 0.6], [0.3, 0.4])
High Importance (HI) / High Satisfactory (HS) / High Relation (HR) / High Difficulty (HD)	([0.6, 0.7], [0.2, 0.3])
Very High Importance (VHI) / Very High Satisfactory (VHS) / Very High Relation (VHR) / Very High Difficulty (VHD)	([0.7, 0.8], [0.1, 0.2])
Absolutely High Importance (AHI) / Absolutely High Satisfactory (AHS) / Absolutely High Relation (CHR) / Absolutely High Difficulty (AHD)	([0.8, 0.9], [0.0, 0.1])

values are turned into SVIF values which is to decrease the vagueness.

$$\overline{x}_t = \frac{\sum_{i=1}^{n_c} w_{c_i} x_i^{\mu L}}{n_c}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_c} w_{c_i} (x_i^{\mu L} - \overline{x})^2}{\frac{(M-1)}{M} \sum_{i=1}^{n_c} w_{c_i}}}, \quad t = 1, 2, \dots, T, \tag{22}$$

$$\overline{x}_t = \frac{\sum_{i=1}^{n_c} w_{c_i} x_i^{\mu U}}{n_c}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_c} w_{c_i} (x_i^{\mu U} - \overline{x})^2}{\frac{(M-1)}{M} \sum_{i=1}^{n_c} w_{c_i}}}, \quad t = 1, 2, \dots, T, \tag{23}$$

$$\overline{x}_t = \frac{\sum_{i=1}^{n_c} w_{c_i} x_i^{vL}}{n_c}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_c} w_{c_i} (x_i^{vL} - \overline{x})^2}{\frac{(M-1)}{M} \sum_{i=1}^{n_c} w_{c_i}}}, \quad t = 1, 2, \dots, T, \tag{24}$$

$$\overline{x}_t = \frac{\sum_{i=1}^{n_c} w_{c_i} x_i^{vU}}{n_c}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_c} w_{c_i} (x_i^{vU} - \overline{x})^2}{\frac{(M-1)}{M} \sum_{i=1}^{n_c} w_{c_i}}}, \quad t = 1, 2, \dots, T, \tag{25}$$

where n_c is the number of customers; M is the number of non-zero weights; w_{c_i} is the weight of customer i; $x_i^{\mu L}$, $x_i^{\mu U}$, x_i^{vL}, x_i^{vU} are the corresponding lower and upper membership and non-membership degrees of customer evaluations, respectively.

Step 2: Let the n_e number of experts define the TDs. The total number of TDs is S. Then translate their linguistic assessments for the CD-TD relationship matrix into IVIF numbers by using Table 2. Experts' weights (w_e) can be assigned differently depending on our trust in their experiences. Next, aggregate each IVIF relation to a SVIF number by using Eqs. (20)–(21). Eqs. (26)–(29) are used to calculate the weighted mean and the weighted standard deviation of the assigned relations, respectively. This is applied for each

Table 3
IVIF correlation scale.

Linguistic term for positive or negative correlations	IVIF number
Absolutely Low Positive Correlation (ALPC) or Absolutely Low Negative Correlation (ALNC)	([0.0, 0.1], [0.8, 0.9])
Very Low Positive Correlation (VLPC) or Very Low Negative Correlation (VLNC)	([0.1, 0.2], [0.7, 0.8])
Low Positive Correlation (LPC) or Low Negative Correlation (LNC)	([0.2, 0.3], [0.6, 0.7])
Medium Low Positive Correlation (MLPC) or Medium Low Negative Correlation (MLNC)	([0.3, 0.4], [0.5, 0.6])
Approximately Equal Positive Correlation (AEPC) or Approximately Equal Negative Correlation (AENC)	([0.4, 0.5], [0.4, 0.5])
Medium High Positive Correlation (MHPC) or Medium High Negative Correlation (MHNC)	([0.5, 0.6], [0.3, 0.4])
High Positive Correlation (HPC) or High Negative Correlation (HNC)	([0.6, 0.7], [0.2, 0.3])
Very High Positive Correlation (VHPC) or Very High Negative Correlation (VHNC)	([0.7, 0.8], [0.1, 0.2])
Absolutely High Positive Correlation (AHPC) or Absolutely High Negative Correlation (AHNC)	([0.8, 0.9], [0.0, 0.1])

element of S number of TDs. Please note that after the aggregation operations, the IVIF values are turned into SVIF values which is to decrease the vagueness.

$$\overline{x}_s = \frac{\sum_{i=1}^{n_e} w_{e_i} x_i^{\mu_L}}{n_e}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_e} w_{e_i}(x_i^{\mu_L} - \overline{x})^2}{\frac{(M-1)}{M}\sum_{i=1}^{n_e} w_{e_i}}}, \qquad s = 1, 2, \dots, S, \tag{26}$$

$$\overline{x}_s = \frac{\sum_{i=1}^{n_e} w_e x_i^{\mu_U}}{n_e}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_e} w_{e_i}(x_i^{\mu_U} - \overline{x})^2}{\frac{(M-1)}{M}\sum_{i=1}^{n_e} w_{e_i}}}, \qquad s = 1, 2, \dots, S, \tag{27}$$

$$\overline{x}_s = \frac{\sum_{i=1}^{n_e} w_e x_i^{\upsilon_L}}{n_e}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_e} w_{e_i}(x_i^{\upsilon_L} - \overline{x})^2}{\frac{(M-1)}{M}\sum_{i=1}^{n_e} w_{e_i}}}, \qquad s = 1, 2, \dots, S, \tag{28}$$

$$\overline{x}_s = \frac{\sum_{i=1}^{n_e} w_{e_i} x_i^{\upsilon_U}}{n_e}, \qquad S_t = \sqrt{\frac{\sum_{i=1}^{n_e} w_{e_i}(x_i^{\upsilon_U} - \overline{x})^2}{\frac{(M-1)}{M}\sum_{i=1}^{n_e} w_{e_i}}}, \qquad s = 1, 2, \dots, S. \tag{29}$$

Step 3: Let the experts determine the level of technical difficulty of the TDs by using the scale given in Table 2. The weights of the experts are accepted to be the same as Step 2 and similar calculations are applied to find the aggregated SVIF values for each TDs' technical difficulty as in Step 2.

Step 4: Construct the correlation matrix among TDs based on the IVIF scale presented in Table 3. In this matrix two types of correlations are considered: positive and negative. Positive correlations and negative correlations are indicated by PC and NC, respectively. PC means that two TDs move to the same direction whereas NC means that two TDs move to the opposite directions whenever the value of one of these two TDs is changed. When there exists no correlation, the cell includes no linguistic value in the correlation matrix. The differences between PCs and NCs are obtained by Eq. (31).

Step 5: Obtain the Chebyshev's inequality-based absolute priority degree ($\widetilde{AP}^C$) for each TD as in Eq. (30):

$$\widetilde{AP}_{ij}^C = \left\{ \left(\bigoplus_{i=1}^{T} \widetilde{CE}_i^C \otimes \widetilde{RM}_j^C \right) \otimes \left(1 + \widetilde{CC}_j^C\right) \right\} \oslash \left(1 + \widetilde{RTDF}_j^C\right), \quad (j = 1, 2, \ldots, S), \tag{30}$$

where $\widetilde{CE}^C$: aggregated linguistic customer evaluations of CDs; $\widetilde{RM}^C$: aggregated linguistic terms in the relationship matrix; and $\widetilde{CC}^C$: the aggregated correlation correction factor. $\widetilde{CC}_j^C$ in Eq. (30) is calculated by Eq. (31).

$$\widetilde{CC}_j^C = \left(n_{cc_j} / (S-1)\right) \times (\widetilde{\overline{PC}}_j \ominus \widetilde{\overline{NC}}_j), \tag{31}$$

where $\widetilde{-1} \leqslant \widetilde{CC}_j^C \leqslant \widetilde{+1}$; n_{cc_j}: correlation number of TD_j with the other TDs; $\widetilde{\overline{PC}}_j$: average value of the PCs for the considered TD_j; and $\widetilde{\overline{NC}}_j$: average value of the NCs for the considered TD_j.

Relative technical difficulty ($\widetilde{RTDF}^C$) in Eq. (30) is calculated as in Eq. (32):

$$\widetilde{RTDF}_j^C = \widetilde{TDF}_j^C \oslash \left(\bigoplus_{j=1}^{S} \widetilde{TDF}_j^C \right), \tag{32}$$

where technical difficulty ($\widetilde{TDF}^C$) indicates the difficulty of an organization to reach the planned level of TD. Our objective is to decrease the impact of TDs whose technical difficulties are bigger. Smaller $\widetilde{AP}_j$ are caused by bigger $\widetilde{TDF}_j^C$ values.

Fuzzy relative absolute priority ($\widetilde{RAP}_{ij}^C$) values are found by Eq. (33):

$$\widetilde{RAP}_{ij}^C = \widetilde{AP}_{ij} \oslash \left(\bigoplus_{j=1}^{S} \widetilde{AP}_{ij} \right), \quad i = 1, 2, \ldots, T. \tag{33}$$

Since division and subtraction operations for SVIF numbers are not clearly defined in the literature, defuzzification is employed for these arithmetic operations in our calculations.

Step 6: Rank the TDs regarding their $\widetilde{RAP}_{ij}^C$ values. The highest $\widetilde{RAP}_{ij}^C$ shows the TD with the highest priority for the product developers to consider in the new product design and development phase.

Phase 2 – Competitive Analysis

Step 7: Determine the customers' linguistic assessments for the competitive analysis through CDs assigned by n_c number of customers using the IVIF scale given in Table 2. To locate the position of our company among the competitors whose number is ŋ, the customer assessments should be first aggregated with regarding the corresponding CDs. Next, the distances between our company and other companies ($\tilde{D}^{CD}_{O-C\ell}$) are calculated by using Eq. (34):

$$\tilde{D}^{CD}_{O-C_\ell} = \bigoplus_{i=1}^{T} \left(\kappa^{CD}_{O-C_\ell} \times d_i^{CD}(O, C_\ell) \times \widetilde{CE}_i^C \right), \quad \ell = 1, \ldots, \mathfrak{y};\ i = 1, \ldots, T, \tag{34}$$

where O and C_ℓ represent our company and competitor ℓ, respectively. $\widetilde{CE}_i$ is the aggregated customer evaluations with respect to the corresponding CD_i.

$\kappa^{CD}_{O-C_{ell}}$ in Eq. (32) is defined as in Eq. (35):

$$\kappa^{CD}_{O-C_\ell} = \begin{cases} +1, & \text{if } O \text{ is better than } C_\ell, \\ -1, & \text{if } C_\ell \text{ is better than } O, \\ 0, & \text{if } O \text{ is equal to } C_\ell, \end{cases} \quad \ell = 1, \ldots, \mathfrak{y} \tag{35}$$

$d_i^{CD}(O, C_\ell)$ in Eq. (34) is calculated by Eq. (36):

$$d_i^{CD}(O, C_\ell) = \sqrt{\frac{1}{2} \left(\begin{array}{l} (\mu_O - \mu_{C_\ell})^2 + (v_O - v_{C_\ell})^2 \\ \quad + ((1 - \mu_O - v_O) - (1 - \mu_{C_\ell} - v_{C_\ell}))^2 \end{array} \right)}, \quad \ell = 1, \ldots, \mathfrak{y};\ i = 1, \ldots, T. \tag{36}$$

Step 8: Find the linguistic customer assessments of the competitive analysis through TDs assigned by n_e number of experts using the IVIF scale given in Table 2. To locate the position of our company among the competitors, the expert assessments should be first aggregated with regarding the corresponding TD_j. Next, the distances between our company and other companies ($\tilde{D}^{TD}_{O-C_\ell}$) are calculated by using Eq. (37):

$$\tilde{D}^{TD}_{O-C_\ell} = \bigotimes_{j=1}^{S} \left(\kappa^{TD}_{O-C_\ell} \times d_j^{TD}(O, C_\ell) \times \widetilde{AP}_{ij}^C \right), \quad \ell = 1, \ldots, \mathfrak{y};\ i = 1, \ldots, T;\ j = 1, \ldots, S, \tag{37}$$

where O and C_ℓ represent our company and competitor ℓ, respectively.

$\kappa^{TD}_{O-C_\ell}$ in Eq. (37) is defined as in Eq. (38):

$$\kappa^{TD}_{O-C_\ell} = \begin{cases} +1, & \text{if } O \text{ is better than } C_\ell, \\ -1, & \text{if } C_\ell \text{ is better than } O, \\ 0, & \text{if } O \text{ is equal to } C_\ell, \end{cases} \quad \ell = 1, \ldots, \mathfrak{y} \tag{38}$$

Fig. 7. Scale to indicate the position of our company.

Table 4
Indicators.

Our company	Distance between $O - C_\ell$
Better than C_ℓ	Positive
Worse than C_ℓ	Negative
Equal to C_ℓ	Zero

$d_j^{TD}(O, C_\ell)$ in Eq. (37) is calculated by Eq. (39):

$$d_j^{TD}(O, C_\ell) = \sqrt{\frac{1}{2}\left(\begin{array}{l}(\mu_O - \mu_{C_\ell})^2 + (v_O - v_{C_\ell})^2 \\ \quad + ((1 - \mu_O - v_O) - (1 - \mu_{C_\ell} - v_{C_\ell}))^2\end{array}\right)},$$
$$\ell = 1, \dots, \mathfrak{y}; \;\; j = 1, \dots, S. \tag{39}$$

Step 9: Calculate our company's combined performance rating score ($\widetilde{CPR}$) to locate the position of our firm among the competitors regarding engineering assessments and customer ratings together as in Eq. (40):

$$\widetilde{CPR} = \chi \tilde{D}^{CD}_{O-C_\ell} \oplus (1 - \chi)\tilde{D}^{TD}_{O-C_\ell}, \quad \ell = 1, \dots, \mathfrak{y}, \tag{40}$$

where χ and $(1 - \chi)$ are the coefficients of importance of CDs and TDs, respectively.

Step 10: Find the location of our company relative to the other competitive firms as in Fig. 7. Larger positive distance between our company and C_ℓ indicates that our company is in a more advantageous position than C_ℓ. At the other negative side, bigger distance between our company and C_ℓ indicates that our company is in a more disadvantageous position than C_ℓ. The relative location of our company is determined by the indicators in Table 4.

5. Application: Hand Sanitizer Design and Development

COVID-19 is a contagious disease, first identified in China, in December 2019 and has since spread worldwide, leading to an ongoing pandemic. Centres for Disease Control and Prevention recommend washing the hands with soap and water for at least 20 seconds to prevent the spread of the virus and minimize the risk of getting infected. However, in many cases especially at public places, they are mostly not available. In such situations, hand sanitizers with at least 60% of alcohol are the most suggested solutions. Hand sanitizers (Fig. 8) are generally liquid, gel or foam form of agents applied on the hands to remove viruses/bacteria/microorganisms.

Fig. 8. Hand sanitizer representation.

In this section an application on hand sanitizer design and development will be presented in steps to illustrate the proposed novel intuitionistic Z-fuzzy QFD approach based on Chebyshev's inequality.

To determine the CDs for hand sanitizer, a questionnaire was designed to ask their expectations from this product. This questionnaire was distributed to the e-mail addresses of the customers of one of the largest markets in İstanbul. The total number of the customers was 2078 and 219 of them replied. Based on these responses, the following CDs from a hand sanitizer product were determined: Easy storage, compact package, nice smell, fast absorption and/or drying, moisturizing formula, aesthetic design, powerful formula, environmentally friendly and cruelty free, easy and convenient use, and no hard chemicals. After determining these CDs from the customers, we gathered a small focus group to interview and discuss with them the importance degrees of these CDs. Then we asked a chemical cleaning supplies producer in İstanbul how these CDs can be met by which TDs. The producer firm determined the following TDs: Active ingredients, hazardous ingredients, colour, fragrance, package design, and compliance with laws. The relations between these CDs and TDs can be seen in Table 8.

Now the steps of the proposed intuitionistic Z-fuzzy QFD approach based on Chebyshev's inequality will be given in details in the following.

Phase 1 – CD&TD Relation Analysis

Step 1: Linguistic CDs are defined, and linguistic customer evaluations are assigned by three customers using the scale in Table 2. Customers' weights are assigned to be $w_{c1} = 3$, $w_{c2} = 2$, and $w_{c3} = 1$, based on the scale in Table 5. Then, the linguistic customer evaluations are translated into IVIF numbers by using Table 2 and aggregated by using Eqs. (20)–(21). The linguistic CDs and corresponding evaluations are given in Table 6 with their aggregated SVIF representations. These are calculated based on the weighted mean and the weighted standard deviation of the assigned customer evaluations by using Eqs. (22)–(25). Please note that after the aggregation operations, the IVIF numbers are turned into SVIF numbers which is to decrease the vagueness.

To have a better understanding with the calculations, a sample calculation is given in Table 7 showing the aggregation operation for the customer demand "Easy Storage, Compact Package" evaluated by three customers.

Table 5
Scale for experience level of customers and experts.

Degree of experience	Corresponding numerical score
Very experienced	3
Quite experienced	2
Slightly experienced	1

Table 6
CDs, linguistic customer evaluations, and aggregated SVIF values.

Customer demands	Linguistic customers evaluations	Aggregated SVIF customer evaluations
Easy storage, compact package	HI, AEI, LI	(0.37, 0.31)
Nice smell	MLI, VHI, AEI	(0.36, 0.32)
Fast absorption and/or drying	AHI, HI, MHI	(0.47, 0.19)
Moisturizing formula	AHI, MHI, HI	(0.46, 0.20)
Aesthetic design	VLI, AEI, VHI	(0.23, 0.35)
Powerful formula	VHI, VHI, AHI	(0.53, 0.24)
Environmentally friendly and cruelty free	VLI, MHI, HI	(0.25, 0.26)
Easy and convenient use	LI, AEI, HI	(0.31, 0.27)
No hard chemicals	MHI, AHI, HI	(0.44, 0.22)

Step 2: TDs are defined by three experts where their weights are $w_{e1} = 1$, $w_{e2} = 2$, and $w_{e3} = 1$ depending on the scale given in Table 5. Then their linguistic assessments for the CD-TD relationship matrix are translated into IVIF numbers by using Table 2. Later, each IVIF relation is aggregated to a SVIF number by using Eqs. (20)–(21). These are calculated based on the weighted mean and the weighted standard deviation of the values in the relationship matrix by using Eqs. (26)–(29). Table 8 presents this linguistic relationship matrix between CDs and TDs, and their aggregated SVIF correspondences.

To have a better understanding with the calculations, a sample calculation is given in Table 9 showing the aggregation operation for the relation between the CD "*Nice Smell*" and the TD "*Active Ingredients*" evaluated by three experts.

Step 3: The level of technical difficulty of the TDs are determined by using the scale given in Table 2 by the three experts. The weights are accepted to be the same as in Step 2 and similar calculations are applied to find the aggregated SVIF numbers for each TDs' technical difficulty. Table 10 shows the linguistic technical difficulty of each TD and their corresponding aggregated SVIF value.

Step 4: The linguistic correlation matrix among TDs is constructed by the experts as given in Fig. 9 by using the scale given in Table 2. In this way the directions of the correlations which can be positive or negative have been determined. These directions of improvements are represented with "+" and "−" signs to show whether the TD is needed to be increased or decreased, respectively. In Fig. 9, each cell shows three assessments from three experts. The blank cells in Fig. 9 indicate no correlation between the considered two TDs.

Step 5: We obtained the Chebyshev's inequality based absolute priority degrees for each TD by using Eq. (30) as given in Table 11.

Table 7
Sample calculations of linguistic CD translation into SVIF value.

	μ_L		μ_U		v_L		v_U	
HI	0.6		0.7		0.2		0.3	
AEI	0.4		0.5		0.4		0.5	
LI	0.2		0.3		0.6		0.7	
Weighted average	$0.47 = \frac{(3\times 0.6)+(2\times 0.4)+(1\times 0.2)}{6}$		0.57		0.33		0.43	
Weighted standard deviation	$0.18 = \sqrt{\frac{(3\times(0.6-0.47)^2)+(2\times(0.4-0.47)^2)+(1\times(0.2-0.47)^2)}{\frac{(3-1)}{3}\times(3+2+1)}}$		0.18		0.18		0.18	
k	2.6		2.4		1.85		2.4	
Lower limit of Chebyshev's inequality	$0.00 = 0.47 - 0.18 \times 2.6$		0.14		0.00		0.00	
Upper limit of Chebyshev's inequality	$0.93 = 0.47 + 0.18 \times 2.6$		1.00		0.67		0.86	
Maximum reliability level	$0.85 = 1 - \frac{1}{2.6^2}$		0.83		0.71		0.83	
IVIF intervals	$0.00 = 0.00 \times 0.85$	$0.80 = 0.93 \times 0.85$	0.11	0.82	0.00	0.47	0.00	0.71
Aggregated SVIF CD	$0.37 = \frac{0.00+0.80+(1-0.11)+(1-0.82)+0.00\times 0.80-\sqrt{(1-0.11)\times(1-0.82)}}{4}$				0.31			

k values are found by trial-and-error and interpolation methods.

Table 8
Linguistic relationship matrix between CDs and TDs, and their aggregated SVIF correspondences.

Technical descriptors \ Customer demands	Active ingredients	Hazardous ingredients	Colour	Fragrance	Package design	Compliance with laws
Easy storage, compact package					AHR, AHR, VHR (0.57, 0.16)	
Nice smell	LR, VLR, VLR (0.26, 0.51)	ALR, VLR, ALR (0.21, 0.54)		AHR, AHR, VHR (0.57, 0.16)		
Fast absorption and/or drying	AHR, VHR, HR (0.51, 0.24)	ALR, LR, AER (0.23, 0.42)				
Moisturizing formula	HR, MHR, VHR (0.44, 0.28)	ALR, LR, VLR (0.24, 0.48)				
Aesthetic design			HR, MHR, MLR (0.38, 0.30)		VHR, AHR, AHR (0.56, 0.19)	
Powerful formula	AHR, HR, VHR (0.48, 0.23)	AER, MLR, MHR (0.37, 0.40)				HR, MHR, HR (0.44, 0.31)
Environmentally friendly and cruelty free	AER, HR, VHR (0.39, 0.28)	AER, VHR, AHR (0.40, 0.22)				VHR, AHR, HR (0.50, 0.22)
Easy and convenient use					AHR, VHR, AHR (0.54, 0.20)	
No hard chemicals	LR, AER, MLR (0.31, 0.41)	VHR, AHR, VHR (0.53, 0.21)		LR, MLR, VLR (0.28, 0.45)		HR, AER, VHR (0.42, 0.27)

Table 9
Sample calculation of linguistic TD's translation into SVIF value.

	μ_L	μ_U	υ_L	υ_U
LR	0.2	0.3	0.6	0.7
VLR	0.1	0.2	0.7	0.8
VLR	0.1	0.2	0.7	0.8
Weighted average	$0.13 = \frac{(1\times0.2)+(2\times0.1)+(1\times0.1)}{4}$	0.23	0.68	0.78
Weighted standard deviation	$0.05 = \sqrt{\frac{(1\times(0.2-0.13)^2)+(2\times(0.1-0.13)^2)+(1\times(0.1-0.13)^2)}{\frac{(3-1)}{3}\times(1+2+1)}}$	0.05	0.05	0.05
k	2.4	4.3	6.2	4.3
Lower limit of Chebyshev's inequality	$0.00 = 0.13 - 0.05 \times 2.4$	0.00	0.35	0.55
Upper limit of Chebyshev's inequality	$0.25 = 0.13 + 0.05 \times 4.3$	0.45	1.00	1.00
Maximum reliability level	$0.83 = 1 - \frac{1}{2.4^2}$	0.95	0.97	0.95
IVIF intervals	$0.00 = 0.00 \times 0.83$ $0.21 = 0.25 \times 0.83$	0.00 0.43	0.34 0.98	0.52 0.95
Aggregated SVIF CD	$0.26 = \frac{0.00+0.21+(1-0.00)+(1-0.43)+0.00\times0.21-\sqrt{(1-0.00)\times(1-0.43)}}{4}$		0.51	

k values are found by trial-and-error and interpolation methods.

Table 10
Linguistic technical difficulties of TDs and their aggregated SVIF correspondences.

Technical descriptors	Active ingredients	Hazardous ingredients	Colour	Fragrance	Package design	Compliance with laws
Linguistic technical difficulty	AHD, VHD, AHD	VHD, AHD, AHD	ALD, VLD, ALD	AED, MLD, MHD	AED, MLD, MHD	HD, MHD, VHD
Aggregated SVIF technical difficulty	(0.54, 0.20)	(0.56, 0.19)	(0.21, 0.54)	(0.37, 0.40)	(0.23, 0.44)	(0.44, 0.28)

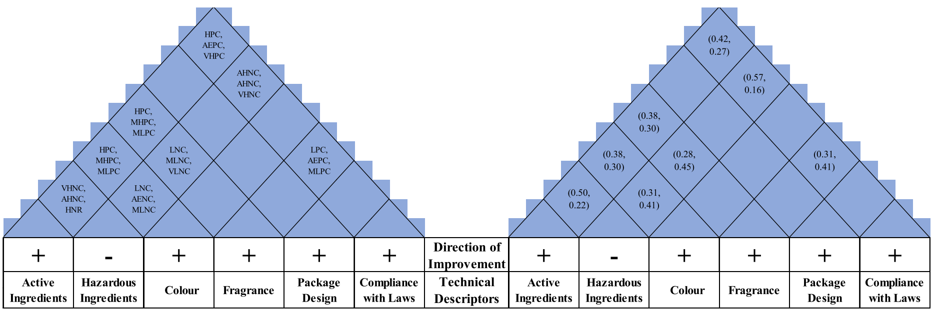


Fig. 9. Linguistic and SVIF correlation matrices.

Table 11
Absolute priorities of TDs.

	Active ingredients	Hazardous ingredients	Colour	Fragrance	Package design	Compliance with laws
Absolute priority	0.50	0.30	0.34	0.44	0.37	0.43

Table 12
Results of SVIF multiplication of customer evaluations by relation matrix of *Active Ingredients*.

Customer demands	SVIF customer evaluations	SVIF relation matrix of active ingredients	Multiplied SVIF values
Easy storage, compact package	(0.37, 0.31)		
Nice smell	(0.36, 0.32)	(0.26, 0.51)	(0.09, 0.67)
Fast absorption and/or drying	(0.47, 0.19)	(0.51, 0.24)	(0.24, 0.38)
Moisturizing formula	(0.46, 0.20)	(0.44, 0.28)	(0.20, 0.42)
Aesthetic design	(0.23, 0.35)		
Powerful formula	(0.53, 0.24)	(0.48, 0.23)	(0.25, 0.41)
Environmentally friendly and cruelty free	(0.25, 0.26)	(0.39, 0.28)	(0.10, 0.47)
Easy and convenient use	(0.31, 0.27)		
No hard chemicals	(0.44, 0.22)	(0.31, 0.41)	(0.14, 0.63)
		Total	(0.68, 0.01)

To better explain this step, a sample calculation is given below for TD "*active ingredients*".

First, we multiplied each SVIF customer evaluation value with the corresponding cell in the relation matrix for TD "*active ingredients*" by using Eq. (4) and then summed these values up by using Eq. (3). Results are shown in Table 12. We added up each SVIF value separately to the summation of the previous ones by applying Eq. (3) successively. The summation result is found to be (0.68, 0.01). Next, we defuzzified this value with Eq. (7) and the result is found as 0.76, where $0.76 = \frac{1-0.01}{2-0.68-0.01}$.

Next, to find the correlation correction factor for TD "*active ingredients*", first we defuzzified the SVIF correlation values. Then applied Eq. (31) as $(4/5) \times (\frac{0.53+0.53+0.56}{3} - 0.61) = -0.06$, where $n_{cc_1} = 4$, $S = 6$. Then, we defuzzified all the SVIF technical difficulty values of TDs and divided the technical difficulty of TD "*active ingredients*" to all technical difficulty's summation as $0.63/(0.63 + 0.65 + 0.37 + 0.49 + 0.42 + 0.56) = 0.20$. This gives us the relative technical difficulty of "*active ingredients*", given in Eq. (32).

Finally, we applied Eq. (30) as follows:

$$AP_1 = \frac{0.76 + (1 + (-0.06))}{(1 + 0.20)} = 0.50.$$

Step 6: We calculated the relative absolute priorities by using Eq. (33) as shown in Table 13. The TD with the highest relative absolute priority is found as TD "*Active Ingredients*" with *RAP*= 0.21 which means that it needs to be taken into consideration promptly by the product developers.

Table 13
Relative absolute priorities of TDs.

	Active Ingredients	Hazardous Ingredients	Colour	Fragrance	Package Design	Compliance with laws
Relative absolute priority	0.21	0.13	0.14	0.18	0.16	0.18

Table 14
Results of competitive analysis through CDs.

CDs	Score of O	Score of C_1	Score of C_2	$\kappa_{O-C_1}^{CD}$	$\kappa_{O-C_2}^{CD}$	$d_i^{CD}(O,C_1)$	$d_i^{CD}(O,C_2)$	CE_i^C	$D_{O-C_1}^{CD}$	$D_{O-C_2}^{CD}$
Easy storage, compact package	0.62	0.45	0.60	1	1	0.44	0.41	0.52	0.23	0.22
Nice smell	0.49	0.40	0.55	1	−1	0.41	0.39	0.52	0.21	−0.20
Fast absorption and/or drying	0.45	0.43	0.62	1	−1	0.41	0.44	0.60	0.25	−0.26
Moisturizing formula	0.60	0.60	0.50	0	1	0.43	0.45	0.60	0.00	0.27
Aesthetic design	0.45	0.62	0.49	−1	−1	0.45	0.39	0.46	−0.21	−0.18
Powerful formula	0.60	0.50	0.60	1	0	0.48	0.43	0.62	0.30	0.00
Environmentally friendly and cruelty free	0.62	0.45	0.43	1	1	0.44	0.45	0.50	0.22	0.22
Easy and convenient use	0.40	0.45	0.62	−1	−1	0.47	0.50	0.51	−0.24	−0.26
No hard chemicals	0.60	0.62	0.49	−1	1	0.41	0.42	0.58	−0.24	0.24
								Total	0.52	0.05

Phase 2- Competitive Analysis

Step 7: First, we collected the linguistic customer assessments for the competitive analysis through CDs assigned by three customers using the IVIF scale given in Table 2. Their linguistic assessments are shown in Fig. 11 and their corresponding aggregated SVIF values are given in Fig. 12. Next, to determine our company's position among the competitors, we applied Eq. (34) and the results of the computations are given in Table 14. The scores of SVIF customers' assessments are found by Eq. (7). $\kappa_{O-C_1}^{CD}$ and $\kappa_{O-C_1}^{CD}$ are calculated by Eq. (35). $d_i^{CD}(O,C_1)$ and $d_i^{CD}(O,C_2)$ are found by Eq. (36). Here, O represents Our Company, C_1 represents Company 1 and C_2 represents Company 2.

In order to better explain the operations used in this table, a sample calculation is presented below for CD "*Easy Storage, Compact Package*".

$$\text{Score of } O = \frac{1-0.23}{2-0.52-0.23} = 0.62,$$

$$\text{Score of } C_1 = \frac{1-0.42}{2-0.29-0.42} = 0.45,$$

$$\text{Score of } C_2 = \frac{1-0.20}{2-0.47-0.20} = 0.60,$$

Table 15
Results of competitive analysis through TDs.

TDs	Score of O	Score of C_1	Score of C_2	$\kappa^{TD}_{O-C_1}$	$\kappa^{TD}_{O-C_2}$	$d^{TD}_j(O, C_1)$	$d^{TD}_j(O, C_2)$	AP^C_{ij}	$D^{TD}_{O-C_1}$	$D^{TD}_{O-C_2}$
Active ingredients	0.56	0.50	0.57	1	−1	0.41	0.45	0.50	0.21	−0.23
Hazardous ingredients	0.42	0.52	0.41	−1	1	0.48	0.50	0.30	−0.15	0.15
Colour	0.56	0.53	0.48	1	1	0.48	0.44	0.34	0.16	0.15
Fragrance	0.57	0.47	0.52	1	1	0.46	0.49	0.44	0.20	0.21
Package design	0.41	0.42	0.50	−1	−1	0.50	0.49	0.37	−0.19	−0.18
Compliance with laws	0.40	0.48	0.56	−1	−1	0.35	0.46	0.43	−0.15	−0.20
								Total	0.08	−0.09

$$\kappa^{CD}_{1O-C_1} = 1, \quad (0.62 > 0.45),$$
$$\kappa^{CD}_{1O-C_2} = 1, \quad (0.62 > 0.60),$$
$$d^{CD}_1(O, C_1) = \sqrt{\frac{1}{2}\big((0.52-0.29)^2 + (0.23-0.42)^2 + \big((1-0.52-0.23)-(1-0.29-0.42)\big)^2\big)} = 0.44,$$
$$d^{CD}_1(O, C_2) = \sqrt{\frac{1}{2}\big((0.52-0.47)^2 + (0.23-0.20)^2 + \big((1-0.52-0.23)-(1-0.47-0.20)\big)^2\big)} = 0.41,$$
$$CE_1 = \frac{1-0.31}{2-0.37-0.31} = 0.52,$$
$$D^{CD}_{1O-C_1} = 1 \times 0.44 \times 0.52 = 0.23,$$
$$D^{CD}_{1O-C_2} = 1 \times 0.41 \times 0.52 = 0.22.$$

Step 8: First, we collected the experts' linguistic assessments for the competitive analysis through TDs assigned by three experts using the IVIF scale given in Table 2. Their linguistic assessments are shown in Fig. 11 and their corresponding aggregated SVIF values are given in Fig. 12. Next, to determine our company's position among the competitors, we applied Eq. (37) and the results of the computations are given in Table 15. The scores of SVIF experts' assessments are found by Eq. (7). $\kappa^{TD}_{O-C_1}$ and $\kappa^{TD}_{O-C_2}$ are calculated by Eq. (38). $d^{TD}_i(O, C_1)$ and $d^{TD}_i(O, C_2)$ are found by Eq. (39).

In order to better understand the operations used in this table, a sample calculation is presented below for TD "*Active Ingredients*".

$$\text{Score of } O = \frac{1-0.27}{2-0.42-0.277} = 0.56,$$
$$\text{Score of } C_1 = \frac{1-0.37}{2-0.37-0.37} = 0.50,$$
$$\text{Score of } C_2 = \frac{1-0.24}{2-0.43-0.24} = 0.57,$$
$$\kappa^{TD}_{1O-C_1} = 1, \quad (0.56 > 0.50),$$

Fig. 10. Scale indicating the location of our company.

$$\kappa_{1O-C_2}^{TD} = -1, \quad (0.56 < 0.57),$$
$$d_1^{TD}(O, C_1) = \sqrt{\frac{1}{2}\left((0.42-0.37)^2 + (0.27-0.37)^2 + \left((1-0.42-0.27)-(1-0.37-0.37)\right)^2\right)} = 0.41,$$
$$d_1^{TD}(O, C_2) = \sqrt{\frac{1}{2}\left((0.42-0.43)^2 + (0.27-0.24)^2 + \left((1-0.42-0.27)-(1-0.43-0.24)\right)^2\right)} = 0.45,$$
$$AP_1 = 0.50,$$
$$D_{1O-C_1}^{TD} = 1 \times 0.41 \times 0.50 = 0.21,$$
$$D_{1O-C_2}^{TD} = -1 \times 0.45 \times 0.50 = -0.23.$$

Step 9: We obtained the combined performance rating score ($C\tilde{P}R$) of our company to determine our position among the competitors by using Eq. (40). Here, we accepted the importance coefficient of CD as $\chi = 0.40$ and importance coefficient of TD as $(1 - \chi) = 0.60$ which means we assigned more weight to the experts' views compared to the customers. CPRs among $O - C_1$ and $O - C_2$ are found as follows:

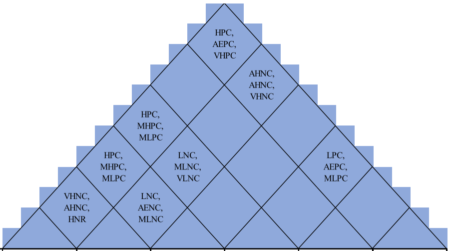
$$CPR_{O-C_1} = (0.40 \times 0.52) + (0.60 \times 0.05) = 0.24,$$
$$CPR_{O-C_2} = (0.40 \times 0.08) + (0.60 \times -0.09) = -0.02.$$

Step 10: We determined the relative position of our company on a scale as in Fig. 10. Since CPR_{O-C_1} found to be a positive number 0.24, it means O is better than C_1 on the scale and the negative value -0.02 for CPR_{O-C_2} shows that C_2 is better than O considering the competitive advantage. But since it is a very small number, we can accept our company equals to C_2.

As mentioned above, the whole linguistic HOQ matrix and the whole aggregated SVIF HOQ matrix are given in Figs. 11 and 12, respectively.

6. Conclusion

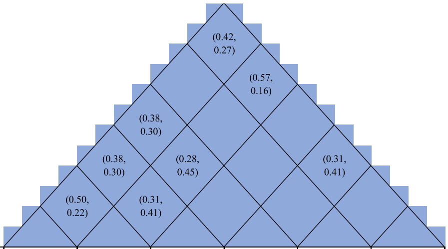
In the literature, the QFD approach has been an effective tool to incorporate customer voice into product design and development. The voice of customer is often included in the QFD approach in linguistic expressions that contain a certain degree of ambiguity. It has been seen that this uncertainty has been modelled mostly with the help of fuzzy sets in the literature. More than ten extensions of ordinary fuzzy sets have been proposed to the literature, each aiming to model human thoughts in a more detailed and accurate way



	Direction of Improvement	+	-	+	+	+	+			
	Technical Descriptors	**Active Ingredients**	**Hazardous Ingredients**	**Colour**	**Fragrance**	**Package Design**	**Compliance with Laws**	**Competitive Analysis Through CDs**		
Customer Demands	**Cutomer Evaluations**							O	C_1	C_2
Easy Storage, Compact Package	HI, AEI, LI					AHR, AHR, VHR		VHS, AHS, HS	LS, AES, VLS	AHS, MHS, VHS
Nice Smell	MLI, VHI, AEI	LR, VLR, VLR	ALR, VLR, ALR		AHR, AHR, VHR			MLS, MHS, AES	ALS, MLS, VLS	AES, VHS, HS
Fast Absorption and/or Drying	AHI, HI, MHI	AHR, VHR, HR	ALR, LR, AER					LS, AES, VLS	LS, MLS, ALS	VHS, AHS, HS
Moisturizing Formula	AHI, MHI, HI	HR, MHR, VHR	ALR, LR, VLR					HS, AHS, VHS	AHS, MHS, VHS	HS, LS, MLS
Aesthetic Design	VLI, AEI, VHI			HR, MHR, MLR		VHR, AHR, AHR		MLS, VLS, MHS	VHS, AHS, HS	MLS, MHS, AES
Powerful Formula	VHI, VHI, AHI	AHR, HR, VHR	AER, MLR, MHR				HR, MHR, HR	AHS, MHS, VHS	HS, LS, MLS	HS, AHS, VHS
Environmentally Friendly and Cruelty Free	VLI, MHI, HI	AER, HR, VHR	AER, VHR, AHR				VHR, AHR, HR	AES, VHS, HS	LS, AES, VLS	LS, MLS, ALS
Easy and Convenient Use	LI, AEI, HI					AHR, VHR, AHR		ALS, MLS, VLS	MLS, VLS, MHS	VHS, AHS, HS
No Hard Chemicals	MHI, AHI, HI	LR, AER, MLR	VHR, AHR, VHR		LR, MLR, VLR		HR, AER, VHR	AHS, MHS, VHS	AES, VHS, HS	MLS, MHS, AES
Technical Difficulty		AHD, VHD, AHD	VHD, AHD, AHD	ALD, VLD, ALD	AED, MLD, MHD	ALD, MLD, VLD	HD, MHD, VHD			
Competitive Analysis Through TDs	O	HS, AES, VHS	ALS, LS, MLS	AHS, MHS, AES	HS,VHS, AES	LS, ALS, AES	LS, VLS, VLS			
	C_1	LS, MHS, AES	VHS, MLS, MHS	HS, MHS, MLS	LS, MLS, MHS	ALR, LS, MLS	MLS, MLS, MHS			
	C_2	HS,VHS, AES	LS, ALS, AES	MLS, MLS, MHS	VHS, MLS, MHS	LS, MHS, AES	AHS, MHS, AES			

Fig. 11. Linguistic HOQ.

through membership functions. Our review revealed that the most used extension in QFD approach is intuitionistic fuzzy sets and the most often integrated decision-making tool is AHP method. In most of the QFD studies the reliability to the assigned fuzzy values of QFD parameters are not considered. The purpose of this study was to develop a novel approach integrating the reliability with the assigned fuzzy values of QFD method based on the principles of the probability theory. The contribution of our method to the literature is the presentation of a new reliability integrated QFD approach under intuitionistic fuzziness with all its aspects such as technical difficulty, competitive analysis through CDs and TDs. Intuitionistic Z-fuzzy numbers have been developed and successfully applied to



	Direction of Improvement	+	-	+	+	+	+			
	Technical Descriptors	Active Ingredients	Hazardous Ingredients	Color	Fragrance	Package Design	Compliance with Laws	Competitive Analysis Through CDs		
Customer Demands	Cutomer Evaluations							O	C_1	C_2
Easy Storage, Compact Package	(0.37, 0.31)					(0.57, 0.16)		(0.52, 0.23)	(0.29, 0.42)	(0.47, 0.20)
Nice Smell	(0.36, 0.32)	(0.26, 0.51)	(0.21, 0.54)		(0.57, 0.16)			(0.38, 0.40)	(0.20, 0.47)	(0.40, 0.28)
Fast Absorption and/or Drying	(0.47, 0.19)	(0.51, 0.24)	(0.23, 0.42)					(0.29, 0.42)	(0.27, 0.44)	(0.52, 0.23)
Moisturizing Formula	(0.46, 0.20)	(0.44, 0.28)	(0.24, 0.48)					(0.49, 0.23)	(0.47, 0.20)	(0.34, 0.33)
Aesthetic Design	(0.23, 0.35)			(0.38, 0.30)		(0.56, 0.19)		(0.28, 0.40)	(0.52, 0.23)	(0.38, 0.40)
Powerful Formula	(0.53, 0.24)	(0.48, 0.23)	(0.37, 0.40)				(0.44, 0.31)	(0.47, 0.20)	(0.34, 0.33)	(0.49, 0.23)
Environmentally Friendly and Cruelty Free	(0.25, 0.26)	(0.39, 0.28)	(0.40, 0.22)				(0.50, 0.22)	(0.52, 0.23)	(0.29, 0.42)	(0.27, 0.44)
Easy and Convenient Use	(0.31, 0.27)					(0.54, 0.20)		(0.20, 0.47)	(0.28, 0.40)	(0.52, 0.23)
No Hard Chemicals	(0.44, 0.22)	(0.31, 0.41)	(0.53, 0.21)		(0.28, 0.45)		(0.42, 0.27)	(0.47, 0.20)	(0.52, 0.23)	(0.38, 0.40)
Technical Difficulty		(0.54, 0.20)	(0.56, 0.19)	(0.21, 0.54)	(0.37, 0.40)	(0.23, 0.44)	(0.44, 0.28)			
Competitive Analysis Through TDs	O	(0.42, 0.27)	(0.24, 0.45)	(0.40, 0.25)	(0.43, 0.24)	(0.17, 0.43)	(0.26, 0.51)			
	C_1	(0.37, 0.37)	(0.35, 0.30)	(0.38, 0.30)	(0.32, 0.39)	(0.24, 0.45)	(0.35, 0.40)			
	C_2	(0.43, 0.24)	(0.17, 0.43)	(0.35, 0.40)	(0.35, 0.30)	(0.37, 0.37)	(0.40, 0.25)			
Absolute Priority		0.50	0.30	0.34	0.44	0.37	0.43			
Relative Absolute Priority		0.21	0.13	0.14	0.18	0.16	0.18			

Fig. 12. Aggregated SVIF HOQ.

represent the uncertainty in linguistic terms of CDs and TDs. Chebyshev's inequality allowed us to objectively obtain the degree of reliability of the restriction function, which is subjectively determined in the previous studies. This study also proposed a model that successfully integrates parts of the QFD approach that are often considered separately in the literature. This model comprehensively integrated customer evaluations, relationship matrix, correlation matrix, and technical difficulties of TDs, to calculate the absolute priority degrees of TDs. One limitation of our study is that IVIF division and subtraction operations are not precisely defined in the literature which forces us to use defuzzification when these operations are needed.

For further research we suggest IVPF, IVSF or IVPiF sets to be used in our model instead of IVIF sets. Besides, aggregation operators can be differentiated by using intuitionistic fuzzy Einstein aggregation operators such as the intuitionistic fuzzy Einstein weighted geometric (IFEWG) operator, or the intuitionistic fuzzy Einstein ordered weighted geometric (IFEOWG) operator. Alternatively, the linguistic intuitionistic fuzzy weighted partitioned Heronian mean (LIFWPHM) operator or the linguistic intuitionistic fuzzy partitioned geometric Heronian mean (LIFPGHM) operator can be used.

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E. Haktanır is currently a lecturer at Altinbas University. She received her MSc and PhD degrees in industrial engineering from Istanbul Technical University. Her research interests are fuzzy decision making, multi-criteria decision making, statistical decision making, quality control and management, and new product development. She is an organization committee member of *International Conference on Intelligent and Fuzzy Systems, INFUS*. Her refereed articles have appeared in a variety of journals including *Computers & Industrial Engineering*, *Journal of Intelligent & Fuzzy Systems*, *Journal of Multiple-Valued Logic & Soft Computing*.

C. Kahraman received his MSc and Phd degrees in industrial engineering from Istanbul Technical University. He is on the editorial board of some journals such as *International Journal of Computational Intelligence Systems* (Atlantis Press), *Journal of Enterprise Information Management* (Emerald), *New Mathematics and Natural Computation* (World Scientific), and *Human and Ecological Risk Assessment* (Taylor And Francis). He has also been the guest editor of special issues of some international journals such as *Information Sciences* (Elsevier), *Journal of Enterprise Information Management* (Emerald), *International Journal of Approximate Reasoning* (Elsevier), *Human and Ecological Risk Assessment*, and *Stochastic Environmental Research and Risk Assessment*. He is the editor of the Springer books *Fuzzy Applications in Industrial Engineering*, *Fuzzy Multi-Criteria Decision Making: Theory and Applications with Recent Developments*, *Fuzzy Engineering Economics with Applications*, *Intelligence Systems in Environmental Management: Theory and Applications*, *Computational Intelligence Systems in Industrial Engineering*, *Fuzzy Statistical Decision-Making – Theory and Applications*, *Production Engineering and Management under Fuzziness*, *Fuzzy Logic in Its 50th Year: New Developments, Directions and Challenges*, *Supply Chain Management Under Fuzziness Recent Developments and Techniques*, *Intelligent Techniques in Engineering Management Theory and Applications*, and *Intelligent Decision Making in Quality Management Theory and Applications*.