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A Novel Z-Fuzzy AHP&EDAS Methodology and Its Application to Wind Turbine Selection

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Abstract. Modelling the reliability information in decision making process is an important issue to inclusively reflect the thoughts of decision makers. The Evaluation Based on Distance from Average Solution (EDAS) and Analytic Hierarchy Process (AHP) are frequently used MCDM methods, yet their fuzzy extensions in the literature are incapable of representing the reliability of experts' fuzzy preferences, which may have important effects on the results. The first goal of this study is to extend the EDAS method by using Z-fuzzy numbers to reinforce its representation ability of fuzzy linguistic expressions. The second goal is to propose a decision making methodology for the solution of fuzzy MCDM problems by using Z-fuzzy AHP method for determining the criteria weights and Z-fuzzy EDAS method for the selection of the best alternative. The contribution of the study is to present an MCDM based decision support tool for the managers under vague and imprecise data, which also considers the reliability of these data. The applicability of the proposed model is presented with an application to wind energy investment problem aiming at the selection of the best wind turbine. Finally, the effectiveness and competitiveness of the proposed methodology is demonstrated by making a comparative analysis with the Z-fuzzy TOPSIS method. The results show that the proposed methodology can not only represent experts' evaluation information extensively, but also reveal a logical and consistent sequence related to wind turbine alternatives using reliability information.
Key words: AHP, EDAS, Z-fuzzy, restriction function, reliability, renewable energy.

1. Introduction

We face decision-making processes at every moment of our lives. In the decision-making process, people express their knowledge and thoughts via their personal opinions and comments. Decision makers (DMs) often use expressions containing doubt and uncertainty in their judgments. Expressions such as "not very clear", "likely", etc., show the uncertainty of human thought and are frequently used in daily or business life. Zadeh (1965) introduced fuzzy set theory in order to model this ambiguity and subjectivity of human judg-

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ments and to use linguistic terms in the decision-making process. Thus, fuzzy set theory enables DMs to incorporate their uncertain information in the decision model.

DMs who have knowledge and experience are often not exactly sure of their assessments when they are making a decision. The probability of correct diagnosis of even a doctor is not one hundred percent (Xian *et al.*, 2019). For example, one doctor can say "you likely have anemia". In the medical world, tests and investigations can be performed to confirm this diagnosis. However, in many fields that need decision-making, subjective judgments cannot be confirmed in that way. Moreover, when quantitative data are used in decision making, they are treated to be exactly accurate since the sources' reliability level is not questioned. However, it would not be correct to assume the numerical data with 100% certainty due to factors such as the concept of time and measurement accuracy. The possible variations that may occur in numerical data can be modelled with different extensions of fuzzy set theory. However, when qualitative data consisting of uncertain judgments is used in decision making, it would be most logical to explicitly ask people about their confidence level in their judgments. In these cases, the reliability of the experts' fuzzy judgments must be considered and incorporated to the decision model. As a result, it is clear that restrictive information must be integrated with reliability information especially when linguistic expressions, which represent subjective judgments, are employed in the decision model.

After the introduction of fuzzy set theory, fuzzy versions of classical multi criteria decision making (MCDM) methods have emerged to capture the DMs' uncertain expressions (Chatterjee *et al.*, 2018a). These methods have been expanded by ordinary fuzzy sets and their several extensions, such as type-2 fuzzy sets, intuitionistic fuzzy sets, hesitant fuzzy sets, Pythagorean fuzzy sets, and neutrosophic sets, to find the best representation of human thinking structure. Although the extensions of fuzzy sets are highly beneficial and suited to deal with vague information, their capabilities are limited to represent the reliability of the assigned fuzzy data. In order to overcome this limitation and to reach more accurate and effective results, reliability information must be incorporated into the decision processes.

Z-fuzzy numbers have been proposed by Zadeh (2011) in order to deal with the vagueness and impreciseness of membership functions by incorporating a reliability function to the evaluation system as a complementary element. This can be commented as a similar effort by Zadeh to his type-2 fuzzy sets for preventing the criticisms that membership functions themselves are not fuzzy. Thus, the requirement of reliability information in the decision-making can be satisfied by the use of Z-fuzzy numbers. Z-fuzzy numbers reflect the uncertainty in DMs' mind through a reliability function, which express how confident they are about their evaluations. In the doctor example, whereas the word "anemia" represents restrictive information, the word "likely" represents reliability information.

Evaluation Based on Distance from Average Solution (EDAS) is one of the recently developed MCDM methods. The EDAS method has been integrated with various fuzzy set extensions to better define the DMs' uncertain judgments. However, these versions of the EDAS method such as intuitionistic fuzzy EDAS or picture fuzzy EDAS do not fully include the reliability information. To the best knowledge of the authors, the EDAS method has not been extended with Z-fuzzy numbers by any researcher. In the literature, there is only one paper trying to use linguistic Z-numbers in EDAS method, different from our study, for quality function deployment (Mao *et al.*, 2021). In this study, EDAS method is extended to Z-fuzzy EDAS method using ordinary Z-fuzzy numbers to strengthen the reliability degree of the given decisions.

Main objectives of the study are as follows:

i. The first aim of the study is to extend the traditional EDAS method to Z-fuzzy EDAS for the solution of MCDM problems under vagueness and impreciseness, which takes the reliability of the experts' data into account.
ii. The second aim of this study is to integrate Z-fuzzy AHP method with Z-fuzzy EDAS method in order to use the criteria weights obtained from AHP in the Z-fuzzy EDAS method for ranking the alternatives.
iii. The proposed methodology is applied to a wind turbine technology selection problem to present its practicality and efficiency. A comparative analysis is performed by using the same data with the Z-fuzzy TOPSIS method.

This study contributes to the literature in four aspects:

i. First, a novel Z-fuzzy EDAS has been developed for the first time by formulating it step by step using Z-fuzzy numbers. Thus, the literature gap on Z-fuzzy MCDM methods will be filled.
ii. Second, to the best of our knowledge, a methodology integrating Z-fuzzy numbers and AHP & EDAS methods has not been developed.
iii. Third, all steps of the Z-fuzzy EDAS method have been performed by Z-fuzzy numbers which prevents the loss of information existing in the fuzzy data.
iv. Finally, the proposed approach has been applied to a renewable energy problem in the literature illustrating how to use the proposed methodology step by step.

The rest of the paper is organized as follows. Section 2 presents a literature review on EDAS and Z-fuzzy MCDM. Section 3 includes the preliminaries of Z-fuzzy numbers. Section 4 presents the proposed Z-fuzzy AHP method and Section 5 gives the steps of the proposed Z-fuzzy EDAS method. Section 6 presents the application on wind turbine technology selection. Section 7 gives a comparative analysis using Z-fuzzy AHP&TOPSIS methodology. The last section presents the conclusions and future research directions.

2. Literature Review on EDAS and Z-Fuzzy MCDM

Decision making problems arise when there is a need for comparison or selection from a set of alternatives, taking into account the impact of multiple conflicting criteria. For this purpose, various multiple criteria decision making (MCDM) methods are constructed to determine the best alternative with respect to all relevant criteria (Chatterjee *et al.*, 2018b). Decisions taken in daily life or business life may have different degrees of difficulty due to the factors such as the considered criteria, the relationship between them and the number of alternatives. However, when DMs need to evaluate the alternatives by considering many criteria; many factors such as the number of criteria and alternatives, criteria weights and conflicts between criteria further complicate the problem and need to be evaluated with more comprehensive methods. Therefore, multi-criteria decision making (MCDM) methods are used in order to get more accurate decisions in solving more complex decision problems.

EDAS method has been introduced to the literature by Keshavarz Ghorabaee *et al.* (2015) as a MCDM method. It is based on the measurement of the positive and negative distances from the average solution rather than calculating the negative ideal solution (NIS) and positive ideal solution (PIS) as in TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) (Chatterjee and Kar, 2016) and VIKOR (Vise Kriterijumska Optimizacija I Kompromisno Resenje) methods. Thus, unlike the TOPSIS and VIKOR methods, EDAS offers a solution based on how far the alternatives are from the average solution instead of PIS and NIS.

After the introduction of EDAS method to the literature, it has been used in many application areas such as supplier selection, project selection, personnel selection, material selection and drug selection. Due to the fact that fuzzy set theory in decision making better defines human thoughts, various fuzzy extensions of EDAS method have been used more frequently than classical EDAS method in the literature. Table 1 presents the classical, stochastic, neutrosophic, and fuzzy EDAS papers published in the literature and their application areas in historical order.

Table 1 shows that the classical EDAS method has been developed by many extensions of ordinary fuzzy sets such as type-2 fuzzy sets, intuitionistic fuzzy sets and hesitant fuzzy sets. However, since it was only put forward in 2015, there is still a gap in the literature about the method and its usage areas.

Since the fuzzy versions of the EDAS method proposed so far do not fully reflect the reliability information, another possible extension of the classical EDAS method is realized in this study through Z-fuzzy numbers, which represent the natural language with better descriptive ability. Thus, apart from the fuzzy extensions in Table 1, the EDAS method has been extended with Z-fuzzy numbers, which are composed of trapezoidal restriction function and triangular fuzzy reliability function.

After Z-fuzzy numbers were introduced to the literature, they have been integrated with several MCDM methods such as AHP (Azadeh *et al.*, 2013; Sergi and Sari, 2021; Tüysüz and Kahraman, 2020a; Kahraman and Otay, 2018), TOPSIS (Krohling *et al.*, 2019), VIKOR (Shen and Wang, 2018), and WASPAS (Sergi and Sari, 2021). Table 2 presents the Z-fuzzy number integrated MCDM methods based on their publication years.

As can be seen in Table 2, Z-fuzzy numbers are integrated with different MCDM methods, and they are used in different application areas. However, there is still a significant literature gap regarding the combined use of Z-fuzzy numbers and MCDM methods. This study contributes to fill this literature gap by integrating the EDAS method with Z-fuzzy numbers.

3. Z-Fuzzy Numbers: Preliminaries

DMs are often not 100% confident in their assignments for membership degrees. Hence, in addition to assigning a membership degree/function $\mu_{\tilde{A}}(x)$, it makes sense to also assign

Table 1
Papers in the literature on EDAS method.

Year	Authors	Extension of EDAS	Application area
2015	Keshavarz Ghorabaee *et al.*	Crisp EDAS	Inventory classification
2016	Keshavarz Ghorabaee *et al.*	Fuzzy EDAS	Supplier selection
2017	Kahraman *et al.*	Intuitionistic EDAS	Solid waste disposal site selection
2017a	Keshavarz Ghorabaee *et al.*	Stochastic EDAS	Performance evaluation of bank branches
2017	Stanujkic *et al.*	Interval grey valued EDAS	Contractor selection
2017b	Keshavarz Ghorabaee *et al.*	Interval type-2 fuzzy EDAS	Supplier selection with respect to environmental criteria
2017c	Keshavarz Ghorabaee *et al.*	Interval type-2 fuzzy EDAS	Evaluation of subcontractors
2017	Peng and Liu	Single valued neutrosophic EDAS	Evaluation of software development project
2018	Stević *et al.*	Fuzzy EDAS	Carpenter manufacturer selection
2018	Feng *et al.*	Hesitant fuzzy EDAS	Project selection
2018c	Chatterjee *et al.*	Crisp EDAS	Material selection
2018	Keshavarz Ghorabaee *et al.*	Dynamic fuzzy EDAS	Evaluation of subcontractors
2018	Karabasevic *et al.*	Crisp EDAS	Personnel Selection
2018	Liang *et al.*	Integrated EDAS-ELECTRE method	Cleaner Production Evaluation
2018	Ilieva	Interval type-2 fuzzy EDAS	An illustrative example
2018	Karaşan and Kahraman	Interval-valued neutrosophic EDAS	Prioritization of the united nations national sustainable development goals
2018	Kutlu Gündoğdu *et al.*	Hesitant fuzzy EDAS	Hospital selection
2019	Karaşan *et al.*	Interval-valued neutrosophic EDAS	Ranking of social responsibility projects
2019	Zhang *et al.*	Picture 2-tuple linguistic EDAS	Green supplier selection
2019	Schitea *et al.*	Intuitionistic EDAS	Selection of hydrogen collection site
2019	Kundakcı	Crisp EDAS	Steam boiler selection
2019	Wang *et al.*	2-tuple linguistic neutrosophic EDAS	Safety assessment of construction project
2019	Stević *et al.*	Fuzzy EDAS	Supplier selection
2020	Yanmaz *et al.*	Interval-valued Pythagorean Fuzzy EDAS	Car selection
2020	Han and Wei	Neutrosophic EDAS	Investment evaluation
2020	Liang	Intuitionistic Fuzzy EDAS	Selection of energy-saving design projects
2020	He *et al.*	Pythagorean 2-tuple linguistic sets based EDAS	Construction project selection
2020	Darko and Liang	q-rang orthopair fuzzy EDAS	Mobile payment platform selection
2020	Li *et al.*	q-rung orthopair fuzzy EDAS	Refrigerator selection
2020	Mishra *et al.*	Intuitionistic fuzzy EDAS	Disposal method selection
2020	Tolga and Basar	Fuzzy EDAS	Hydroponic system evaluation
2021	Wei *et al.*	Probabilistic EDAS	Supplier selection
2021	Chinram *et al.*	Intuitionistic fuzzy EDAS	Geographical site selection for construction
2021	Özçelik and Nalkıran	Trapezoidal bipolar Fuzzy numbers based EDAS	Medical device selection
2021	Jana and Pal	Bipolar fuzzy EDAS	Construction company selection

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Table 1
(*continued*)

Year	Authors	Extension of EDAS	Application area
2021	Mao *et al.*	Z-fuzzy EDAS	Ranking of engineering characteristics in quality function deployment
2022	Mitra	Crisp EDAS	Selection of cotton fabric
2022	Batool *et al.*	EDAS method under Pythagorean probabilistic hesitant fuzzy information	Drug selection for coronavirus disease
2022	Garg and Sharaf	Spherical fuzzy EDAS	Supplier selection and industrial robot selection
2022	Mishra *et al.*	Fermatean fuzzy EDAS	Evaluation of sustainable third-party reverse logistics providers
2022	Naz *et al.*	2-tuple linguistic T-spherical fuzzy EDAS	Selecting of the best COVID-19 vaccine
2022	Liao *et al.*	Probabilistic hesitant fuzzy EDAS	Evaluation of the commercial vehicles and green suppliers
2022	Demircan and Acarbay	Neutrosophic fuzzy EDAS	Vendor selection
2022	Rogulj *et al.*	Intuitionistic fuzzy EDAS	Prioritization of historic bridges
2022	Huang *et al.*	2-tuple spherical linguistic EDAS	Selection of the optimal emergency response solution
2022	Polat and Bayhan	Fuzzy EDAS	Supplier selection
2022	Su *et al.*	Probabilistic uncertain linguistic EDAS	Green finance evaluation of enterprises
2023	Akram *et al.*	Linguistic Pythagorean fuzzy EDAS	Selection of waste management technique

Table 2
A literature review on MCDM studies using Z-fuzzy numbers.

Year	Authors	MCDM method's used Z-fuzzy number	Application areas
2012a	Kang *et al.*	A proposed approach	Vehicle selection
2013	Azadeh *et al.*	AHP	Weighing the performance evaluation factors of universities
2014	Xiao	A proposed approach	Evaluation of cloths
2015	Sahrom and Dom	AHP and DEA	Risk assessment
2015	Yaakob and Gegov	TOPSIS	Stock selection
2016	Azadeh and Kokabi	DEA	Portfolio selection
2016	Sadi-Nezhad and Sotoudeh-Anvari	DEA	Efficiency assessment
2016	Yaakob and Gegov	TOPSIS	Stock selection
2017	Peng and Wang	A proposed approach	ERP selection
2017a	Khalif *et al.*	TOPSIS	Performance assessment
2017b	Khalif *et al.*	TOPSIS	Staff selection
2017	Wang *et al.*	TODIM	Evaluation of medical inquiry applications
2018	Karthika and Sudha	AHP	Risk assessment
2018	Forghani *et al.*	TOPSIS	Supplier selection
2018	Chatterjee and Kar	COPRAS	Renewable energy selection
2018	Aboutorab *et al.*	Best-worst method	Supplier development problem
2018	Peng and Wang	MULTIMOORA	Evaluation of potential areas of air pollution
2018	Shen and Wang	VIKOR	Selection of economic development plan
2018	Akbarian Saravi *et al.*	DEA	Evaluation of biomass power plants location

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Table 2
(*continued*)

Year	Authors	MCDM method's used Z-fuzzy number	Application areas
2018	Kahraman and Otay	AHP	Power plant location selection
2019	Gardashova	TOPSIS	Vehicle selection
2019	Wang and Mao	TOPSIS	Supplier selection
2019	Xian *et al.*	TOPSIS	Numerical examples on investment and medical diagnosis
2019	Kahraman *et al.*	AHP	Evaluation of law offices
2019	Krohling *et al.*	TODIM and TOPSIS	Case studies from literature
2019	Shen *et al.*	MABAC	Selection of economy development program
2020	Yildiz and Kahraman	AHP	Prioritization of social sustainable development factors
2020	Qiao *et al.*	PROMETHEE	Travel plan selection
2020	Das *et al.*	VIKOR	Prioritizing risk of hazards for crane operations.
2020	Jiang *et al.*	DEMATEL	Hospital performance measurement
2020	Mohtashami and Ghiasvand	DEA	Evaluation of banks and financial institutes
2020	Liu *et al.*	ANP and TODIM	Evaluation of suppliers for the nuclear power industry
2020a	Tüysüz and Kahraman	AHP	Evaluation of social sustainable development factors
2020b	Tüysüz and Kahraman	CODAS	Supplier selection
2021	Akhavein *et al.*	DEMATEL and VIKOR	Evaluation of projects
2021	Zhu and Hu	DEMATEL	Evaluation of sustainable value propositions for smart product-service systems
2021	Wang *et al.*	DEMATEL	Evaluation of human error probability for cargo loading operations.
2021	Mao *et al.*	EDAS	Ranking of engineering characteristics in quality function deployment
2021	Sergi and Ucal Sari	AHP and WASPAS	Evaluation of public services
2021	Karaşan *et al.*	DEMATEL	Blockchain risk assessment
2022	Peng *et al.*	MULTIMOORA	Hotel selection
2022	İlbahar *et al.*	DEMATEL and VIKOR	Evaluation of hydrogen energy storage systems
2022	Sari and Tüysüz	AHP and TOPSIS	Covid-19 risk assessment of occupations
2022	Liu *et al.*	ELECTRE II	Selection of logistics provider
2022	Rahmati *et al.*	SWARA and WASPAS	Prioritization of financial risk factors
2022	Gai *et al.*	MULTIMOORA	Green supplier selection
2022	RezaHoseini *et al.*	AHP and DEA	Performance evaluation of sustainable projects
2022	Božanić *et al.*	MABAC	Selection of the best contingency strategy

a reliability degree $\mu_{\tilde{B}}(x)$ so that DMs can reflect their confidence to the membership. The corresponding pairs $(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x))$ are known as a Z-fuzzy number which was introduced by Zadeh (2011).

A Z-fuzzy number is an ordered pair of fuzzy numbers $Z(\tilde{A}, \tilde{B})$, as given in Fig. 1. The first component $\tilde{A}$ is a restriction function whereas the second component $\tilde{B}$ is a measure of reliability for the first component.

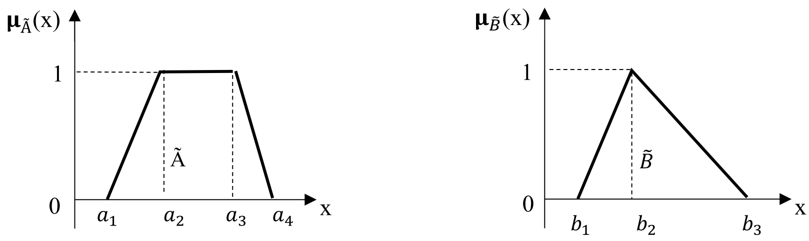

Fig. 1. A simple Z-fuzzy number, $Z(\tilde{A}, \tilde{B})$.

The concept of a Z-fuzzy number is intended to provide a basis for computation with ordinary fuzzy numbers which are not reliable.

Definition 1. Let a fuzzy set $\tilde{A}$ be defined on a universe X, which may be given as: $\tilde{A} = \{\langle x, \mu_{\tilde{A}}(x)\rangle \mid x \epsilon X\}$ where $\mu_{\tilde{A}} : X \rightarrow [0, 1]$ is the membership function $\tilde{A}$. The membership value $\mu_{\tilde{A}}(x)$ describes the degree of belongingness of $x \in X$ in $\tilde{A}$. The Fuzzy Expectation of a fuzzy set is given in Eq. (1):

$$E_A(x) = \int_x x\mu_A(x)dx, \tag{1}$$

which is not the Expectation of Probability Space.

Definition 2 (*Converting Z-fuzzy number to Regular Fuzzy Number,* Kang *et al.*, 2012b). Consider a Z-fuzzy number $Z = (\tilde{A}, \tilde{B})$, which is described by Fig. 1. The figure on the left is the part of restriction, and the figure on the right is the part of reliability. Let $\tilde{A} = \{\langle x, \mu_{\tilde{A}}(x)\rangle \mid \mu(x) \in [0, 1]\}$ and $\tilde{B} = \{\langle x, \mu_{\tilde{B}}(x)\rangle \mid \mu(x) \in [0, 1]\}$, $\mu_{\tilde{A}}(x)$ is a trapezoidal membership function, $\mu_{\tilde{B}}(x)$ is a triangular membership function.

(1) Convert the reliability function into a crisp number using Eq. (2):

$$\alpha = \frac{\int x\mu_{\tilde{B}}(x)dx}{\int \mu_{\tilde{B}}(x)dx}, \tag{2}$$

where $\int$ denotes an algebraic integration.

Alternatively, the defuzzification equation $(a_1 + 2 * a_2 + 2 * a_3 + a_4)/6$ for symmetrical trapezoidal fuzzy numbers and $(a_1 + 2 * a_2 + a_3)/4$ for symmetrical triangular fuzzy numbers can be used.

(2) Weigh the restriction function with the crisp value of the reliability function (α). The weighted restriction number is denoted in Eq. (3).

$$\tilde{Z}^{\alpha} = \left\{\langle x, \mu_{\tilde{A}^{\alpha}}(x)\rangle \,\middle|\, \mu_{\tilde{A}^{\alpha}}(x) = \alpha\mu_{\tilde{A}}(x),\ \mu(x) \in [0, 1]\right\}. \tag{3}$$

(3) Convert the weighted restriction number to ordinary fuzzy number using Eq. (4):

$$\tilde{Z}' = \left\{\langle x, \mu_{\tilde{Z}'}(x)\rangle \,\middle|\, \mu_{\tilde{Z}'}(x) = \mu_{\tilde{A}}\left(\frac{x}{\sqrt{\alpha}}\right),\ \mu(x) \in [0, 1]\right\}, \tag{4}$$

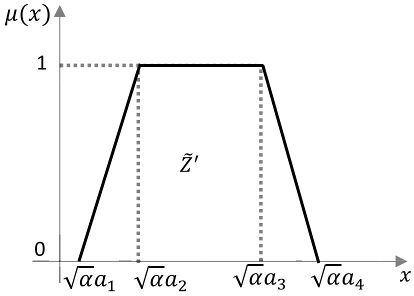

Fig. 2. Ordinary fuzzy number converted from Z-fuzzy number.

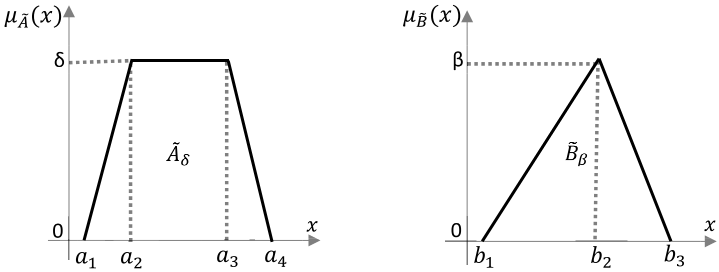

Fig. 3. A simple $\tilde{Z}_{\delta,\beta}$ number, $\tilde{Z}_{\delta,\beta} = (\tilde{A}_\delta, \tilde{B}_\beta)$.

$\tilde{Z}'$ has the same Fuzzy Expectation with $\tilde{Z}^\alpha$, and they are equal with respect to Fuzzy Expectation, which can be denoted by Fig. 2.

(4) If the restriction function and reliability function are defined as in Fig. 3, the calculations are modified as follows:

Let $\tilde{A}_\delta = \{\langle x, (\mu_{\tilde{A}}(x); \delta)\rangle \mid \mu(x) \in [0, 1]\}$ and $\tilde{B}_\beta = \{\langle x, (\mu_{\tilde{B}}(x); \beta)\rangle \mid \mu(x) \in [0, 1]\}$, $\mu^\delta_{\tilde{A}}(x)$ is a trapezoidal membership function, $\mu^\beta_{\tilde{B}}(x)$ is a triangular membership function.

In this case, restriction and reliability functions are given in Eqs. (5)–(6), respectively. The reliability membership function in Eq. (6) is substituted into the defuzzification formula Eq. (2); so that, Eq. (7) is obtained.

$$\mu^\delta_{\tilde{A}}(x) = \begin{cases} \frac{x-a_1}{a_2-a_1}\delta, & \text{if } a_1 \leqslant x \leqslant a_2, \\ \delta, & \text{if } a_2 \leqslant x \leqslant a_3, \\ \frac{a_4-x}{a_4-a_3}\delta, & \text{if } a_3 \leqslant x \leqslant a_4, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

$$\mu^\beta_{\tilde{B}}(x) = \begin{cases} \frac{x-b_1}{b_2-b_1}\beta, & \text{if } b_1 \leqslant x \leqslant b_2, \\ \frac{b_3-x}{b_3-b_2}\beta, & \text{if } b_2 \leqslant x \leqslant b_3, \\ 0, & \text{otherwise}. \end{cases} \tag{6}$$

Thus, we have

$$\sqrt{\alpha} = \sqrt{\frac{\int x\mu_{\tilde{B}}^{\beta}(x)dx}{\int \mu_{\tilde{B}}^{\beta}(x)dx}}. \tag{7}$$

Then, the weighted $\tilde{Z}_{\delta,\beta}$ number can be denoted as in Eq. (8):

$$\tilde{Z}_{\delta,\beta}^{\alpha} = \left\{\langle x, \mu_{\tilde{A}^{\alpha}}^{\delta}(x)\rangle \mid \mu_{\tilde{A}^{\alpha}}^{\delta}(x) = \frac{\int x\mu_{\tilde{B}}^{\beta}(x)dx}{\int \mu_{\tilde{B}}^{\beta}(x)dx}\mu_{\tilde{A}}^{\delta}(x),\ \mu(x) \in [0, 1]\right\}. \tag{8}$$

The ordinary fuzzy number converted from Z-fuzzy number can be given as in Eq. (9):

$$\tilde{Z}'_{\delta,\beta} = \left\{\langle x, \mu_{\tilde{Z}'}^{\delta}(x)\rangle \mid \mu_{\tilde{Z}'}^{\delta}(x) = \mu_{\tilde{A}}^{\delta}\left(x\frac{\int \mu_{\tilde{B}}^{\beta}(x)dx}{\int x\mu_{\tilde{B}}^{\beta}(x)dx}\right),\ \mu(x) \in [0, 1]\right\}. \tag{9}$$

4. Z-Fuzzy AHP

The AHP method is one of the most widely used MCDM methods to calculate the criteria weights and there are several versions of it (Chatterjee and Kar, 2017). Due to the nature, it is usual for DMs to have hesitation while making pairwise comparisons, and in these situations, it is expected that they will not be absolutely sure about their evaluations. These preferences can be included in the decision methods by modelling the DMs' thinking structure under the concept of Z-fuzzy numbers. Therefore, in this study, to obtain criteria weights, it is suggested to collect DMs' judgments using Z-fuzzy numbers integrated AHP method rather than commonly used fuzzy versions of AHP method.

To calculate criteria weights, the steps of the Z-fuzzy AHP method are presented in the following:

Step 1. Determine the criteria set of the decision problem. Fig. 4 can be used to establish the hierarchical structure of goal, main criteria and sub-criteria. Level 1 of the hierarchy represents a goal whereas Level 2 and Level 3 are composed of main-criteria and sub-criteria, respectively.

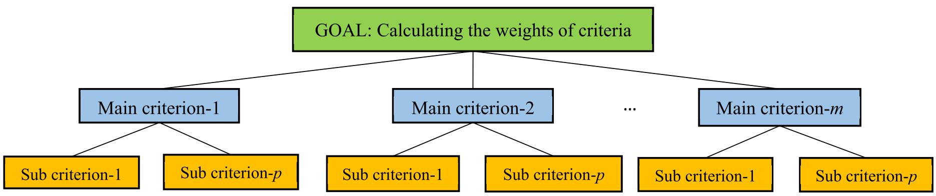

Fig. 4. Hierarchical structure for criteria.

Table 3
Triangular restriction scale for pairwise comparisons of criteria.

Linguistic terms	Abbreviation	Restriction function
Equally Important	EI	(1, 1, 1; 1)
Slightly Important	SLI	(1, 1, 3; 1)
Moderately Important	MI	(1, 3, 5; 1)
Strongly Important	STI	(3, 5, 7; 1)
Very Strongly Important	VSTI	(5, 7, 9; 1)
Certainly Important	CI	(7, 9, 10; 1)
Absolutely Important	AI	(9, 10, 10; 1)

Table 4
Triangular reliability scale.

Linguistic terms	Abbreviation	Reliability function
Certainly Reliable	CR	(1, 1, 1; 1)
Very Strongly Reliable	VSR	(0.8, 0.9, 1; 1)
Strongly Reliable	SR	(0.7, 0.8, 0.9; 1)
Very Highly Reliable	VHR	(0.6, 0.7, 0.8; 1)
Highly Reliable	HR	(0.5, 0.6, 0.7; 1)
Fairly Reliable	FR	(0.4, 0.5, 0.6; 1)
Weakly Reliable	WR	(0.3, 0.4, 0.5; 1)
Very Weakly Reliable	VWR	(0.2, 0.3, 0.4; 1)
Strongly Unreliable	SU	(0.1, 0.2, 0.3; 1),
Absolutely Unreliable	AU	(0, 0.1, 0.2; 1)

Step 2. Determine the linguistic terms and their corresponding Z-fuzzy restriction and reliability numbers. Collect the linguistic pairwise comparison evaluations from each DM for the main criteria and sub-criteria by using questionnaires. Then, Z-fuzzy pairwise comparison matrices are constructed based on these evaluations. Each DM can use Z-fuzzy linguistic scales given in Tables 3–4 for his/her assessments, respectively.

Let each decision maker (DM_k) assign an independent assessment for any pairwise comparison as shown in Eq. (10):

$$Z^{DMk} = (\tilde{A}, \tilde{B}) = \big(\big(a_1^{DMk}, a_2^{DMk}, a_3^{DMk}\big), \big(b_1^{DMk}, b_2^{DMk}, b_3^{DMk}\big)\big). \tag{10}$$

Step 3. Calculate the consistency ratio (CR) of each Z-fuzzy pairwise comparison matrix obtained by the DMs' assessments. Defuzzify the restriction functions of Z-fuzzy numbers in the pairwise comparison matrix using Eq. (2) and obtain the crisp pairwise comparison matrix. Apply Saaty's classical consistency procedure and check if CR is less than 0.1, which is accepted as the consistency limit in the literature (Saaty, 1980).

Step 4. Apply the aggregation procedure for DMs' Z-fuzzy assessments. Each element of restriction and reliability functions of Z-fuzzy assessments is aggregated by using geometric mean and one Z-fuzzy decision matrix is obtained.

Assume three DMs assign the following terms:

$$\tilde{Z}^{DM1} = (\tilde{A}, \tilde{B}) = \big((a_1^{DM1}, a_2^{DM1}, a_3^{DM1}), (b_1^{DM1}, b_2^{DM1}, b_3^{DM1})\big),$$
$$\tilde{Z}^{DM2} = (\tilde{A}, \tilde{B}) = \big((a_1^{DM2}, a_2^{DM2}, a_3^{DM2}), (b_1^{DM2}, b_2^{DM2}, b_3^{DM2})\big),$$
$$\tilde{Z}^{DM3} = (\tilde{A}, \tilde{B}) = \big((a_1^{DM3}, a_2^{DM3}, a_3^{DM3}), (b_1^{DM3}, b_2^{DM3}, b_3^{DM3})\big).$$

Aggregation of these three DMs' assessments is made by using the geometric mean operator given in Eqs. (11)–(12):

$$\tilde{Z}^{Agg} = \big(\tilde{A}^{Agg}, \tilde{B}^{Agg}\big) = \begin{bmatrix} \tilde{c}_{11} & \tilde{c}_{12} & \dots & \tilde{c}_{1m} \\ \tilde{c}_{21} & \tilde{c}_{22} & \dots & \tilde{c}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{c}_{m1} & \tilde{c}_{m2} & \dots & \tilde{c}_{mm} \end{bmatrix}, \tag{11}$$

where

$$\tilde{c}_{ij} = \left(\begin{array}{l} \Big(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}}, \sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}}, \sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}}\Big), \\ \Big(\sqrt[3]{b_{1,ij}^{DM1} * b_{1,ij}^{DM2} * b_{1,ij}^{DM3}}, \sqrt[3]{b_{2,ij}^{DM1} * b_{2,ij}^{DM2} * b_{2,ij}^{DM3}}, \sqrt[3]{b_{3,ij}^{DM1} * b_{3,ij}^{DM2} * b_{3,ij}^{DM3}}\Big) \end{array} \right),$$
$$i = 1, 2, \dots, m; \;\; j = 1, 2, \dots, m. \tag{12}$$

Step 5. Calculate the alpha (α) from the reliability components of the aggregated pairwise comparison matrix by using Eq. (13). The reciprocal reliability values are the multiplicative inverse of the calculated α values.

$$\alpha_{ij} = \frac{\Big(\sqrt[3]{b_{1,ij}^{DM1} * b_{1,ij}^{DM2} * b_{1,ij}^{DM3}} + 2 * \sqrt[3]{b_{2,ij}^{DM1} * b_{2,ij}^{DM2} * b_{2,ij}^{DM3}} + \sqrt[3]{b_{3,ij}^{DM1} * b_{3,ij}^{DM2} * b_{3,ij}^{DM3}}\Big)}{4},$$
$$i = 1, 2, \dots, m; \;\; j = 1, 2, \dots, m. \tag{13}$$

Step 6. Convert the Z-fuzzy numbers ($\tilde{Z}^{Agg}$) to ordinary fuzzy numbers ($\tilde{O}$) using the matrix obtained in Step 5 by using Eqs. (14) and (15):

$$\tilde{O} = \begin{bmatrix} \tilde{o}_{11} & \tilde{o}_{12} & \dots & \tilde{o}_{1m} \\ \tilde{o}_{21} & \tilde{o}_{22} & \dots & \tilde{o}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{o}_{m1} & \tilde{o}_{m2} & \dots & \tilde{o}_{mm} \end{bmatrix}, \tag{14}$$

where

$$\tilde{o}_{ij} = \left(\begin{array}{l} \sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}}\sqrt{\alpha_{ij}}, \sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}}\sqrt{\alpha_{ij}}, \\ \sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}}\sqrt{\alpha_{ij}} \end{array} \right). \tag{15}$$

Step 7. Apply the ordinary fuzzy AHP method using Buckley's method (Buckley, 1985).

Step 7.1. Calculate the geometric mean vector ($\widetilde{GM}$) whose elements are given in Eqs. (16)–(17). Thus, $m \times 1$ matrix is obtained from $m \times m$ matrix.

$$\widetilde{GM} = \begin{bmatrix} \tilde{g}_{11} \\ \tilde{g}_{21} \\ \vdots \\ \tilde{g}_{m1} \end{bmatrix}, \tag{16}$$

where

$$\tilde{g}_{i1} = \begin{pmatrix} \sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}, \\ \sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}, \\ \sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)} \end{pmatrix}, \quad i = 1, 2, \ldots, m. \tag{17}$$

Step 7.2. Sum the values in $\widetilde{GM}$ vector using Eq. (18):

$$\tilde{S} = \begin{pmatrix} \sum_{i=1}^{m}\left(\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}\right), \\ \sum_{i=1}^{m}\left(\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}\right), \\ \sum_{i=1}^{m}\left(\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}\right) \end{pmatrix}. \tag{18}$$

Step 7.3. Apply fuzzy division operation to obtain relative fuzzy weights vector ($\tilde{R}$) of criteria as given in Eqs. (19)–(20):

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} \\ \tilde{r}_{21} \\ \vdots \\ \tilde{r}_{m1} \end{bmatrix} = \begin{bmatrix} \tilde{g}_{11}/\tilde{S} \\ \tilde{g}_{21}/\tilde{S} \\ \vdots \\ \tilde{g}_{m1}/\tilde{S} \end{bmatrix}, \tag{19}$$

where

$$\tilde{r}_{i1} = \begin{pmatrix} \dfrac{\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}}{\sum_{i=1}^{m}\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}}, \\ \dfrac{\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}}{\sum_{i=1}^{m}\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}}, \\ \dfrac{\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}}{\sum_{i=1}^{m}\sqrt[m]{\prod_{j=1}^{m}\left(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}}\sqrt{\alpha_{ij}}\right)}} \end{pmatrix}, \quad i = 1, 2, \ldots, m. \tag{20}$$

Step 7.4. Defuzzify the relative fuzzy weights vector ($\tilde{R}$) using Eq. (21):

$$d_j = \left(\frac{\sqrt[m]{\prod_{j=1}^{m} \left(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}} \sqrt{\alpha_{ij}} \right)}}{\sum_{i=1}^{m} \sqrt[m]{\prod_{j=1}^{m} \left(\sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}} \sqrt{\alpha_{ij}} \right)}} + 2 * \frac{\sqrt[m]{\prod_{j=1}^{m} \left(\sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}} \sqrt{\alpha_{ij}} \right)}}{\sum_{i=1}^{m} \sqrt[m]{\prod_{j=1}^{m} \left(\sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}} \sqrt{\alpha_{ij}} \right)}} + \frac{\sqrt[m]{\prod_{j=1}^{m} \left(\sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}} \sqrt{\alpha_{ij}} \right)}}{\sum_{i=1}^{m} \sqrt[m]{\prod_{j=1}^{m} \left(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}} \sqrt{\alpha_{ij}} \right)}} \right) * 4^{-1},$$

$$j = 1, 2, \ldots, m. \tag{21}$$

Step 7.5. Normalize the defuzzified weights to satisfy $\sum w_j = 1$ using Eq. (22). Thus, the weights of the criteria are obtained as crisp values.

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j}, \quad j = 1, 2, \ldots, m. \tag{22}$$

Step 8. Apply Steps 3–6 for the other Z-fuzzy pairwise comparison matrices of DMs for the sub-criteria under each main criterion and obtain the weight of each sub-criterion $\acute{j}$, $\acute{j} = 1, 2, \ldots, p$.

$$w_{j\acute{j}} \quad \text{where } j = 1, 2, \ldots, m \quad \text{and} \quad \acute{j} = 1, 2, \ldots, p \quad \text{for each } j.$$

Step 9. Combine the local sub-criteria weights ($w_{j\acute{j}}$) and main criteria weights (w_j) in order to obtain global criteria weights ($w_{j\acute{j}}^G$) as in Eq. (23).

$$w_{j\acute{j}}^G = w_j * w_{j\acute{j}}, \quad j = 1, 2, \ldots, m \quad \text{and} \quad \acute{j} = 1, 2, \ldots, p \quad \text{for each } j. \tag{23}$$

5. Z-Fuzzy EDAS

The first fuzzy EDAS method is introduced by Keshavarz Ghorabaee *et al.* (2016) for the solution of MCDM problems under uncertainty. It is integrated with various fuzzy set extensions to model the vagueness and impreciseness. In this study, due to the fact that these extensions cannot completely combine the reliability information with the EDAS method, it is extended to Z-fuzzy EDAS method by using ordinary Z-fuzzy numbers. This method allows to define the DMs' preferences over the alternatives with their degree of confidence, which creates a more comprehensive and flexible decision-making environment. Z-Fuzzy EDAS method is presented as follows:

Table 5
Z-fuzzy restriction scale for evaluation of alternatives.

Linguistic terms	Abbreviation	Restriction function
Very Poor	VP	(1/4, 1/2, 1/2, 1; 1)
Poor	P	(1/2, 1, 1, 3; 1)
Medium Poor	MP	(1, 3, 3, 5; 1)
Fair	F	(3, 5, 5, 7; 1)
Medium Good	MG	(5, 7, 7, 9; 1)
Good	G	(7, 9, 9, 10; 1)
Very Good	VG	(9, 10, 10, 10; 1)

Step 1. Determine the evaluation criteria $C = (C_1, C_2, \dots, C_m)$ and alternatives $A = (A_1, A_2, \dots, A_n)$ for the decision problem.

Step 2. Construct the fuzzy decision matrix $(\tilde{D})$ using Z-fuzzy numbers, shown as in Eq. (24):

$$\tilde{D} = [\tilde{x}_{ij}]_{n\times m} = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1m} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \dots & \tilde{x}_{nm} \end{bmatrix}, \tag{24}$$

where $\tilde{x}_{ij} \geqslant 0$ and it denotes the Z-fuzzy performance value of ith alternative on jth criterion

$$\big(i \in \{1, 2, \dots, n\} \text{ and } j \in \{1, 2, \dots, m\}\big).$$

Z-fuzzy linguistic restriction scale presented in Table 5 and the reliability scale in Table 4 are used for DMs' assessments in the decision matrix.

Step 3. Aggregate the Z-fuzzy evaluation matrices of all DMs. Aggregation of three DMs' assessments is made by using the geometric mean given in Eqs. (25)–(26):

$$\tilde{Z}_{\tilde{D}}^{Agg} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1m} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \dots & \tilde{x}_{nm} \end{bmatrix}, \tag{25}$$

where

$$\tilde{x}_{ij} = \left(\begin{matrix} \left(\sqrt[3]{a_{1,ij}^{DM1} * a_{1,ij}^{DM2} * a_{1,ij}^{DM3}}, \sqrt[3]{a_{2,ij}^{DM1} * a_{2,ij}^{DM2} * a_{2,ij}^{DM3}}, \sqrt[3]{a_{3,ij}^{DM1} * a_{3,ij}^{DM2} * a_{3,ij}^{DM3}}\right), \\ \left(\sqrt[3]{b_{1,ij}^{DM1} * b_{1,ij}^{DM2} * b_{1,ij}^{DM3}}, \sqrt[3]{b_{2,ij}^{DM1} * b_{2,ij}^{DM2} * b_{2,ij}^{DM3}}, \sqrt[3]{b_{3,ij}^{DM1} * b_{3,ij}^{DM2} * b_{3,ij}^{DM3}}\right) \end{matrix} \right),$$
$$i = 1, 2, \dots, n; \ \ j = 1, 2, \dots, m. \tag{26}$$

Step 4. Calculate the Z-fuzzy average values ($\widetilde{AV}$) by using Eqs. (27)–(28):

$$\widetilde{AV} = [\widetilde{AV}_j]_{1\times m} = \begin{bmatrix} \widetilde{AV}_1 & \widetilde{AV}_2 & \dots & \widetilde{AV}_j \end{bmatrix}, \tag{27}$$

$$\widetilde{AV}_j = \frac{\sum_{i=1}^{n} \tilde{X}_{ij}}{n}, \quad \forall j,\ j = 1, 2, \dots, m. \tag{28}$$

Step 5. Calculate the Z-fuzzy positive distance from average ($\widetilde{PDA}$) and Z-fuzzy negative distance from average ($\widetilde{NDA}$) for each alternative by employing Eqs. (29)–(32):

$$\widetilde{PDA} = [\widetilde{PDA}_{ij}]_{n\times m}, \tag{29}$$

$$\widetilde{NDA} = [\widetilde{NDA}_{ij}]_{n\times m}, \tag{30}$$

$$\begin{cases} \widetilde{PDA}_{ij} = \frac{\max(0, (\tilde{x}_{ij} - \widetilde{AV}_j))}{\widetilde{AV}_j}, \\ \widetilde{NDA}_{ij} = \frac{\max(0, (\widetilde{AV}_j - \tilde{x}_{ij}))}{\widetilde{AV}_j}, \end{cases} \quad \text{for benefit criteria,} \tag{31}$$

$$\begin{cases} \widetilde{PDA}_{ij} = \frac{\max(0, (\widetilde{AV}_j - \tilde{x}_{ij}))}{\widetilde{AV}_j}, \\ \widetilde{NDA}_{ij} = \frac{\max(0, (\tilde{x}_{ij} - \widetilde{AV}_j))}{\widetilde{AV}_j}, \end{cases} \quad \text{for cost criteria,} \tag{32}$$

where $\widetilde{PDA}_{ij}$ and $\widetilde{NDA}_{ij}$ represent the Z-fuzzy positive and negative distances from average value of ith alternative according to jth criterion, respectively.

To determine $\max(0, (\tilde{x}_{ij} - \widetilde{AV}_j))$, Z-fuzzy numbers are defuzzified as in Eqs. (33)–(34) and compared with each other.

$$a_j = \frac{(a_{1,ij} + 2 * a_{2,ij} + 2 * a_{3,ij} + a_{4,ij})}{6}, \quad \forall j, \ \text{for restriction function,} \tag{33}$$

$$b_j = \frac{(b_{1,ij} + 2 * b_{2,ij} + b_{3,ij})}{4}, \quad \forall j, \ \text{for reliability function.} \tag{34}$$

After determining the $\max(0, (\tilde{x}_{ij} - \widetilde{AV}_j))$, we still continue with Z-fuzzy numbers. Then, $\max(0, (\tilde{x}_{ij} - \widetilde{AV}_j))$ is divided by $\widetilde{AV}_j$ using Z-fuzzy numbers.

Step 6. Use the criteria weights obtained by Z-fuzzy AHP method in Section 4 and calculate the weighted summation of $\widetilde{PDA}$ and $\widetilde{NDA}$ shown as in Eqs. (35)–(36):

$$\widetilde{SP}_i = \sum_{j=1}^{m} w_j * \widetilde{PDA}_{ij}, \tag{35}$$

$$\widetilde{SN}_i = \sum_{j=1}^{m} w_j * \widetilde{NDA}_{ij}, \tag{36}$$

where $w_j = (w_1, w_2, \dots, w_m)$ and it is the weight of jth criterion.
w_j $(0 < w_j < 1)$ denotes the weight of jth criterion and $\sum_{j=1}^{m} w_j = 1$.

Step 7. Transform the obtained Z-fuzzy $\widetilde{SP}_i$ and $\widetilde{SN}_i$ values to positive values if there is any negative value among them for all alternatives shown as in Eqs. (37)–(40). Thus, we obtain the shifted $\widetilde{SP}_i$ and $\widetilde{SN}_i$ values, $\widetilde{SSP}_i$ and $\widetilde{SSN}_i$, respectively.

For restriction function:

$$\widetilde{SSP}_i^{Res} = \widetilde{SP}_i^{Res} + \max_i \left| \left(\widetilde{SP}_{i_{a1}}^{Res} \right) \right|, \quad \text{if any } a_1 < 0, \tag{37}$$

$$\widetilde{SSN}_i^{Res} = \widetilde{SN}_i^{Res} + \max_i \left| \left(\widetilde{SN}_{i_{a1}}^{Res} \right) \right|, \quad \text{if any } a_1 < 0. \tag{38}$$

For reliability function:

$$\widetilde{SSP}_i^{Rel} = \widetilde{SP}_i^{Rel} + \max_i \left| \left(\widetilde{SP}_{i_{b1}}^{Rel} \right) \right|, \quad \text{if any } b_1 < 0, \tag{39}$$

$$\widetilde{SSN}_i^{Rel} = \widetilde{SN}_i^{Rel} + \max_i \left| \left(\widetilde{SN}_{i_{b1}}^{Rel} \right) \right|, \quad \text{if any } b_1 < 0. \tag{40}$$

Step 8. Normalize the Z-fuzzy $\widetilde{SSP}_i$ and $\widetilde{SSN}_i$ values by using Eqs. (41)–(44).

For restriction function

$$\widetilde{NSP}_{i_a}^{Res} = \left(\frac{\widetilde{SSP}_{ia_1}}{\max_i(\widetilde{SP}_i^{Res})}, \frac{\widetilde{SSP}_{ia_2}}{\max_i(\widetilde{SP}_i^{Res})}, \frac{\widetilde{SSP}_{ia_3}}{\max_i(\widetilde{SP}_i^{Res})}, \frac{\widetilde{SSP}_{ia_4}}{\max_i(\widetilde{SP}_i^{Res})} \right) \tag{41}$$

and

$$\widetilde{NSN}_{i_a}^{Res} = (1,1,1,1) - \left(\frac{\widetilde{SSN}_{ia_4}}{\max_i(\widetilde{SN}_i^{Res})}, \frac{\widetilde{SSN}_{ia_3}}{\max_i(\widetilde{SN}_i^{Res})}, \frac{\widetilde{SSN}_{ia_2}}{\max_i(\widetilde{SN}_i^{Res})}, \frac{\widetilde{SSN}_{ia_1}}{\max_i(\widetilde{SN}_i^{Res})} \right) \tag{42}$$

for reliability function

$$\widetilde{NSP}_{i_b}^{Rel} = \left(\frac{\widetilde{SSP}_{ib_1}}{\max_i(\widetilde{SP}_i^{Rel})}, \frac{\widetilde{SSP}_{ib_2}}{\max_i(\widetilde{SP}_i^{Rel})}, \frac{\widetilde{SSP}_{ib_3}}{\max_i(\widetilde{SP}_i^{Rel})} \right) \tag{43}$$

and

$$\widetilde{NSN}_{i_b}^{Rel} = (1,1,1) - \left(\frac{\widetilde{SSN}_{ib_3}}{\max_i(\widetilde{SN}_i^{Rel})}, \frac{\widetilde{SSN}_{ib_2}}{\max_i(\widetilde{SN}_i^{Rel})}, \frac{\widetilde{SSN}_{ib_1}}{\max_i(\widetilde{SN}_i^{Rel})} \right). \tag{44}$$

Step 9. Calculate the Z-fuzzy appraisal score ($\widetilde{AS}_i = (AS_{i_a}^{Res}, AS_{i_b}^{Rel})$) of alternatives, as shown in Eqs. (45)–(46):

$$AS_{i_a}^{Res} = \frac{1}{2}\left(\widetilde{NSP}_{i_a}^{Res} + \widetilde{NSN}_{i_a}^{Res} \right), \tag{45}$$

$$AS_{i_b}^{Rel} = \frac{1}{2}\left(\widetilde{NSP}_{i_b}^{Rel} + \widetilde{NSN}_{i_b}^{Rel} \right). \tag{46}$$

Step 10. Convert the Z-fuzzy $\widetilde{AS}_i$ to ordinary fuzzy number using Definition 2.

Step 11. Transform the ordinary fuzzy $\widetilde{AS}_i$ to a crisp number using Eq. (2).

Step 12. Rank the alternatives according to the decreasing values of crisp AS_i. The alternative which has the highest AS_i is the best choice among the alternatives.

Fig. 5 shows the flowchart of the methodology which integrates Z-fuzzy AHP and Z-fuzzy EDAS methods. The proposed methodology aims at finding the weights of the criteria to be used in wind turbine selection (Z-fuzzy AHP) and also ranking the alternatives (Z-fuzzy EDAS) according to these criteria.

6. Application: Wind Turbine Selection

Wind power is one of the fastest growing renewable energy alternatives. Due to the increasing energy demand, investments toward renewable energy sources are getting more importance day by day. Wind energy is the most widely used renewable energy source in Turkey (Kahraman and Kaya, 2010). According to the March 2022 TEİAŞ (Turkish Electricity Transmission Corporation) report, there are 355 wind power plants, and approximately 10861 megawatts of energy are produced from the wind in Turkey (TEİAŞ, 2022). In order to produce energy efficiently from the wind, the turbine characteristics of the power plant to be established have great importance. Therefore, the selection of wind turbines in a wind energy investment is extremely important for investors. There are many types of wind turbines according to their characteristics. In order to produce energy efficiently from the wind, the right wind turbine should be selected by the DMs according to the wind characteristics of the region to be established. In addition, the problem should be considered as a MCDM problem since many factors should be evaluated together in wind turbine selection. The MCDM studies of wind turbine selection in the literature are quite limited (Supciller and Toprak, 2020). Studies related to wind turbine selection can be found in Supciller and Toprak (2020) and Pang *et al.* (2021).

The proposed Z-fuzzy AHP&EDAS methodology is applied for the selection of the best alternative among wind turbines in the Aegean region of Turkey. For this purpose, in Step 1, the alternatives and criteria have been determined. There are five wind turbine alternatives represented by A1, A2, A3, A4 and A5 and six criteria which are reliability (C1), technical characteristics (C2), performance (C3), cost factors (C4), availability (C5) and maintenance (C6) (Cevik Onar *et al.*, 2015). In Step 2, decision matrices have been constructed by three DMs using the linguistic terms given in Tables 4 and 5. Three DMs' pairwise comparison matrices for the criteria are presented in Tables 6–8.

Applying the Z-fuzzy AHP method in Section 4 the criteria weights have been obtained as in Table 9.

After the DMs have compared the criteria, the evaluations of the alternatives according to the criteria have been collected. Tables 10–12 show the Z-fuzzy decision matrices including the linguistic evaluations of three DMs.

In Step 3, the individual evaluations of DMs are aggregated by using geometric mean method given by Eqs. (25)–(26). The obtained aggregated matrix is presented in Table 13.

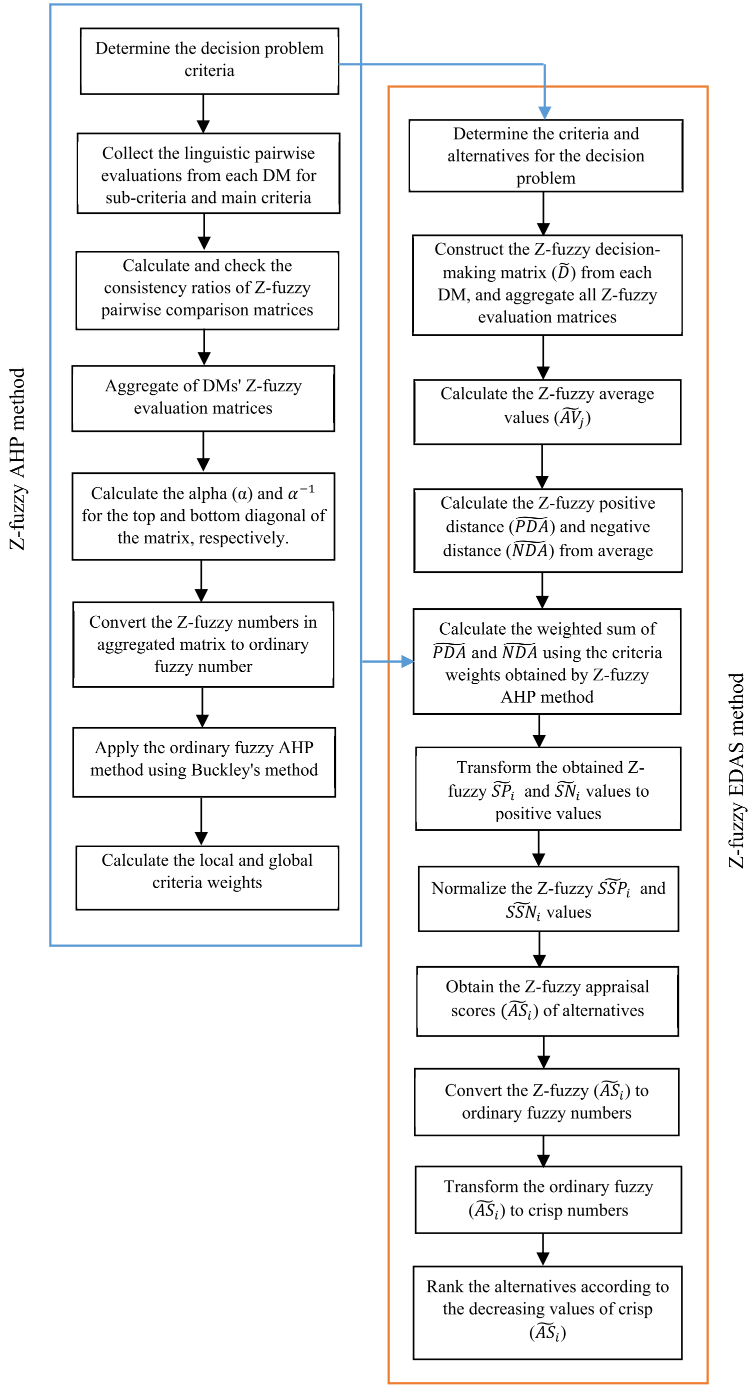

Fig. 5. Proposed Z-fuzzy AHP&EDAS methodology.

Table 6
Pairwise comparisons of the criteria by DM1.

DM1	C1	C2	C3	C4	C5	C6
C1	(EI, CR)	(CI, VSR)	(STI, HR)	(SLI, VSR)	(VSTI, VHR)	(CI, VSR)
C2	(1/CI, VSR)	(EI, CR)	(1/MI, SR)	(1/VSTI, FR)	(1/MI, SR)	(MI, FR)
C3	(1/STI, HR)	(MI, SR)	(EI, CR)	(1/MI, VHR)	(SLI, VSR)	(STI, VHR)
C4	(1/SLI, VSR)	(VSTI, FR)	(MI, VHR)	(EI, CR)	(STI, FR)	(CI, VSR)
C5	(1/VSTI, VHR)	(MI, SR)	(1/SLI, VSR)	(1/STI, FR)	(EI, CR)	(STI, WR)
C6	(1/CI, VSR)	(1/MI, FR)	(1/STI, VHR)	(1/CI, VSR)	(1/STI, WR)	(EI, CR)

$\lambda_{max} = 6.6085$, Consistency index (CI) = 0.1216, Consistency ratio (CR) = 0.097.

Table 7
Pairwise comparisons of the criteria by DM2.

DM2	C1	C2	C3	C4	C5	C6
C1	(EI, CR)	(VSTI, VHR)	(MI, FR)	(EI, SR)	(STI, SR)	(VSTI, HR)
C2	(1/VSTI, VHR)	(EI, CR)	(1/STI, VHR)	(1/CI, HR)	(1/SLI, VSR)	(SLI, VSR)
C3	(1/MI, FR)	(STI, VHR)	(EI, CR)	(1/STI, FR)	(MI, FR)	(MI, HR)
C4	(EI, SR)	(CI, HR)	(STI, FR)	(EI, CR)	(VSTI, VHR)	(CI, VHR)
C5	(1/STI, SR)	(SLI, VSR)	(1/MI, FR)	(1/VSTI, VHR)	(EI, CR)	(MI, FR)
C6	(1/VSTI, HR)	(1/SLI, VSR)	(1/MI, HR)	(1/CI, VHR)	(1/MI, FR)	(EI, CR)

$\lambda_{max} = 6.5761$, Consistency index (CI) = 0.1152, Consistency ratio (CR) = 0.092.

Table 8
Pairwise comparisons of the criteria by DM3.

DM3	C1	C2	C3	C4	C5	C6
C1	(EI, CR)	(AI, SR)	(VSTI, VHR)	(MI, WR)	(VSTI, VHR)	(STI, HR)
C2	(1/AI, SR)	(EI, CR)	(1/SLI, SR)	(1/STI, VHR)	(EI, VSR)	(1/SLI, SR)
C3	(1/VSTI, VHR)	(SLI, SR)	(EI, CR)	(1/MI, VSR)	(MI, FR)	(SLI, FR)
C4	(1/MI, WR)	(STI, VHR)	(MI, VSR)	(EI, CR)	(CI, HR)	(VSTI, HR)
C5	(1/VSTI, VHR)	(EI, VSR)	(1/MI, FR)	(1/CI, HR)	(EI, CR)	(1/SLI, VSR)
C6	(1/STI, HR)	(SLI, SR)	(1/SLI, FR)	(1/VSTI, HR)	(SLI, VSR)	(EI, CR)

$\lambda_{max} = 6.5962$, Consistency index (CI) = 0.1192, Consistency ratio (CR) = 0.095.

Table 9
Criteria weights obtained by Z-fuzzy AHP method.

Reliability	Technical char.	Performance	Cost factors	Availability	Maintenance
0.353	0.046	0.118	0.355	0.074	0.053

Table 10
Z-fuzzy decision matrix of DM1.

	C1	C2	C3	C4	C5	C6
A1	(MG, SR)	(VP, HR)	(VG, SR)	(F, HR)	(MG, FR)	(P, SR)
A2	(VG, FR)	(F, VHR)	(P, SU)	(G, VHR)	(P, WR)	(VG, SR)
A3	(MG, HR)	(MG, HR)	(G, HR)	(VG, FR)	(MP, SU)	(G, HR)
A4	(G, HR)	(G, SR)	(F, WR)	(P, SR)	(VG, HR)	(F, SU)
A5	(P, SR)	(VG, HR)	(VP, FR)	(G, HR)	(MG, HR)	(VG, HR)

Table 11
Z-fuzzy decision matrix of DM2.

	C1	C2	C3	C4	C5	C6
A1	(F, VHR)	(MP, VHR)	(MG, HR)	(G, SR)	(MG, SR)	(F, FR)
A2	(G, SR)	(G, WR)	(F, VWR)	(G, WR)	(P, HR)	(G, FR)
A3	(MP, SU)	(G, VSR)	(VG, FR)	(G, HR)	(G, HR)	(MG, SR)
A4	(VG, FR)	(VG, HR)	(G, HR)	(VP, HR)	(VG, SU)	(G, HR)
A5	(F, HR)	(G, SR)	(P, HR)	(MG, FR)	(MG, VHR)	(G, VSR)

Table 12
Z-fuzzy decision matrix of DM3.

	C1	C2	C3	C4	C5	C6
A1	(MP, HR)	(F, SR)	(G, FR)	(MG, SU)	(G,SU)	(MP, HR)
A2	(MG, WR)	(MG, FR)	(MP, HR)	(VG, FR)	(VP, VHR)	(VG, VHR)
A3	(G, FR)	(MG, SR)	(G, SR)	(G, SR)	(F, SU)	(F, WR)
A4	(F, HR)	(VG, FR)	(MG, FR)	(P, WR)	(G, SR)	(MG, SR)
A5	(MP, VHR)	(G, FR)	(F, CR)	(MG, SU)	(F, HR)	(G, WR)

Table 13
Aggregated evaluations of wind turbines.

	Criteria	Z-fuzzy aggregated evaluations
A1	Reliability	((2.47,4.72, 4.72, 6.80), (0.59, 0.70, 0.80))
	Technical characteristics	((0.91, 1.96, 1.96, 3.27), (0.59, 0.70, 0.80))
	Performance	((6.80, 8.57, 8.57, 9.65), (0.52, 0.62, 0.72))
	Cost factors	((4.72, 6.80, 6.80, 8.57), (0.33, 0.46, 0.57))
	Availability	((5.59, 7.61, 7.61, 9.32), (0.30, 0.43, 0.55))
	Maintenance	((1.14, 2.47, 2.47, 4.72), (0.52, 0.62, 0.72))
A2	Reliability	((6.80, 8.57, 8.57, 9.65), (0.44, 0.54, 0.65))
	Technical characteristics	((4.72, 6.80, 6.80, 8.57), (0.42, 0.52, 0.62))
	Performance	((1.14, 2.47, 2.47, 4.72), (0.22, 0.33, 0.44))
	Cost factors	((7.61, 9.32, 9.32, 10.00), (0.42, 0.52, 0.62))
	Availability	((0.40, 0.79, 0.79, 2.08), (0.45, 0.55, 0.65))
	Maintenance	((8.28, 9.65, 9.65, 10.00), (0.55, 0.65, 0.76))
A3	Reliability	((3.27, 5.74, 5.74, 7.66), (0.27, 0.39, 0.50))
	Technical characteristics	((5.59, 7.61, 7.61, 9.32), (0.63, 0.73, 0.83))
	Performance	((7.61, 9.32, 9.32, 10.00), (0.52, 0.62, 0.72))
	Cost factors	((7.61, 9.32, 9.32, 10.00), (0.52, 0.62, 0.72))
	Availability	((2.76, 5.13, 5.13, 7.05), (0.17, 0.29, 0.40))
	Maintenance	((4.72, 6.80, 6.80, 8.57), (0.47, 0.58, 0.68))
A4	Reliability	((5.74, 7.66, 7.66, 8.88), (0.46, 0.56, 0.66)
	Technical characteristics	((8.28, 9.65, 9.65, 10.00), (0.52, 0.62, 0.72))
	Performance	((4.72, 6.80, 6.80, 8.57), (0.39, 0.49, 0.59))
	Cost factors	((0.40, 0.79, 0.79, 2.08), (0.47, 0.58, 0.68))
	Availability	((8.28, 9.65, 9.65, 10.00), (0.33, 0.46, 0.57))
	Maintenance	((4.72, 6.80, 6.80, 8.57), (0.33, 0.46, 0.57))
A5	Reliability	((1.14, 2.47, 2.47, 4.72), (0.59, 0.70, 0.80))
	Technical characteristics	((7.61, 9.32, 9.32, 10.00), (0.52, 0.62, 0.72))
	Performance	((0.72, 1.36, 1.36, 2.76), (0.54, 0.65, 0.75))
	Cost factors	((5.59, 7.61, 7.61, 9.32), (0.27, 0.39, 0.50))
	Availability	((4.22, 6.26, 6.26, 8.28), (0.53, 0.63, 0.73))
	Maintenance	((7.61, 9.32, 9.32, 10.00), (0.47, 0.58, 0.68))

Table 14
Z-fuzzy average values.

Criteria	Z-fuzzy average values
Reliability	((3.88, 5.83, 5.83, 7.54), (0.47, 0.58, 0,68))
Technical characteristics	((5.42, 7.07, 7.07, 8.23), (0.53, 0.64, 0.74))
Performance	((4.2, 5.7, 5.7, 7.14), (0.44, 0.54, 0.65))
Cost factors	((5.19, 6.77, 6.77, 7.99), (0.4, 0.51, 0.62))
Availability	((4.25, 5.89, 5.89, 7.35), (0.36, 0.47, 0.58))
Maintenance	((5.29, 7.01, 7.01, 8.37), (0.47, 0.58, 0.68))

Table 15
Z-fuzzy $\widetilde{PDA}$ values.

	Criteria	Z-fuzzy $\widetilde{PDA}$ values
A1	Reliability	((0, 0, 0, 0), (−0.127, 0.203, 0.684))
	Technical characteristics	((0, 0, 0, 0), (−0.195, 0.092, 0.488))
	Performance	((−0.047, 0.503, 0.503, 1.299), (−0.196, 0.145, 0.652))
	Cost factors	((0, 0, 0, 0), (−0.279, 0.108, 0.73))
	Availability	((−0.238, 0.292, 0.292, 1.194), (0, 0, 0))
	Maintenance	((0.069, 0.648, 0.648, 1.365), (0, 0, 0))
A2	Reliability	((−0.098, 0.47, 0.47, 1.485), (0, 0, 0))
	Technical characteristics	((0, 0, 0, 0), (0, 0, 0))
	Performance	((0, 0, 0, 0), (0, 0, 0))
	Cost factors	((0, 0, 0, 0), (0, 0, 0))
	Availability	((0, 0, 0, 0), (−0.228, 0.169, 0.836))
	Maintenance	((0, 0, 0, 0), (0, 0, 0))
A3	Reliability	((0, 0, 0, 0), (0, 0, 0))
	Technical characteristics	((−0.321, 0.077, 0.077, 0.719), (−0.152, 0.141, 0.547))
	Performance	((0.066, 0.634, 0.634, 1.381), (−0.196, 0.145, 0.652))
	Cost factors	((0, 0, 0, 0), (0, 0, 0))
	Availability	((0, 0, 0, 0), (0, 0, 0))
	Maintenance	((−0.392, 0.029, 0.029, 0.69), (−0.311, 0.001, 0.45))
A4	Reliability	((−0.239, 0.314, 0.314, 1.285), (0, 0, 0))
	Technical characteristics	((0.005, 0.366, 0.366, 0.844), (0, 0, 0))
	Performance	((−0.339, 0.193, 0.193, 1.041), (0, 0, 0))
	Cost factors	((0.389, 0.883, 0.883, 1.465), (0, 0, 0))
	Availability	((0.127, 0.639, 0.639, 1.354), (0, 0, 0))
	Maintenance	((−0.392, 0.029, 0.029, 0.69), (−0.155, 0.207, 0.759))
A5	Reliability	((0, 0, 0, 0), (−0.127, 0.203, 0.684))
	Technical characteristics	((−0.075, 0.318, 0.318, 0.844), (0, 0, 0))
	Performance	((0, 0, 0, 0), (−0.159, 0.191, 0.711))
	Cost factors	((0, 0, 0, 0), (−0.162, 0.237, 0.869))
	Availability	((−0.426, 0.062, 0.062, 0.948), (−0.085, 0.338, 1.054))
	Maintenance	((0, 0, 0, 0), (−0.311, 0.001, 0.45))

In Step 4, using the aggregated evaluations and Eqs. (27)–(28), the Z-fuzzy average values are calculated for both the restriction and reliability functions separately, and the resulting values are shown in Table 14.

In Step 5, Z-fuzzy $\widetilde{PDA}$ and $\widetilde{NDA}$ values are obtained for each alternative using Eqs. (29)–(34) and they are shown in Tables 15–16, respectively.

Table 16
Z-fuzzy $\widetilde{NDA}$ values.

	Criteria	Z-fuzzy $\widetilde{NDA}$ values
A1	Reliability	((−0.387, 0.191, 0.191, 1.307), (−0.475, −0.203, 0.183))
	Technical characteristics	((0.261, 0.723, 0.723, 1.351), (−0.353, −0.092, 0.269))
	Performance	((0, 0, 0, 0), (0, 0, 0))
	Cost factors	((−0.41, 0.005, 0.005, 0.653), (−0.472, −0.108, 0.431))
	Availability	((0, 0, 0, 0), (0, 0, 0))
	Maintenance	((0, 0, 0, 0), (0, 0, 0))
A2	Reliability	((0, 0, 0, 0), (0, 0, 0))
	Technical characteristics	((−0.383, 0.038, 0.038, 0.648), (−0.117, 0.185, 0.602))
	Performance	((−0.073, 0.568, 0.568, 1.428), (0, 0.391, 0.983))
	Cost factors	((−0.048, 0.377, 0.377, 0.928), (−0.329, 0.011, 0.549))
	Availability	((0.295, 0.865, 0.865, 1.635), (−0.513, −0.169, 0.372))
	Maintenance	((−0.011, 0.377, 0.377, 0.889), (−0.192, 0.133, 0.614))
A3	Reliability	((−0.501, 0.016, 0.016, 1.1), (−0.042, 0.323, 0.867))
	Technical characteristics	((0, 0, 0, 0), (0, 0, 0))
	Performance	((0, 0, 0, 0), (0, 0, 0))
	Cost factors	((−0.048, 0.377, 0.377, 0.928), (−0.163, 0.21, 0.803))
	Availability	((−0.381, 0.129, 0.129, 1.079), (−0.072, 0.389, 1.15))
	Maintenance	((0, 0, 0, 0), (0, 0, 0))
A4	Reliability	((0, 0, 0, 0), (0, 0, 0))
	Technical characteristics	((0, 0, 0, 0), (0, 0, 0))
	Performance	((0, 0, 0, 0), (0, 0, 0))
	Cost factors	((0, 0, 0, 0), (0, 0, 0))
	Availability	((0, 0, 0, 0), (0, 0, 0))
	Maintenance	((0, 0, 0, 0), (0, 0, 0))
A5	Reliability	((−0.11, 0.577, 0.577, 1.647), (−0.475, −0.203, 0.183))
	Technical characteristics	((0, 0, 0, 0), (0, 0, 0))
	Performance	((0.202, 0.762, 0.762, 1.529), (−0.482, −0.191, 0.234))
	Cost factors	((−0.3, 0.124, 0.124, 0.797), (−0.562, −0.237, 0.25))
	Availability	((0, 0, 0, 0), (0, 0, 0))
	Maintenance	((−0.091, 0.33, 0.33, 0.889), (−0.309, −0.001, 0.453))

Table 17
$\widetilde{SP}$ values for each alternative.

	Z-fuzzy $\widetilde{SP}$ values
A1	((−0.02, 0.115, 0.115, 0.314), (−0.176, 0.132, 0.601))
A2	((−0.035, 0.166, 0.166, 0.525), (−0.017, 0.013, 0.062))
A3	((−0.028, 0.08, 0.08, 0.233), (−0.046, 0.024, 0.126))
A4	((0.003, 0.513, 0.513, 1.274), (−0.008, 0.011, 0.04))
A5	((−0.035, 0.019, 0.019, 0.11), (−0.144, 0.204, 0.737))

In Step 6, the criteria weights obtained in Section 4 by using Z-fuzzy AHP method are employed to find $\widetilde{SP}_i$ and $\widetilde{SN}_i$ values. They are given in Tables 17–18, respectively.

In Step 7, $\widetilde{SSP}_i$ and $\widetilde{SSN}_i$ values are calculated by Eqs. (37)–(40) and presented in Tables 19 and 20, respectively.

In Step 8, Z-fuzzy $\widetilde{SSP}_i$ and $\widetilde{SSN}_i$ values are normalized for both restriction and reliability functions separately by using Eqs. (41)–(44). The obtained $\widetilde{NSP}_i$ and $\widetilde{NSN}_i$ values are given in Tables 21–22, respectively.

Table 18
$\widetilde{SN}$ values for each alternative.

	Z-fuzzy $\widetilde{SN}$ values
A1	((−0.27, 0.103, 0.103, 0.756), (−0.352, −0.114, 0.23))
A2	((−0.022, 0.287, 0.287, 0.697), (−0.171, 0.053, 0.399))
A3	((−0.222, 0.149, 0.149, 0.799), (−0.078, 0.218, 0.677))
A4	((0, 0, 0, 0), (0, 0, 0))
A5	((−0.127, 0.355, 0.355, 1.093), (−0.441, −0.179, 0.205))

Table 19
$\widetilde{SSP}$ values for each alternative.

	Z-fuzzy $\widetilde{SSP}$ values
A1	((0.015, 0.150, 0.150, 0.349), (0, 0.308, 0.777))
A2	((0, 0.201, 0.201, 0.560), (0.159, 0.189, 0.238))
A3	((0.007, 0.115, 0.115, 0.268), (0.130, 0.200, 0.302))
A4	((0.038, 0.549, 0.549, 1.309), (0.168, 0.187, 0.216))
A5	((0, 0.055, 0.055, 0.145), (0.032, 0.380, 0.913))

Table 20
$\widetilde{SSN}$ values for each alternative.

	Z-fuzzy $\widetilde{SSN}$ values
A1	((0, 0.373, 0.373, 1.027), (0.089, 0.326, 0.671))
A2	((0.248, 0.557, 0.557, 0.967), (0.270, 0.494, 0.840))
A3	((0.048, 0.419, 0.419, 1.069), (0.363, 0.658, 1.118))
A4	((0.270, 0.270, 0.270, 0.270), (0.441, 0.441, 0.441))
A5	((0.144, 0.626, 0.626, 1.363), (0, 0.262, 0.646))

Table 21
$\widetilde{NSP}$ values for each alternative.

	Z-fuzzy $\widetilde{NSP}$ values
A1	((0.012, 0.115, 0.115, 0.267), (0, 0.337, 0.851))
A2	((0, 0.154, 0.154, 0.428), (0.174, 0.207, 0.261))
A3	((0.006, 0.088, 0.088, 0.205), (0.142, 0.219, 0.331))
A4	((0.029, 0.419, 0.419, 1), (0.184, 0.205, 0.237))
A5	((0, 0.042, 0.042, 0.11), (0.035, 0.416, 1))

In Step 9, Z-fuzzy $\widetilde{AS}_i$ values for all alternatives are calculated by Eqs. (45)–(46) and obtained values are given in Table 23.

In Step 10, Z-fuzzy $\widetilde{AS}_i$ values are converted to ordinary fuzzy numbers using Definition 2. The obtained trapezoidal fuzzy numbers are shown in Table 24.

In Step 11, trapezoidal fuzzy $\widetilde{AS}_i$ values are transformed to crisp numbers using Eq. (2). In Step 12, alternatives are ranked according to the decreasing values of crisp AS_i. Crisp AS_i values and ranking of the alternatives are presented in Table 25. A4 which has the highest AS_i is the best choice among five alternatives. Based on the computed AS_i values, the ranking of the alternatives is A4 > A1 > A2 > A5 >A3. These results show that

Table 22
$\widetilde{NSN}$ values for each alternative.

	Z-fuzzy $\widetilde{NSN}$ values
A1	((0.247, 0.726, 0.726, 1), (0.4, 0.708, 0.921))
A2	((0.291, 0.591, 0.591, 0.818), (0.249, 0.558, 0.758))
A3	((0.216, 0.692, 0.692, 0.965), (0, 0.411, 0.675))
A4	((0.802, 0.802, 0.802, 0.802), (0.606, 0.606, 0.606))
A5	((0, 0.541, 0.541, 0.895), (0.422, 0.766, 1))

Table 23
$\widetilde{AS}_i$ values for each alternative.

	Z-fuzzy $\widetilde{AS}_i$ values
A1	((0.129, 0.421, 0.421, 0.633), (0.200, 0.522, 0.886))
A2	((0.145, 0.373, 0.373, 0.623), (0.211, 0.382, 0.51))
A3	((0.111, 0.390, 0.390, 0.585), (0.071, 0.315, 0.503))
A4	((0.415, 0.610, 0.610, 0.901), (0.395, 0.405, 0.421))
A5	((0, 0.291, 0.291, 0.503), (0.229, 0.591, 1))

Table 24
Trapezoidal fuzzy $\widetilde{AS}_i$ values converted from Z-fuzzy $\widetilde{AS}_i$.

	Trapezoidal fuzzy $\widetilde{AS}_i$ values of alternatives
A1	(0.094, 0.307, 0.307, 0.462)
A2	(0.089, 0.227, 0.227, 0.380)
A3	(0.061, 0.214, 0.214, 0.321)
A4	(0.265, 0.389, 0.389, 0.574)
A5	(0, 0.226, 0.226, 0.39)

Table 25
Crisp AS_i values.

Alternative	Crisp AS_i
A1	0.2926
A2	0.2306
A3	0.2024
A4	0.4044
A5	0.2106

alternative A4 is the best choice among the wind turbine alternatives according to the determined criteria.

In order to investigate the importance of reliability information, the reliability judgments regarding all DMs' evaluations have been accepted as "*certainly reliable*" when applying the Z-fuzzy EDAS method without changing the criteria weights. Then, Z-fuzzy EDAS method has been re-applied. The obtained AS_i values are presented in the Table 26.

According to these results, when the reliability information is neglected (accepted as $(1, 1, 1)$ for all evaluations), the ranking of all alternatives except for the alternatives A4

Table 26
Crisp AS_i values (DMs' reliability judgments accepted as (1, 1, 1)).

Alternative	Crisp AS_i
A1	0.2431
A2	0.2751
A3	0.3071
A4	0.5332
A5	0.2220

Table 27
Criteria weights obtained by Z-fuzzy AHP method (DMs' reliability judgements accepted as (1, 1, 1)).

Reliability	Technical char.	Performance	Cost factors	Availability	Maintenance
0.396	0.049	0.119	0.328	0.066	0.042

and A2 has changed. A4 alternative has been found as the best alternative again. Although the best alternative does not change, this difference shows that the reliability information should not be neglected. The fact that the ranking of the best alternative (A4) remains the same can be interpreted as the DMs stated their restriction judgments quite dominantly when comparing the alternative A4 with the other alternatives.

Similarly, while the Z-fuzzy AHP method has been applied to find the criteria weights, the reliability information has been accepted as "*certainly reliable*", and the criteria weights have been recalculated. The obtained criteria weights are presented in Table 27.

Table 27 shows that the ranking of cost factor and reliability factor, which are in the first two rankings, have changed when compared to previous results (Table 9). Among the six criteria, only the rankings of the *performance* and *availability* factors have not changed. These results support the obtained result regarding the importance of reliability information as in the EDAS method.

7. Comparative Analysis Using Z-Fuzzy AHP&TOPSIS Methodology

To compare the results, the Z-fuzzy TOPSIS methodology proposed by Yaakob and Gegov (2016) is used. Z-fuzzy TOPSIS is one of the first fuzzy extensions which is performed by Z-fuzzy numbers in MCDM methodology. TOPSIS method was developed by Yoon and Hwang (1981). It is one of the most commonly used MCDM methodology by researchers in the literature. TOPSIS method allows to reach the solution by using the distances of the alternatives from the positive and negative ideal solutions.

Z-fuzzy TOPSIS methodology consists of the following steps; (i) construction of Z-fuzzy decision matrix, (ii) conversion of Z-fuzzy numbers to ordinary fuzzy numbers, (iii) normalization procedure, (iv) weighing the normalized decision matrix, (v) calculation of distances from positive and negative ideal solutions, and (vi) calculation of closeness coefficients (Yaakob and Gegov, 2016).

Table 28
Results of Z-fuzzy TOPSIS methodology.

	d^*	d^-	CC*
A1	5.5530	1.4140	0.2030
A2	5.5551	1.3976	0.2010
A3	5.5572	1.3945	0.2006
A4	5.4034	1.5714	0.2253
A5	5.6267	1.3523	0.1938

Table 29
Comparison of Z-fuzzy EDAS and Z-fuzzy TOPSIS.

Alternatives	Ranking of Z-fuzzy EDAS	Ranking of Z-fuzzy TOPSIS
A1	2	2
A2	3	3
A3	5	4
A4	1	1
A5	4	5

Table 28 presents the results of Z-fuzzy AHP&TOPSIS methodology and it shows the distances from positive and negative ideal solutions (d^* and d^-), and closeness coefficients (CC*), respectively. Based on the computed CC* values, the ranking of the alternatives is obtained as A4 > A1 > A2 > A3 > A5.

According to the results obtained by the Z-fuzzy TOPSIS method, the ranking of the alternatives, except alternatives 3 and 5, is the same as the methodology proposed in this study. The comparison of the rankings can be seen in Table 29.

EDAS method considers the positive and negative distances from the average solution rather than calculating the negative and positive ideal solutions as in TOPSIS method. According to the results of both methods, the closeness coefficients in Z-fuzzy TOPSIS are composed of quite closer values whereas appraisal scores in Z-fuzzy EDAS indicate larger differences between alternatives. In general, it can be concluded that the proposed method is consistent since the rankings of two methods are quite similar. The only difference is between alternatives A3 and A5. The first three best alternatives are the same in both methods.

As a result of the comparative analysis, obtaining similar results with the Z-fuzzy TOPSIS method shows the consistency and competitiveness of the proposed method.

8. Conclusion

Extensions of ordinary fuzzy sets are quite successful in modelling the uncertainty in the decision-making process. However, they do not exactly represent the reliability information inherent in the solutions. The reliability information of the evaluations is very important as it can have significant impacts on the obtained results. The Z-fuzzy numbers introduced by Zadeh (2011) allow the reliability of the DMs' judgments to be included in the decision models. In this study, a novel Z-fuzzy EDAS method is introduced to the literature. Then, an integrated usage of Z-fuzzy AHP and Z-fuzzy EDAS method is proposed to the field for the first time to deal with uncertain expressions of DMs in real life decision making problems. The inclusion of the reliability information of the DMs in the decision model makes the decision making process more realistic in both daily and business decisions as in the case of renewable energy investment decisions.

The importance of renewable energy sources has increased considerably with the concern of leaving a sustainable world to future generations in recent years. In this study, the selection of a suitable wind turbine problem has been handled by considering the multiple factors affecting the decision. Criteria weights to be used in alternative selection have been calculated by using Z-fuzzy AHP method which has also been integrated to Z-fuzzy EDAS method. Z-fuzzy numbers integrated AHP method offers a more realistic solution by reflecting the DMs' hesitancy in pairwise comparisons to the proposed Z-fuzzy AHP&EDAS methodology. After defining the criteria weights, three DMs have evaluated the five alternatives using Z-fuzzy EDAS method. All the DMs' evaluations have been expressed by Z-fuzzy numbers in both methods, and all steps of the Z-fuzzy EDAS method have been performed by Z-fuzzy numbers. The proposed methodology allows DMs to express both restriction and reliability information about criteria and alternatives. In order to show the effects of reliability component on the decision system, the reliability information of all evaluations have been made "*certainly reliable*" and the calculations have been re-performed, then the results were compared with the proposed method. It is concluded from this analysis that the difference in the ranking results displays the importance of consideration of the reliability information. Therefore, the proposed methodology offers a more reliable evaluation system to DMs, including their degree of confidence to their assessments.

In order to show the robustness and stability of the proposed method, the obtained results have been compared with the results of the Z-Fuzzy AHP&TOPSIS methodology. It can be stated that the suggested methodology is an effective and useful method for researchers who want to make decisions based on distances from average solution rather than the distance from positive and negative ideal solutions. For further research, other MCDM approaches integrated with Z-fuzzy numbers can be used and compared with the results of this paper.

Although there are many fuzzy versions of the AHP method in the literature, its integration with Z-fuzzy numbers is limited. This research gap in the literature can be filled with increased application of Z-fuzzy AHP method, then importance and advantages of Z-fuzzy numbers can be further analysed. In addition, other fuzzy set extensions such as fermatean fuzzy sets or picture fuzzy sets can be used in the improvement of Z-fuzzy numbers. Then, in future research, it can be suggested to combine these extensions of Z-fuzzy numbers with different MCDM methods to expand the related literature.

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