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ORIGINAL ARTICLE

Location selection of electric vehicles charging stations by using a fuzzy MCDM method: a case study in Turkey

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Abstract
Pollution, climate change, fast natural resource depletion, deforestation and global warming have become major worldwide problems relevant with the petroleum-based powered vehicles and alternatives for this conventional transportation type have been started to change in the last decade. In this modification process, electric vehicles (EVs) have a leading position due to their low damage effect to the environment. Selecting the most sustainable location for charging station for EVs plays an important role in the life cycle of them. This process needs to consider some conflicting criteria and has a complex decision problem that can be modeled as a multi-criteria decision-making problem. The inclusion of such criteria in a location selection requires the fuzzy sets to be used in the decision-making methodology. For this aim, intuitionistic fuzzy sets have been used in this paper. By the way, a decision-making procedure based on intuitionistic fuzzy sets and consists of the decision-making trial and evaluation laboratory, analytic hierarchy process and technique for order preference by similarity to ideal solution has been suggested for the location selection of charge stations. The proposed fuzzy-based model is applied to a case study for Istanbul in Turkey.

Keywords Electric vehicles charging stations · Location selection · Intuitionistic fuzzy sets · Decision making · DEMATEL · AHP · TOPSIS

1 Introduction

Due to the increase in the effects of global warming and its adverse effects of air pollution on human life recently, the eyes are stuck in fossil fuels which are the most common cause of greenhouse effects. One of the approaches that have been developed over the years to reduce this effect is the dissemination of the use of electric vehicles. This tendency is a vital way to reduce CO/CO_2 emissions and achieves climate targets [1]. Electric vehicles (EVs) reduce the emissions of greenhouse gases by converting energy demand from gas to electricity [2]. EVs can reduce fossil fuel dependence and reduce transport-related pollutions from CO/CO_2 emissions and other pollutants [3]. In order to increase environmental sustainability, many countries will increase the number of EVs [4]. Allowing EVs users to easily access charging stations is crucial for the expansion of using EVs [5]. The most critical point in it is the charging of the EV batteries before they consumed. Therefore, it has utmost importance that the charging stations are correctly positioned [3]. Improper placement and sizing of EV charging stations may cause adverse effects on the development of EVs, deployment of the city traffic network and ease of operation of EVs [6]. Charging station location decisions are critical to the acceptance of EVs. Moreover, users' safety in EVs can be enhanced by the corrected placements of the charging infrastructure [7]. EVs charging stations are important infrastructures that directly affect the ease and economics of EVs. The rationality of the charge station locations is one of the most significant factors determining the popularity of EVs [8]. Improving the network construction of EVs charging facilities will affect the acceptance of EVs that will directly define the EVs development and implementation scale [9]. More emphasis has been placed on the optimal planning of

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EVs charging stations in both industry and academia. There are many factors that influence the regulation of EVs charging stations both tangible and intangible [6]. Since the problem includes many conflicting and both tangible and intangible criteria, one of the approaches that makes possible to choose the most appropriate place that satisfies the decision maker is a multi-criteria decision-making methodology (MCDM) [10]. The fuzzy set theory proposed by Zadeh [11] is dealing with vague, imprecise, uncertain information and a powerful mathematical approach applied to many areas [12–18]. Fuzzy sets are generalized by Atanassov [19] which also takes into account the values of non-membership values and named as intuitionistic fuzzy sets (IFSs). IFSs provide a theoretical basis for managing the knowledge of hesitation by people when evaluating the questions [20]. In dealing with the uncertainties in the problem that we handle, we also use MCDMs with triangular IFSs and interval-valued intuitionistic fuzzy numbers (IVIFNs).

In this paper, an integrated MCDM methodology consists of the decision-making trial and evaluation laboratory (DEMATEL), analytic hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) which are extended by IFSs and applied to evaluate alternative locations for charge station of EVs. One of the most difficult issues in the MCDM problems is representing intangible criteria evaluations for the experts. By extending MCDM problems with fuzzy sets, they have capability to capture uncertainty of these evaluations and to obtain robust results. These methods have been applied in the fuzzy environment developed by Zadeh in [11] to handle not only linguistic evaluations but also decision makers' hesitancy. Shortly, we use an IFSs MCDM methodology based on DEMATEL, AHP and TOPSIS methods for the evaluation of possible locations of the charge stations. The IF DEMATEL method has been used to check correlation among the criteria. DEMATEL method is an MCDM technique which allows to determine interdependency among the criteria/factors and reflect relative relationships within them [21]. When we examine the literature, it can be seen that DEMATEL is applied with ANP in the 44.5% of the papers that involve DEMATEL in their solution process [22]. Through this analysis, it can be obviously said that DEMATEL is used to determine dependency relations of criteria/factors. The method, AHP, can be successfully used by pairwise comparison matrices to reach final decision [23]. In the proposed methodology, it has been used to evaluate criteria weights on the decision process by utilizing these pairwise comparisons. TOPSIS is a distance-based method that uses both positive and negative ideal solutions to determine the ranks of the alternatives [23]. Therefore, in the proposed methodology, TOPSIS method has been used to rank of the location alternatives. By the way, the highlights of this paper can be indicated as follows.

IFSs have an advantage to present a larger domain than ordinary fuzzy sets and their extensions. IFSs represent uncertainty by using both membership and non-membership functions simultaneously. This provides convenience for handling vagueness by the decision makers who studies uncertain environments. Also, applied integrated methodology consists of DEMATEL, AHP and TOPSIS has more discriminatory power than the compared methods by using IFSs. This ability provides decision makers to evaluate more accurately. We desire to use this main advantage on our MCDM problem to evaluate alternative locations for charge station of EVs. By the way, for the first time in the literature, an IFSs integrated MCDM methodology has been applied to EVs charge station location selection problem to determine the most appropriate location. The results about sensitivity and comparative analyses show that the proposed methodology is applicable, and its results are robust.

The rest of the paper has been presented as follows: In Sect. 2, a literature review about the EVs and their selection methodologies is given. In Sect. 3, the proposed methodology for the selection process is presented with all its details. In Sect. 4, the application is carried out for the city of Istanbul. The paper ends with conclusions, discussions and suggestions for future researches.

2 Literature review

In this section, the relevant literature about EVs and selection procedures of charging stations has been briefly analyzed. Wang and Lin [24] presented the concept to propose a refueling station position model for EVs in Taiwan by using a mixed integer programming method based on vehicle orientation. Pan et al. [25] explored how to best use EVs stations on both the transport system and how they can support the electricity grid by using two-stage stochastic program. Schill [26] offered a game-theoretical model to analyze the effects of the hypothetical fleet of plug-in EVs in the German electric market. Kley et al. [27] presented a holistic approach to developing business models for electric mobility which analyze the system as a whole and provide decision support for affected enterprises. Wirges et al. [28] proposed a dynamic spatial model for development of a charging infrastructure for EVs in the German metropolitan area of Stuttgart. Traut et al. [2] offered an optimization model to determine optimal design of electric vehicles. Jia et al. [9] suggested an optimization model for the sizing and placement of EV charging stations. Andrews et al. [29] presented an optimization model for locating the charging

stations required to support EV use. Liu et al. [6] firstly identified the most suitable locations of EV charging stations by using a mathematical model for reducing the total cost associated with the EV charging stations. Pazouki et al. [30] presented the optimal planning of charging stations taking loss and voltage into consideration. He et al. [31] proposed an equilibrium modeling framework that captures the interaction between public wage opportunities and the electricity prices, and location and route options for plug-in hybrid electric vehicles combined with plug-and-run hybrid electric vehicles in regional transport and power transmission networks. Lam et al. [32] formulated the problem of placing the EV charging station by reducing the total construction cost subject to restrictions within the charging station and the ease of the drivers for the EV charging with the proposed method. Wagner et al. [33] presented an intelligence system to identify the most appropriate locations for charging stations. Yi and Bauer [5] developed a methodology that can easily combine additional constraints to reduce the search space initially for optimal charging station placement. Micari et al. [34] intended to analyze Italian lands to provide an assessment of charging stations meeting the demand for population. Zhenghui et al. [35] presented a new model for location selection and fixed volume charging stations for EVs. Eisel et al. [1] stated that the building's charging stations are based on the number of existing EVs, but at the same time potential users are reluctant to buy EVs due to the inadequate charging infrastructure. Sadeghi-Barzani et al. [36] proposed a mixed integer nonlinear optimization approach for optimal placement and sizing of fast charging stations. Eisel et al. [1] presented an approach considering the customer preferences for the location planning problem of EV charging stations. Sadeghi-Barzani et al. [36] suggested a mixed integer nonlinear programming optimization approach for optimum placement and sizing of fast charging stations, taking into consideration factors such as cost of station development, EV energy loss and loss of electricity input. Xu et al. [8] presented the characteristics of EVs and proposed a model of charging EVs according to the travel chain. Kong et al. [7] presented a three-layered system model for fast charging stations. Meng and kai [37] proposed a spatial clustering algorithm to determine the charging station location. Unlike all these studies, it is the first paper to develop the MCDM method-based intuitionistic fuzzy sets for electric vehicle charging station location selection. Because of intuitionistic fuzzy sets are more successful than general fuzzy clusters in handling uncertainties, we applied to MCDM methods with this extended fuzzy numbers. It is expected that paper will guide the researchers in this area.

3 The proposed methodology

Atanassov introduces intuitionistic fuzzy sets (IFSs) to express decision maker's opinions more freely by using not only membership functions but also non-membership functions for the elements in a fuzzy set [19]. Extension of IFSs is conducted to many areas and methods due to its applicability. Here, we use IFSs to extend DEMATEL, AHP and TOPSIS methodologies to apply the selection of the most appropriate location for the EVs charge station problem. In the following subsection, we will give the preliminaries IVIFSs and the steps of the integrated methodology for the selection process that are used in the proposed methodology.

3.1 Preliminaries on interval-valued intuitionistic fuzzy sets

Definition 1 Let X be a non-empty set, an IVIFS in X is an object $\tilde{A}$ given as in Eq. (1) [19]:

$$\tilde{A} = \left\{ x, \left[\mu_{\tilde{A}}^{-}, \mu_{\tilde{A}}^{+}\right], \left[\upsilon_{\tilde{A}}^{-}, \upsilon_{\tilde{A}}^{+}\right]; x \in X \right\} \tag{1}$$

where $0 \le \mu_{\tilde{A}}^{+} + \upsilon_{\tilde{A}}^{+} \le 1$ for every $x \in X$.

Definition 2 Let $\tilde{A} = \left(\left[\mu_{\tilde{A}}^{-}, \mu_{\tilde{A}}^{+}\right], \left[v_{\tilde{A}}^{-}, v_{\tilde{A}}^{+}\right]\right)$ and $\tilde{B} = \left(\left[\mu_{\tilde{B}}^{-}, \mu_{\tilde{B}}^{+}\right], \left[v_{\tilde{B}}^{-}, v_{\tilde{B}}^{+}\right]\right)$ be two IVIFNs. Then,

$$\tilde{A} \oplus \tilde{B} = \left(\left[\mu_{\tilde{A}}^{-} + \mu_{\tilde{B}}^{-} - \mu_{\tilde{A}}^{-}\mu_{\tilde{B}}^{-}, \mu_{\tilde{A}}^{+} + \mu_{\tilde{B}}^{+} - \mu_{\tilde{A}}^{+}\mu_{\tilde{B}}^{+}\right], \left[v_{\tilde{A}}^{-}v_{\tilde{B}}^{-}, v_{\tilde{A}}^{+}v_{\tilde{B}}^{+}\right]\right) \tag{2}$$

$$\tilde{A} \otimes \tilde{B} = \left(\left[\mu_{\tilde{A}}^{-}\mu_{2}^{-}, \mu_{\tilde{A}}^{+}\mu_{2}^{+}\right], \left[v_{\tilde{A}}^{-} + v_{2}^{-} - v_{\tilde{A}}^{-}v_{2}^{-}, v_{\tilde{A}}^{+} + v_{2}^{+} - v_{\tilde{A}}^{+}v_{2}^{+}\right]\right) \tag{3}$$

Definition 3 Let $\tilde{r}_{ij}^{k} = \left(\left[\mu_{\tilde{r}}^{-}, \mu_{\tilde{r}}^{+}\right], \left[v_{\tilde{r}}^{-}, v_{\tilde{r}}^{+}\right]\right)$ be the IVIFNs where $k = 1, 2, \ldots, n$. Then, the aggregated IVIFN $(\tilde{r}_{ij}^{A})$ is obtained by using IVIF hybrid geometric operator as in Eq. (4) [38]:

$$\tilde{r}_{ij}^{A} = \left[\prod_{k=1}^{n}\left(\mu_{k}^{-}\right)^{\omega_k}, \prod_{k=1}^{n}\left(\mu_{k}^{+}\right)^{\omega_k}\right], \left[1 - \prod_{k=1}^{n}\left(1 - v_{k}^{-}\right)^{\omega_k}, 1 - \prod_{k=1}^{n}\left(1 - v_{k}^{+}\right)^{\omega_k}\right] \tag{4}$$

where ω_k is the weight vector of decision maker k where $\sum_{k=1}^{n} \omega_k = 1$.

Definition 4 Let $\tilde{r}_1 = \left(\left[\mu_1^{-}, \mu_1^{+}\right], \left[v_1^{-}, v_1^{+}\right]\right)$ and $\tilde{r}_2 = \left(\left[\mu_2^{-}, \mu_2^{+}\right], \left[v_2^{-}, v_2^{+}\right]\right)$ be two IVIFNs. The distance between these two IVIFNs is obtained by Hamming distance as in Eq. (5) [39]:

$$\mathrm{HD} = \frac{1}{4}\sum\left(\left|\mu_1^- - \mu_2^-\right| + \left|\mu_1^+ - \mu_2^+\right| + \left|v_1^- - v_2^-\right| + \left|v_1^+ - v_2^+\right|\right) \quad (5)$$

Definition 5 Let $\tilde{r}_{ij}^k = \left\langle \left(\mu_{\tilde{r}}^L, \mu_{\tilde{r}}^M, \mu_{\tilde{r}}^R\right), \left(v_{\tilde{r}}^L, v_{\tilde{r}}^M, v_{\tilde{r}}^R\right)\right\rangle$ be a triangular IFS. Then, the defuzzified value of this fuzzy number can be obtained by using Eq. (6) [40]:

$$d_f = \frac{\mu_{\tilde{r}}^L + \mu_{\tilde{r}}^M + \mu_{\tilde{r}}^R}{3} + \frac{v_{\tilde{r}}^L + v_{\tilde{r}}^M + v_{\tilde{r}}^R}{\tau} \quad (6)$$

where τ is a very big number.

3.2 Steps of the proposed methodology

The proposed methodology is composed of IF DEMATEL, IVIF-AHP and IVIF-TOPSIS methods. IVIF-AHP is applied to obtain the weights of the main and subcriteria. Then, IVIF-TOPSIS method is conducted to evaluate alternative locations.

In the proposed approach, we used two different scales, as shown in Tables 1, 2 and 3, which belong to IF DEMATEL, IVIF-AHP and IVIF-TOPSIS methods, respectively. In the literature, setting of AHP linguistic scale is essentially realized in two ways: the studies using constant linguistic scales as in [41–45] and the studies using tools such as mathematical programming or statistical modeling to determine the intervals corresponding to the linguistic terms as in [46–51]. Our paper falls in the studies using a constant linguistic scale since both membership and non-membership intervals for the scales have to be determined in intuitionistic fuzzy environment. The same idea is also applied for the DEMATEL and TOPSIS methods while we constructed the linguistic scale for IF DEMATEL and IVIF-TOPSIS methods. By doing this, we aimed to apply IFSs and their rules to our integrated MCDM method for handling uncertainty. The steps of the approach are given as below:

Step 1: Determine the alternatives and relevant criteria based on consolidation of the managerial board and construct the framework of the application. The framework of the application is illustrated in Fig. 1 as follows:

Step 2: Construct the average matrix $\tilde{Z}$.

Step 3: Calculate the normalized initial direct-relation matrix $\tilde{M}$. The normalized initial direct-relation matrix $\tilde{M} = \left[\tilde{d}_{ij}\right]$, where the value of each element in matrix $\tilde{M}$ is in range between [0, 1]. The calculation is given in Eq. (7):

$$\tilde{M} = k * \tilde{Z} \quad (7)$$

Table 2 Linguistic scale for weights of the criteria

Linguistic term	IVIF number
Certainly low—CL	<[0.1, 0.25], [0.65, 0.75]>
Very low—VL	<[0.15, 0.3], [0.6, 0.7]>
Low—L	<[0.2, 0.35], [0.55, 0.65]>
Below medium—BM	<[0.25, 0.4], [0.5, 0.6]>
Exactly equal—EE	<[0.5, 0.5], [0.5, 0.5]>
Above medium—AM	<[0.5, 0.6], [0.25, 0.4]>
High—H	<[0.55, 0.65], [0.2, 0.35]>
Very high—VH	<[0.6, 0.7], [0.15, 0.3]>
Certainly high—CH	<[0.65, 0.75], [0.1, 0.25]>

Table 3 Linguistic scale for ratings of alternatives

Linguistic term	IVIF number
Certainly bad—CB	<[0, 0.15], [0.7, 0.85]>
Very bad—VB	<[0.1, 0.25], [0.6, 0.75]>
Bad—B	<[0.2, 0.35], [0.5, 0.65]>
Below average—BA	<[0.3, 0.45], [0.4, 0.55]>
Average—A	<[0.4, 0.55], [0.3, 0.45]>
Above average—AA	<[0.5, 0.65], [0.2, 0.35]>
Good—G	<[0.6, 0.75], [0.1, 0.25]>
Very good—VG	<[0.7, 0.85], [0, 0.15]>

Table 1 Linguistic scale for the average matrix of IF DEMATEL method

Fuzzy numbers	Linguistic terms
((0, 0.1, 0.2), (0.65, 0.7, 0.8))	Reverse of very important (RVI)
((0.2, 0.25, 0.3), (0.6, 0.65, 0.7))	Reverse of quite important (RQI)
((0.35, 0.4, 0.45), (0.45, 0.5, 0.55))	Reverse of bit important (RBI)
((0.5, 0.5, 0.5), (0.5, 0.5, 0.5))	Equal (E)
((0.45, 0.5, 0.55), (0.35, 0.4, 0.45))	Bit important (BI)
((0.6, 0.65, 0.7), (0.2, 0.25, 0.3))	Quite important (QI)
((0.65, 0.7, 0.8), (0, 0.1, 0.2))	Very important (VI)

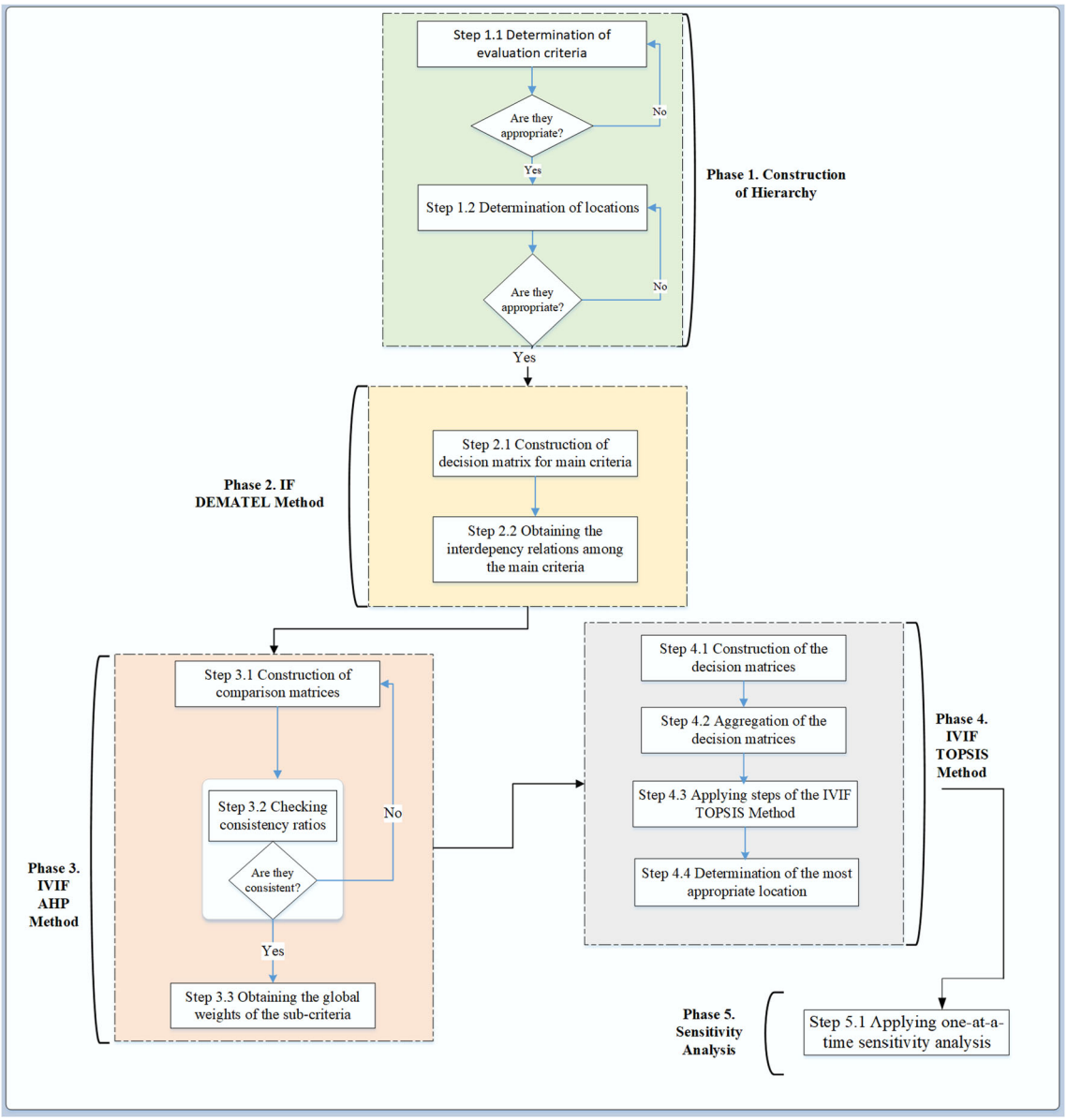


Fig. 1 Framework of the application

where

$$k = \text{Min}\left(\frac{1}{\max\limits_{l \le i \le n}\sum\limits_{i=1}^{n}|a_{ij}|}, \frac{1}{\max\limits_{l \le j \le n}\sum\limits_{j=1}^{n}|a_{ij}|}\right) \tag{8}$$

where $i, j = \{1, 2, 3, \ldots, n\}$

Step 4: Derive the total relation matrix $\tilde{S}$. The total-influence matrix $\tilde{S}$ is obtained by utilizing Eq. (9), in which, I is an *nxn* identity matrix. The matrix $\tilde{S}$ reflects the total relationship between elements of membership and non-membership functions.

$$\tilde{S} = \tilde{M} + \tilde{M}^2 + \tilde{M}^3 + \cdots = \sum_{i=1}^{\infty\leftarrow}\tilde{M}^i \tag{9}$$

where

$$\tilde{S} = \tilde{M}\left(I - \tilde{M}\right)^{-1}.$$

Step 5: Calculate the sums of rows and columns of matrix $\tilde{S}$. In the total-influence matrix $\tilde{S}$, the sum of rows and the sum of columns are represented by vectors $\tilde{D}$ and $\tilde{R}$, respectively.

$$\tilde{S} = \left[\tilde{S}_{i,j}\right]_{n*n}, i,j \in \{1,2,3,\ldots n\}$$

$$\tilde{D} = \sum_{i=1}^{n} s_{ij} \tag{10}$$

$$\tilde{R} = \sum_{j=1}^{n} s_{ij} \tag{11}$$

Step 6: Set a threshold value (α). The threshold value (α), is computed by the average of the elements in matrix $\tilde{S}$, as computed by Eq. (12). This calculation aimed to show inner and outer dependencies of main criteria in matrix $\tilde{S}$.

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[t_{ij}\right]}{N} \tag{12}$$

Step 7: Build a cause and effect relationship diagram. We defuzzify $\tilde{D}$ and $\tilde{R}$ in this step using Eq. (6). The cause and effect diagram is constructed by mapping all coordinate sets of $(D_i + R_i), (D_i - R_i)$ to visualize the complex interrelationship and provide information to judge which are the most important main criteria. The scale given in Table 1 is used to assign the interval-valued intuitionistic fuzzy preferences.

Step 8: (Wu et al. [52]): Construct the pairwise comparison matrix $\left(\tilde{R} = \left(\tilde{r}_{ij}\right)_{n\times n}\right)$ by using related linguistic scale as in Table 2 as shown in Eq. (13):

$$\tilde{R} = \begin{bmatrix} \left(\left[\mu_{11}^{-}, \mu_{11}^{+}\right], \left[v_{11}^{-}, v_{11}^{+}\right]\right) & \cdots & \left(\left[\mu_{1n}^{-}, \mu_{1n}^{+}\right], \left[v_{1n}^{-}, v_{1n}^{+}\right]\right) \\ \vdots & \ddots & \vdots \\ \left(\left[\mu_{n1}^{-}, \mu_{n1}^{+}\right], \left[v_{n1}^{-}, v_{n1}^{+}\right]\right) & \cdots & \left(\left[\mu_{nn}^{-}, \mu_{nn}^{+}\right], \left[v_{nn}^{-}, v_{nn}^{+}\right]\right) \end{bmatrix} \tag{13}$$

Before applying the next steps, we calculated the consistency ratios of the pairwise comparison matrices based on the Saaty's method [53]. To illustrate Saaty's consistency procedure, we matched the linguistic terms with Saaty's AHP scale as follows: "1 = Exactly Equal—EE; 3 = Above Medium—AM; 5 = High—H; 7 = Very High—VH; 9 = Certainly High—CH." For the reciprocal terms, we took reverse of the numbers. For example, if the linguistic term is *Low*, the corresponded value is equal to 0.2.

Step 9: Calculate the score judgment matrix $\left(\tilde{S} = \left(\tilde{S}_{ij}\right)_{n\times n}\right)$ as shown in Eq. (14):

$$\tilde{S} = \begin{bmatrix} \left[\mu_{11}^{-} - v_{11}^{+}, \mu_{11}^{+} - v_{11}^{-}\right] & \cdots & \left[\mu_{1n}^{-} - v_{1n}^{+}, \mu_{1n}^{+} - v_{1n}^{-}\right] \\ \vdots & \ddots & \vdots \\ \left[\mu_{n1}^{-} - v_{n1}^{+}, \mu_{n1}^{+} - v_{n1}^{-}\right] & \cdots & \left[\mu_{nn}^{-} - v_{nn}^{+}, \mu_{nn}^{+} - v_{nn}^{-}\right] \end{bmatrix} \tag{14}$$

where $\tilde{s}_{ij} = \left[\mu_{ij}^{-} - v_{ij}^{+}, \mu_{ij}^{+} - v_{ij}^{-}\right]$.

Step 10: Calculate the interval multiplicative matrix $\left(\tilde{A} = \left(\tilde{a}_{ij}\right)_{n\times n}\right)$ as shown in Eq. (15):

$$\tilde{A} = \begin{bmatrix} \left[10^{\left(\mu_{11}^{-} - v_{11}^{+}\right)}, 10^{\left(\mu_{1n}^{+} - v_{1n}^{-}\right)}\right] & \cdots & \left[10^{\left(\mu_{ij}^{-} - v_{ij}^{+}\right)}, 10^{\left(\mu_{ij}^{+} - v_{ij}^{-}\right)}\right] \\ \vdots & \ddots & \vdots \\ \left[10^{\left(\mu_{n1}^{-} - v_{n1}^{+}\right)}, 10^{\left(\mu_{n1}^{+} - v_{n1}^{-}\right)}\right] & \cdots & \left[10^{\left(\mu_{nn}^{-} - v_{nn}^{+}\right)}, 10^{\left(\mu_{nn}^{+} - v_{nn}^{-}\right)}\right] \end{bmatrix} \tag{15}$$

where $\tilde{a}_{ij} = \left[10^{\left(\mu_{ij}^{-} - v_{ij}^{+}\right)}, 10^{\left(\mu_{ij}^{+} - v_{ij}^{-}\right)}\right]$.

Step 11: Calculate the $\tilde{w}_i$ interval for each criterion by using Eq. (16):

$$\tilde{w}_i = \left[\frac{\sum_{j=1}^{n}\tilde{a}_{ij}^{-}}{\sum_{i=1}^{n}\sum_{j=1}^{n}\tilde{a}_{ij}^{+}}, \frac{\sum_{j=1}^{n}\tilde{a}_{ij}^{+}}{\sum_{i=1}^{n}\sum_{j=1}^{n}\tilde{a}_{ij}^{-}}\right] \tag{16}$$

Step 12: Obtain the possibility degree matrix $\left(P = \left(p_{ij}\right)_{m\times n}\right)$ by using Eq. (17):

$$P\left(w_i \geq w_j\right) = \frac{\min\left\{L_{w_i} + L_{w_j}, \max\left(w_i^{+} - w_j^{-}, 0\right)\right\}}{L_{w_i} + L_{w_j}} \tag{17}$$

where $L_{w_i} = w_i^{+} - w_i^{-}$ and $L_{w_j} = w_j^{+} - w_j^{-}$ and $p_{ij} \geq 0$. $p_{ij} + p_{ji} = 1$, $p_{ii} = 1/2$.

Step 13: Calculate the $P = \left(p_{ij}\right)_{m\times n}$ by Eq. (18):

$$w_i = \frac{1}{n}\left[\sum_{j=1}^{n} p_{ij} + \frac{n}{2} - 1\right] \tag{18}$$

Step 14: Normalize the weights (w_i) and obtain the final weights.

The obtained final weights will be used in the IVIF-TOPSIS method [54].

Step 15: Assign the interval-valued intuitionistic preferences matrix $R^k = \left(\tilde{r}_{ij}^{k}\right)_{m\times n}$ where k is the decision maker opinions' by using related linguistic scale as in Table 3.

Step 16: Aggregate $R^k = \left(\tilde{r}_{ij}^{k}\right)_{m\times n}$ matrix by using Eq. (4) to obtain collective IVIF decision matrix $R = \left(\tilde{r}_{ij}^{A}\right)_{m\times n}$.

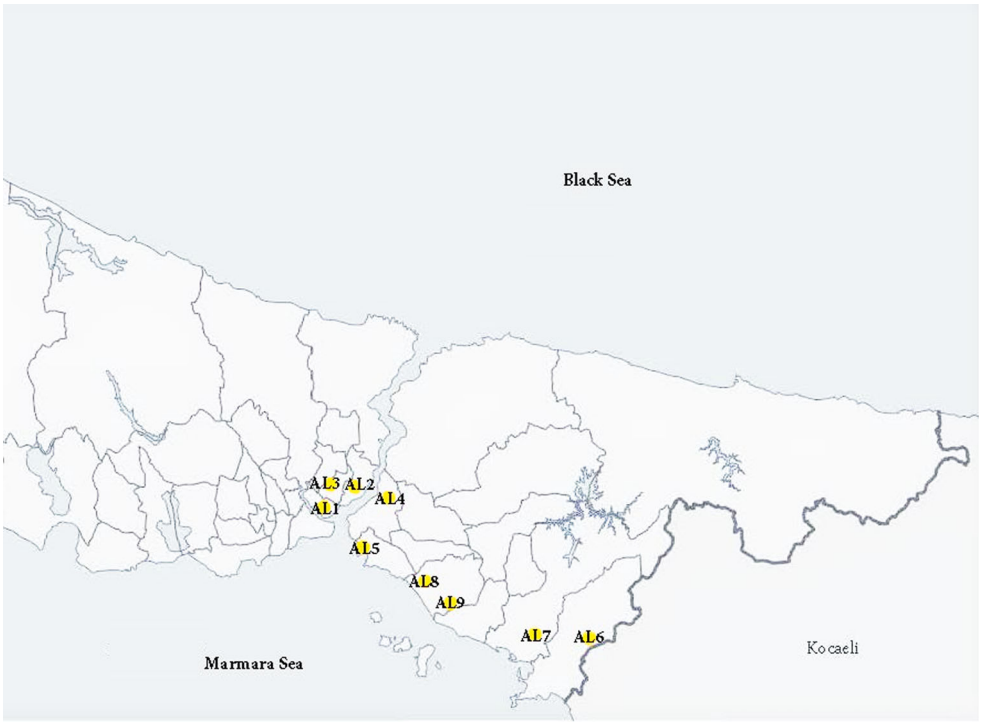


Fig. 2 Locations of the alternatives

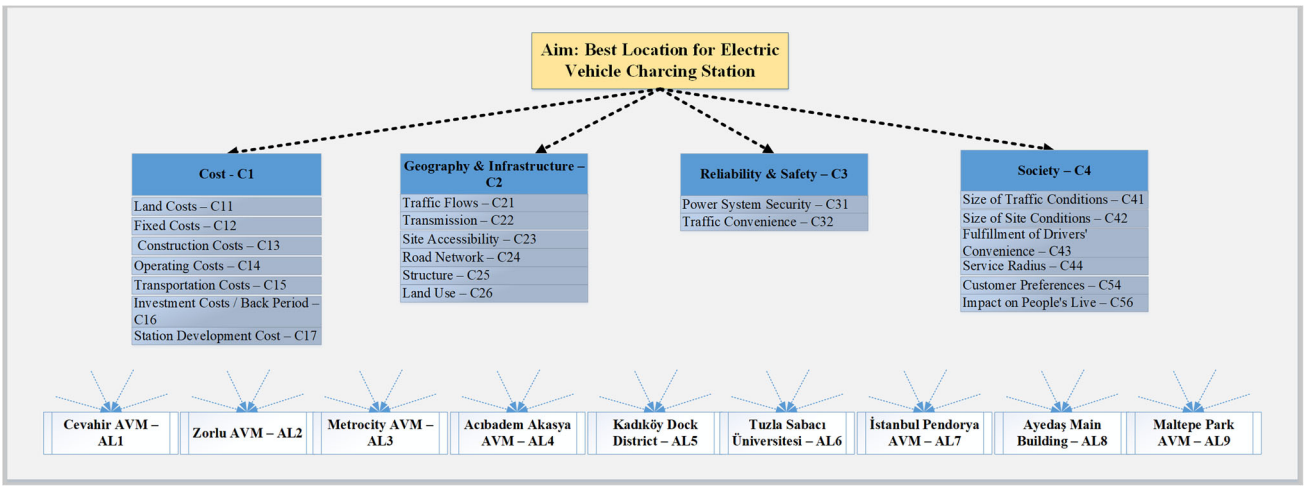


Fig. 3 The hierarchical structure of the application

Table 4 Linguistic average matrix of IF DEMATEL based on main criteria

	C1	C2	C3	C4
C1	E	RBI	BI	BI
C2	RBI	E	RBI	RVI
C3	RVI	RVI	E	RVI
C4	RBI	RBI	RBI	E

Step 17: Calculate the weighted $R^* = \left(\tilde{r}_{ij}^*\right)_{m\times n}$ by using Eq. (19):

$$\tilde{r}_{ij}^* = w_i \otimes \tilde{r}_{ij}^A \tag{19}$$

Step 18: Determine the IVIF positive ideal solutions (O^*) IVIF negative ideal solutions (O^-) by using Eqs. (20) and (21), respectively.

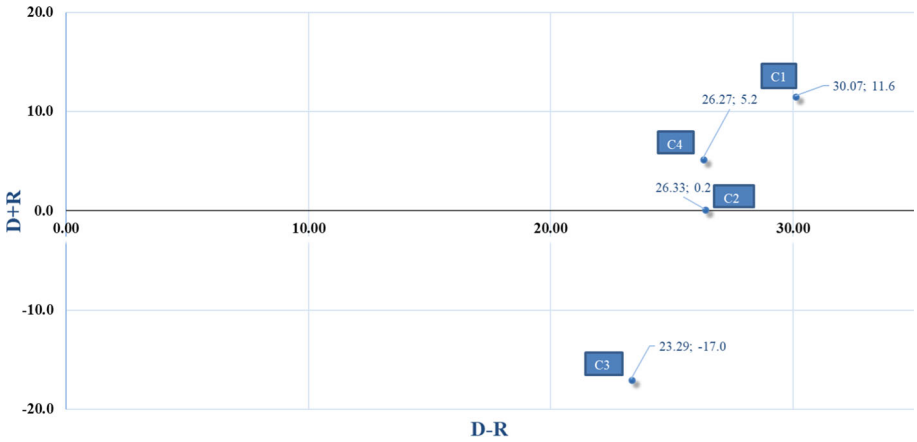


Fig. 4 Cause and effect diagram of the main criteria

$$O^* = \left\{ui, \left(\max_j \tilde{r}_{ij}^* | i \in J_1\right), \left(\min_j \tilde{r}_{ij}^* | i \in J_2\right) | i = 1, 2, \ldots, m\right\}^T = \left\{\tilde{r}_1^+, \tilde{r}_1^+, \ldots, \tilde{r}_m^+\right\}^T \tag{20}$$

Table 5 Linguistic pairwise comparison matrix based on DM1 evaluations

C1	C11	C12	C13	C14	C15	C16	C17
C11	EE	EE	BM	VH	CH	EE	EE
C12	EE	EE	EE	VH	VH	AM	AM
C13	AM	EE	EE	CH	CH	AM	H
C14	VL	VL	CL	EE	EE	VL	CL
C15	CL	VL	CL	EE	EE	VL	VL
C16	EE	BM	BM	VH	EE	EE	EE
C17	EE	BM	L	CH	VH	EE	EE

$$O^- = \left\{ui, \left(\min_j \tilde{r}_{ij}^* | i \in J_1\right), \left(\max_j \tilde{r}_{ij}^* | i \in J_2\right) | i = 1, 2, \ldots, m\right\}^T = \left\{\tilde{r}_1^-, \tilde{r}_1^-, \ldots, \tilde{r}_m^-\right\}^T \tag{21}$$

where $\tilde{r}_i^+ = [a_i^+, b_i^+], [c_i^+, d_i^+]$ and $\tilde{r}_i^- = [a_i^-, b_i^-], [c_i^-, d_i^-]$ where $i = 1, 2, \ldots, m$.

Step 19: Calculate the S_j^* and S_j^- of all alternatives with respect to values of O^* and O^- based on Eqs. (22) and (23), respectively.

$$S_{j^*} = \frac{1}{4}\sum_{i=1}^{m}\left(\left|\mu_{ij}^* - \mu_i^-\right| + \left|\mu_{ij}^* - \mu_i^+\right| + \left|v_{ij}^* - v_i^-\right| + \left|v_{ij}^* - v_i^+\right|\right) \tag{22}$$

Table 6 Corresponded IVN values of the linguistic pairwise comparison matrix

C1	C11	C12	C13	C14	C15	C16	C17
C11	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>	<[0.25,0.4], [0.5,0.6]>	<[0.6,0.7], [0.15,0.3]>	<[0.65,0.75], [0.1,0.25]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>
C12	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>	<[0.6,0.7], [0.15,0.3]>	<[0.6,0.7], [0.15,0.3]>	<[0.5,0.6], [0.25,0.4]>	<[0.5,0.6], [0.25,0.4]>
C13	<[0.5,0.6], [0.25,0.4]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>	<[0.65,0.75], [0.1,0.25]>	<[0.65,0.75], [0.1,0.25]>	<[0.5,0.6], [0.25,0.4]>	<[0.55,0.65], [0.2,0.35]>
C14	<[0.15,0.3], [0.6,0.7]>	<[0.15,0.3], [0.6,0.7]>	<[0.1,0.25], [0.65,0.75]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>	<[0.15,0.3], [0.6,0.7]>	<[0.1,0.25], [0.65,0.75]>
C15	<[0.1,0.25], [0.65,0.75]>	<[0.15,0.3], [0.6,0.7]>	<[0.1,0.25], [0.65,0.75]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>	<[0.15,0.3], [0.6,0.7]>	<[0.15,0.3], [0.6,0.7]>
C16	<[0.5,0.5], [0.5,0.5]>	<[0.25,0.4], [0.5,0.6]>	<[0.25,0.4], [0.5,0.6]>	<[0.6,0.7], [0.15,0.3]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>
C17	<[0.5,0.5], [0.5,0.5]>	<[0.25,0.4], [0.5,0.6]>	<[0.2,0.35], [0.55,0.65]>	<[0.65,0.75], [0.1,0.25]>	<[0.6,0.7], [0.15,0.3]>	<[0.5,0.5], [0.5,0.5]>	<[0.5,0.5], [0.5,0.5]>

Table 7 Score judgment matrix $(\tilde{S})$

C1	C11	C12	C13	C14	C15	C16	C17
C11	[0, 0]	[0, 0]	[0, 0]	[0, − 0.35]	[− 0.35, − 0.1]	[− 0.1, 0.3]	[0.3, 0.55]
C12	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0.3]	[0.3, 0.55]
C13	[0.1, 0.35]	[0.35, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0.4]	[0.4, 0.65]
C14	[− 0.55, − 0.3]	[− 0.3, − 0.55]	[− 0.55, − 0.3]	[− 0.3, − 0.65]	[− 0.65, − 0.4]	[− 0.4, 0]	[0, 0]
C15	[− 0.65, − 0.4]	[− 0.4, − 0.55]	[− 0.55, − 0.3]	[− 0.3, − 0.65]	[− 0.65, − 0.4]	[− 0.4, 0]	[0, 0]
C16	[0, 0]	[0, − 0.35]	[− 0.35, − 0.1]	[− 0.1, − 0.35]	[− 0.35, − 0.1]	[− 0.1, 0.3]	[0.3, 0.55]
C17	[0, 0]	[0, − 0.35]	[− 0.35, − 0.1]	[− 0.1, − 0.45]	[− 0.45, − 0.2]	[− 0.2, 0.4]	[0.4, 0.65]

Table 8 Interval multiplicative matrix $(\tilde{A})$

C1	C11	C12	C13	C14	C15	C16	C17
C11	[1, 1]	[1, 1]	[0.45, 0.79]	[2, 3.55]	[2.51, 4.47]	[1, 1]	[1, 1]
C12	[1, 1]	[1, 1]	[1, 1]	[2, 3.55]	[2, 3.55]	[1.26, 2.24]	[1.26, 2.24]
C13	[1.26, 2.24]	[1, 1]	[1, 1]	[2.51, 4.47]	[2.51, 4.47]	[1.26, 2.24]	[1.58, 2.82]
C14	[0.28, 0.5]	[0.28, 0.5]	[0.22, 0.4]	[1, 1]	[1, 1]	[0.28, 0.5]	[0.22, 0.4]
C15	[0.22, 0.4]	[0.28, 0.5]	[0.22, 0.4]	[1, 1]	[1, 1]	[0.28, 0.5]	[0.28, 0.5]
C16	[1, 1]	[0.45, 0.79]	[0.45, 0.79]	[2, 3.55]	[1, 1]	[1, 1]	[1, 1]
C17	[1, 1]	[0.45, 0.79]	[0.35, 0.63]	[2.51, 4.47]	[2, 3.55]	[1, 1]	[1, 1]

Table 9 w^+, w^-, and L_w values

	C11	C12	C13	C14	C15	C16	C17
w^+	0.25	0.28	0.35	0.08	0.08	0.18	0.24
w^-	0.12	0.13	0.15	0.04	0.04	0.09	0.11
L_w	0.13	0.16	0.21	0.04	0.04	0.09	0.13

$$S_{j^-} = \frac{1}{4}\sum_{i=1}^{m}\left(\left|\mu_{ij}^{*} - \mu_i^{-}\right| + \left|\mu_{ij}^{*} - \mu_i^{+}\right| + \left|v_{ij}^{*} - v_i^{-}\right| + \left|v_{ij}^{*} - v_i^{+}\right|\right) \tag{23}$$

Step 20: Calculate the relative closeness C_j^* by using Eq. (24):

$$C_j^* = \frac{S_{j^-}}{S_{j^*} + S_{j^-}},\ j = 1, 2, \ldots, n. \tag{24}$$

Table 10 Possibility degree matrices of the criteria

C11	C12	0.43	C12	C11	0.57	C13	C11	0.7	C14	C11	0
C11	C13	0.3	C12	C13	0.37	C13	C12	0.63	C14	C12	0
C11	C14	1	C12	C14	1	C13	C14	1	C14	C13	0
C11	C15	1	C12	C15	1	C13	C15	1	C14	C15	0.5
C11	C16	0.73	C12	C16	0.79	C13	C16	0.89	C14	C16	0
C11	C17	0.53	C12	C17	0.6	C13	C17	0.72	C14	C17	0

C15	C11	0	C16	C11	0.27	C17	C11	0.47
C15	C12	0	C16	C12	0.21	C17	C12	0.4
C15	C13	0	C16	C13	0.11	C17	C13	0.28
C15	C14	0.5	C16	C14	1	C17	C14	1
C15	C16	0	C16	C15	1	C17	C15	1
C15	C17	0	C16	C17	0.31	C17	C16	0.69

Table 11 Comparison matrices of main and subcriteria corresponded with the linguistic terms based on experts' evaluations

Expert 1								Expert 2							
GOAL	C1	C2	C3	C4				GOAL	C1	C2	C3	C4			
C1	EE	L	VL	VL				**C1**	EE	L	VL	VL			
C2	H	EE	L	L				**C2**	H	EE	L	L			
C3	VH	H	EE	EE				**C3**	VH	H	EE	EE			
C4	VH	H	EE	EE				**C4**	VH	H	EE	EE			
C1	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C1**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**
C11	EE	EE	BM	VH	CH	EE	EE	**C11**	EE	EE	BM	VH	CH	EE	EE
C12	EE	EE	EE	VH	VH	AM	AM	**C12**	EE	EE	EE	VH	VH	AM	AM
C13	AM	EE	EE	CH	CH	AM	H	**C13**	AM	EE	EE	CH	CH	AM	H
C14	VL	VL	CL	EE	EE	VL	CL	**C14**	VL	VL	CL	EE	EE	VL	CL
C15	CL	VL	CL	EE	EE	VL	VL	**C15**	CL	VL	CL	EE	EE	VL	VL
C16	EE	BM	BM	VH	EE	EE	EE	**C16**	EE	BM	BM	VH	EE	EE	EE
C17	EE	BM	L	CH	VH	EE	EE	**C17**	EE	BM	L	CH	VH	EE	EE
C2	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**		**C2**	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**	
C21	EE	EE	BM	VH	CH	EE		**C21**	EE	EE	BM	VH	CH	EE	
C22	EE	EE	EE	VH	VH	AM		**C22**	EE	EE	EE	VH	VH	AM	
C23	AM	EE	EE	CH	CH	AM		**C23**	AM	EE	EE	CH	CH	AM	
C24	VL	VL	CL	EE	EE	VL		**C24**	VL	VL	CL	EE	EE	VL	
C25	CL	VL	CL	EE	EE	VL		**C25**	CL	VL	CL	EE	EE	VL	
C26	EE	BM	BM	VH	EE	EE		**C26**	EE	BM	BM	VH	EE	EE	
C3	**C31**	**C32**						**C3**	**C31**	**C32**					
C31	EE	H						**C31**	EE	AM					
C32	L	EE						**C32**	BM	EE					
C4	**C41**	**C42**	**C43**	**C44**	**C45**	**C46**		**C4**	**C41**	**C42**	**C43**	**C44**	**C45**	**C46**	
C41	EE	EE	BM	VH	CH	EE		**C41**	EE	EE	BM	VH	CH	EE	
C42	EE	EE	EE	VH	VH	AM		**C42**	EE	EE	EE	VH	VH	AM	
C43	AM	EE	EE	CH	CH	AM		**C43**	AM	EE	EE	CH	CH	AM	
C44	VL	VL	CL	EE	EE	VL		**C44**	VL	VL	CL	EE	EE	VL	
C45	CL	VL	CL	EE	EE	VL		**C45**	CL	VL	CL	EE	EE	VL	
C46	EE	BM	BM	VH	EE	EE		**C46**	EE	BM	BM	VH	EE	EE	

Expert 3							
GOAL	C1	C2	C3	C4			
C1	EE	L	VL	VL			
C2	H	EE	L	L			
C3	VH	H	EE	EE			
C4	VH	H	EE	EE			
C1	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**
C11	EE	EE	BM	VH	CH	EE	EE
C12	EE	EE	EE	VH	VH	AM	AM
C13	AM	EE	EE	CH	CH	AM	H
C14	VL	VL	CL	EE	EE	VL	CL
C15	CL	VL	CL	EE	EE	VL	VL
C16	EE	BM	BM	VH	EE	EE	EE
C17	EE	BM	L	CH	VH	EE	EE
C2	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**	
C21	EE	EE	BM	VH	CH	EE	
C22	EE	EE	EE	VH	VH	AM	

Table 11 (continued)

Expert 3						
GOAL	C1	C2	C3	C4		
C23	AM	EE	EE	CH	CH	AM
C24	VL	VL	CL	EE	EE	VL
C25	CL	VL	CL	EE	EE	VL
C26	EE	BM	BM	VH	EE	EE
C3	**C31**	**C32**				
C31	EE	EE				
C32	EE	EE				
C4	**C41**	**C42**	**C43**	**C44**	**C45**	**C46**
C41	EE	EE	BM	VH	CH	EE
C42	EE	EE	EE	VH	VH	AM
C43	AM	EE	EE	CH	CH	AM
C44	VL	VL	CL	EE	EE	VL
C45	CL	VL	CL	EE	EE	VL
C46	EE	BM	BM	VH	EE	EE

Table 12 Main criteria weights

Main criterion	DM1	DM2	DM3	Aggregated weight
Cost				
C1	0.111	0.129	0.296	0.161
Geography and infrastructure				
C2	0.226	0.206	0.158	0.194
Reliability and safety				
C3	0.332	0.34	0.162	0.264
Society				
C4	0.332	0.326	0.384	0.346

Step 21: Determine the ranks by using C_j^* values of the alternatives.

4 A real case application

Today, the major problems of the world are pollution, climate change, fast natural resource depletion, deforestation and global warming. These problems are mainly connected with the human populations and their needs. In the city of Istanbul, there are 20 million of people who are living in and almost 4 million of motor vehicles that are used by them. The effect of these motor vehicles to the atmosphere and the human health are highly critical since they are petroleum-based powered vehicles. To reduce the usage of them, government promotes people to buy EVs and provides incentives to companies to invest in this area. Through these conditions, a company that has investments in renewable energy and its applications is willing to determine appropriate locations for charging stations of EVs to be located in Istanbul. After a couple of meetings held by the company management, the company decides to create an expert team that will carry out the application process. This expert team is composed of three people: One is an executive from the investment department, other is an executive from the planning department and the last one is an academician whose expertise is in decision making under fuzziness environments and is abbreviated as DM1, DM2 and DM3, respectively. The determined alternatives are illustrated in the map of Istanbul as in Fig. 2. As a result of the evaluation of the field surveys, the existing installed charging stations and the studies in the literature, the expert group determines the alternatives and criteria given in Fig. 3.

Table 13 Subcriteria weights

Subcriterion	DM1	DM2	DM3	Aggregated weight
Land costs				
C11	0.093	0.089	0.096	0.093
Fixed costs				
C12	0.097	0.106	0.100	0.101
Construction costs				
C13	0.105	0.110	0.108	0.108
Operating costs				
C14	0.050	0.049	0.049	0.049
Transportation costs				
C15	0.050	0.060	0.055	0.055
Investment costs/back period				
C16	0.080	0.087	0.088	0.085
Station development cost				
C17	0.525	0.498	0.504	0.509
Traffic flows				
C21	0.192	0.185	0.189	0.189
Transmission				
C22	0.196	0.201	0.202	0.200
Site accessibility				
C23	0.207	0.199	0.208	0.205
Road network				
C24	0.112	0.110	0.113	0.111
Structure				
C25	0.111	0.113	0.109	0.111
Land use				
C26	0.183	0.192	0.179	0.185
Power system security				
C31	0.600	0.550	0.500	0.548
Traffic convenience				
C32	0.400	0.450	0.500	0.448
Size of traffic conditions				
C41	0.196	0.196	0.194	0.195
Size of site conditions				
C42	0.199	0.199	0.201	0.200
Fulfillment of drivers' convenience				
C43	0.211	0.212	0.194	0.206
Service radius				
C44	0.112	0.112	0.110	0.111
Customer preferences				
C45	0.111	0.111	0.113	0.111
Impact on people's life				
C46	0.171	0.171	0.189	0.177

4.1 Problem description

A decision-making procedure consisting of four phases is established. Nine alternatives, 4 main criteria and 21 subcriteria have been determined in Phase 1 on the basis of the experts' evaluations. IF DEMATEL method is applied to determine interdependencies of main criteria among themselves. Since the results show that there is no interdependency, we will apply IVIF-AHP method as a next phase. IVIF-AHP method is conducted for the calculation

of weights of the subcriteria in Phase 3. After the integration of these weights into the IVIF-TOPSIS method, the final scores of the locations are obtained in Phase 4. Sensitivity analysis has been also utilized in order to check the robustness of the final decisions in Phase 5.

4.2 Problem solution

Before presenting solution of the application, the scale that is used for the average matrix is given in Table 1.

The scale that is used for the comparison matrices is given in Table 2.

The scale that is also used for the decision matrices is given in Table 3.

We present the linguistic terms and average matrix of the IF DEMATEL method in Table 4.

After we applied the steps of IF DEMATEL, from Step 2 to Step 6, we obtain the cause and effect diagram and interdependency results as in Fig. 4. As a result of the IF DEMATEL, there is no interdependency among the main criteria. Thus, we will apply IVIF-AHP method as a next phase.

This diagram presents which criterion is more effective than the others, and this information guides decision makers to fill the comparison matrices.

In Phase 3, we only present steps of the *C1-Cost* subcriteria based on DM1 because of the paper's space constraints. The calculations start with the construction of comparison matrix. The constructed linguistic pairwise comparison based on DM1 evaluations is given in Table 5 as follows:

These linguistic variables are converted corresponded IVN values by using Table 1. The corresponded IVN values are given in Table 6.

Table 14 Consistency ratios of the pairwise comparison matrices

With respect to	DM1	DM2	DM3
Goal	0.081	0.102	0.083
C1	0.025	0.055	0.092
C2	0.075	0.089	0.080
C3	0	0	0
C4	0.022	0.083	0.064

$\tilde{S} = \left(\tilde{s}_{ij}\right)_{4\times4}$ is calculated by using Eq. (8) as shown in Table 7.

$\tilde{A} = \left(\tilde{a}_{ij}\right)_{4\times4}$ is calculated by using Eq. (9) as in Table 8.

Before applying possibility degree matrix steps, w^{+}, w^{-}, and L_w values are calculated as shown in Table 9.

Possibility degree matrices (P) are calculated by using Eq. (11) for all criteria as shown in Table 10.

As final step, total weights are calculated and then normalized by using Eq. (12). The normalized weights of the subcriteria are clarified as below:

C11-Land costs: 0.093
C12-Fixed costs: 0.097
C13-Construction costs: 0.105
C14-Operating costs: 0.050
C15-Transportation costs: 0.050
C16-Investment costs/back period: 0.080
C17-Station development cost: 0.525

From Tables 5, 6, 7, 8, 9 and 10, we illustrated the steps of the proposed method for C1-Cost subcriteria as an example. We applied similar steps to obtain the weights of the main and submain criteria which their pairwise comparison matrices corresponded with the linguistic terms are given in Table 11. The other numerical values can be obtained in similar way.

Finally, IVIF-AHP steps are applied for all pairwise comparison matrices. Then, main criteria and subcriteria weights are obtained as in Tables 12 and 13, respectively.

As it can be seen from Table 12, Society—C4 main criterion has the most important criterion among the others with 0.346 weight score. The least important main criterion is Cost—C1 with 0.161 weight score.

When the local weights of the subcriterion are analyzed, it can be seen that *Power system security—C31* is the most important subcriteria among the others.

The consistency ratios of the all pairwise comparison matrices are given in Table 14. When the results of the consistency analyses are examined, all of the matrices' index is lower than threshold value which is 0.1 except the evaluation of main criteria with respect to goal based on DM2. Since the gap between the index and threshold value is equal to 0.02, it can be negligible.

The global weights of the subcriteria which are used in IVIF-TOPSIS method are presented in Table 15. The results

Table 15 Global weights of the subcriteria

C11	C12	C13	C14	C15	C16	C17	C21	C22	C23	C24
0.015	0.016	0.017	0.008	0.009	0.014	0.082	0.037	0.039	0.040	0.022
C25	C26	C31	C32	C41	C42	C43	C44	C45	C46	
0.022	0.036	0.145	0.155	0.068	0.069	0.071	0.039	0.039	0.061	

Table 16 Linguistic decision matrix

Cri.	Type	Weight	DM1									DM2								
			AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
C11	C	0.015	VG	A	CB	B	VG	AA	VB	B	G	G	G	AA	A	A	AA	G	BA	BA
C12	C	0.016	BA	AA	B	VG	VG	A	CB	CB	AA	VG	VG	VG	VG	A	A	VG	BA	VB
C13	C	0.017	A	VG	B	BA	B	BA	CB	A	B	CB	BA	BA	CB	VG	A	VB	A	AA
C14	C	0.008	AA	BA	BA	A	AA	BA	G	BA	BA	CB	A	BA	BA	BA	G	B	A	AA
C15	C	0.009	VG	A	B	G	CB	G	G	A	A	BA	G	A	B	AA	VG	BA	VG	VG
C16	C	0.014	AA	AA	CB	VB	CB	G	AA	AA	G	A	VG	A	VG	VG	VG	B	G	BA
C17	C	0.082	G	VG	B	BA	B	VB	A	G	AA	G	AA	G	G	BA	A	VG	G	A
C21	C	0.037	VG	BA	VG	A	BA	B	BA	VG	VG	VG	A	BA	A	A	CB	BA	BA	VG
C22	B	0.039	CB	VG	AA	G	AA	B	A	G	CB	BA	AA	VG	AA	G	CB	BA	VB	A
C23	B	0.040	CB	VG	VG	VG	VG	AA	BA	CB	VB	A	A	A	VG	VG	BA	B	AA	G
C24	B	0.022	BA	BA	BA	BA	BA	A	G	BA	BA	AA	AA	VG	G	B	B	B	AA	B
C25	B	0.022	A	A	A	A	A	A	G	G	G	VG	B	A	B	B	A	VG	BA	VG
C26	C	0.036	AA	B	A	B	A	G	VG	B	AA	VG	VG	VG	VG	G	AA	AA	VG	BA
C31	B	0.145	B	G	A	VB	VG	VG	G	B	B	VG	BA	BA	VB	CB	G	VB	AA	AA
C32	B	0.155	VG	VG	G	BA	BA	VG	VB	VG	VG	BA	A	A	VB	VB	VG	B	G	VB
C41	C	0.068	BA	CB	VB	B	AA	A	BA	BA	BA	A	AA	AA	B	B	VG	BA	CB	CB
C42	C	0.069	A	CB	VG	G	VG	CB	BA	A	VB	G	VG	VG	G	BA	VG	G	VB	G
C43	B	0.071	AA	BA	VB	BA	BA	CB	BA	B	AA	VG	VG	A	B	BA	A	B	VG	VG
C44	B	0.039	VG	A	VG	G	B	AA	A	VG	G	AA	G	G	VG	A	A	VG	AA	AA
C45	B	0.039	BA	BA	AA	AA	B	G	AA	G	BA	A	A	A	A	CB	CB	A	CB	A
C46	B	0.061	A	A	BA	A	BA	VG	VB	A	A	G	BA	BA	BA	BA	B	BA	BA	BA

Cri.	Type	Weight	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
C11	C	0.015	CB	B	B	G	BA	BA	BA	VG	AA
C12	C	0.016	BA	VG	VG	VG	G	B	A	VG	G
C13	C	0.017	A	B	B	B	BA	VB	BA	BA	G
C14	C	0.008	AA	VG	VG	G	AA	B	G	VB	A
C15	C	0.009	B	BA	BA	BA	B	AA	G	AA	AA
C16	C	0.014	G	A	A	VB	VG	G	VG	G	VB
C17	C	0.082	VG	AA	AA	AA	AA	G	BA	VG	AA
C21	C	0.037	BA	VG	VG	VG	VG	G	BA	VB	A
C22	B	0.039	A	B	B	B	AA	AA	B	B	AA
C23	B	0.040	B	B	A	B	VG	A	B	BA	B
C24	B	0.022	VG	VG	VG	VG	AA	VG	BA	G	VG
C25	B	0.022	BA	VG	B	G	B	G	AA	VB	BA

Table 16 (continued)

Cri.	Type	Weight	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
C26	C	0.036	A	BA	A	VB	G	AA	A	G	G
C31	B	0.145	AA	A	AA	AA	CB	BA	B	VG	VG
C32	B	0.155	VG	G	A	BA	VB	VB	BA	B	CB
C41	C	0.068	BA	VG	A	A	AA	AA	BA	G	CB
C42	C	0.069	A	AA	AA	G	AA	A	A	BA	A
C43	B	0.071	AA	AA	VG	VG	VG	AA	VG	A	G
C44	B	0.039	CB	CB	BA	BA	BA	CB	BA	G	VB
C45	B	0.039	AA	AA	A	A	AA	VB	A	A	G
C46	B	0.061	CB	CB	VG	A	AA	G	AA	VB	A

C: Cost

B: Benefit

Table 17 Aggregated decision matrix

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
C11	<[0, 0.52], [0.29, 0.48]>	<[0.4, 0.56], [0.29, 0.44]>	<[0, 0.33], [0.5, 0.67]>	<[0.35, 0.51], [0.34, 0.49]>	<[0.45, 0.61], [0.24, 0.39]>	<[0.44, 0.59], [0.26, 0.41]>	<[0.27, 0.45], [0.39, 0.55]>	<[0.32, 0.48], [0.36, 0.52]>	<[0.43, 0.59], [0.26, 0.41]>
C12	<[0.42, 0.58], [0.26, 0.42]>	<[0.62, 0.77], [0.08, 0.23]>	<[0.45, 0.62], [0.22, 0.38]>	<[0.7, 0.85], [0, 0.15]>	<[0.54, 0.69], [0.16, 0.31]>	<[0.34, 0.49], [0.36, 0.51]>	<[0, 0.42], [0.4, 0.58]>	<[0, 0.36], [0.47, 0.64]>	<[0.27, 0.46], [0.38, 0.54]>
C13	<[0, 0.33], [0.5, 0.67]>	<[0.36, 0.53], [0.31, 0.47]>	<[0.24, 0.39], [0.46, 0.61]>	<[0, 0.27], [0.57, 0.73]>	<[0.37, 0.53], [0.31, 0.47]>	<[0.26, 0.42], [0.42, 0.58]>	<[0, 0.24], [0.6, 0.76]>	<[0.37, 0.52], [0.33, 0.48]>	<[0.38, 0.54], [0.3, 0.46]>
C14	<[0, 0.36], [0.46, 0.64]>	<[0.42, 0.57], [0.27, 0.43]>	<[0.37, 0.53], [0.32, 0.47]>	<[0.39, 0.55], [0.3, 0.45]>	<[0.41, 0.56], [0.29, 0.44]>	<[0.36, 0.52], [0.33, 0.48]>	<[0.39, 0.55], [0.29, 0.45]>	<[0.26, 0.42], [0.42, 0.58]>	<[0.4, 0.55], [0.3, 0.45]>
C15	<[0.36, 0.53], [0.31, 0.47]>	<[0.44, 0.59], [0.26, 0.41]>	<[0.29, 0.45], [0.4, 0.55]>	<[0.33, 0.49], [0.36, 0.51]>	<[0, 0.33], [0.5, 0.67]>	<[0.61, 0.76], [0.09, 0.24]>	<[0.45, 0.61], [0.23, 0.39]>	<[0.53, 0.68], [0.17, 0.32]>	<[0.53, 0.68], [0.17, 0.32]>
C16	<[0.48, 0.63], [0.22, 0.37]>	<[0.54, 0.69], [0.15, 0.31]>	<[0, 0.35], [0.48, 0.65]>	<[0.22, 0.41], [0.42, 0.59]>	<[0, 0.46], [0.34, 0.54]>	<[0.64, 0.79], [0.06, 0.21]>	<[0.38, 0.54], [0.3, 0.46]>	<[0.56, 0.71], [0.14, 0.29]>	<[0.29, 0.46], [0.38, 0.54]>
C17	<[0.62, 0.77], [0.08, 0.23]>	<[0.56, 0.71], [0.14, 0.29]>	<[0.39, 0.55], [0.29, 0.45]>	<[0.45, 0.61], [0.24, 0.39]>	<[0.3, 0.45], [0.4, 0.55]>	<[0.27, 0.45], [0.39, 0.55]>	<[0.47, 0.62], [0.22, 0.38]>	<[0.62, 0.77], [0.08, 0.23]>	<[0.46, 0.61], [0.24, 0.39]>
C21	<[0.57, 0.73], [0.12, 0.27]>	<[0.42, 0.57], [0.27, 0.43]>	<[0.5, 0.66], [0.18, 0.34]>	<[0.46, 0.61], [0.23, 0.39]>	<[0.42, 0.57], [0.27, 0.43]>	<[0, 0.3], [0.53, 0.7]>	<[0.3, 0.45], [0.4, 0.55]>	<[0.31, 0.49], [0.35, 0.51]>	<[0.61, 0.76], [0.09, 0.24]>
C22	<[0, 0.32], [0.51, 0.68]>	<[0.45, 0.61], [0.23, 0.39]>	<[0.45, 0.62], [0.22, 0.38]>	<[0.42, 0.59], [0.26, 0.41]>	<[0.54, 0.69], [0.16, 0.31]>	<[0, 0.29], [0.54, 0.71]>	<[0.3, 0.45], [0.39, 0.55]>	<[0.22, 0.4], [0.44, 0.6]>	<[0, 0.36], [0.46, 0.64]>

Table 17 (continued)

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
C23	<[0, 0.31], [0.52, 0.69]>	<[0.41, 0.57], [0.27, 0.43]>	<[0.49, 0.64], [0.21, 0.36]>	<[0.51, 0.68], [0.16, 0.32]>	<[0.7, 0.85], [0, 0.15]>	<[0.39, 0.54], [0.31, 0.46]>	<[0.23, 0.38], [0.47, 0.62]>	<[0, 0.35], [0.47, 0.65]>	<[0.24, 0.42], [0.41, 0.58]>
C24	<[0.45, 0.61], [0.24, 0.39]>	<[0.45, 0.61], [0.24, 0.39]>	<[0.52, 0.68], [0.16, 0.32]>	<[0.49, 0.65], [0.2, 0.35]>	<[0.29, 0.45], [0.4, 0.55]>	<[0.35, 0.51], [0.33, 0.49]>	<[0.33, 0.49], [0.36, 0.51]>	<[0.44, 0.59], [0.26, 0.41]>	<[0.32, 0.48], [0.37, 0.52]>
C25	<[0.47, 0.62], [0.22, 0.38]>	<[0.35, 0.51], [0.33, 0.49]>	<[0.34, 0.49], [0.36, 0.51]>	<[0.34, 0.5], [0.35, 0.5]>	<[0.25, 0.41], [0.44, 0.59]>	<[0.44, 0.59], [0.25, 0.41]>	<[0.61, 0.76], [0.09, 0.24]>	<[0.29, 0.46], [0.38, 0.54]>	<[0.54, 0.69], [0.15, 0.31]>
C26	<[0.54, 0.69], [0.15, 0.31]>	<[0.37, 0.53], [0.31, 0.47]>	<[0.5, 0.65], [0.19, 0.35]>	<[0.28, 0.46], [0.38, 0.54]>	<[0.52, 0.67], [0.18, 0.33]>	<[0.53, 0.68], [0.17, 0.32]>	<[0.53, 0.68], [0.16, 0.32]>	<[0.43, 0.6], [0.24, 0.4]>	<[0.43, 0.58], [0.27, 0.42]>
C31	<[0.42, 0.58], [0.26, 0.42]>	<[0.41, 0.57], [0.28, 0.43]>	<[0.38, 0.53], [0.32, 0.47]>	<[0.15, 0.32], [0.52, 0.68]>	<[0, 0.28], [0.54, 0.72]>	<[0.53, 0.69], [0.16, 0.31]>	<[0.22, 0.4], [0.44, 0.6]>	<[0.39, 0.56], [0.28, 0.44]>	<[0.39, 0.56], [0.28, 0.44]>
C32	<[0.5, 0.66], [0.18, 0.34]>	<[0.54, 0.69], [0.16, 0.31]>	<[0.46, 0.61], [0.24, 0.39]>	<[0.19, 0.36], [0.49, 0.64]>	<[0.15, 0.31], [0.54, 0.69]>	<[0.43, 0.63], [0.2, 0.37]>	<[0.17, 0.33], [0.52, 0.67]>	<[0.48, 0.65], [0.19, 0.35]>	<[0, 0.34], [0.49, 0.66]>
C41	<[0.34, 0.49], [0.36, 0.51]>	<[0, 0.42], [0.4, 0.58]>	<[0.27, 0.45], [0.39, 0.55]>	<[0.24, 0.39], [0.46, 0.61]>	<[0.35, 0.51], [0.34, 0.49]>	<[0.53, 0.68], [0.17, 0.32]>	<[0.3, 0.45], [0.4, 0.55]>	<[0, 0.33], [0.5, 0.67]>	<[0, 0.22], [0.62, 0.78]>
C42	<[0.47, 0.62], [0.23, 0.38]>	<[0, 0.43], [0.38, 0.57]>	<[0.64, 0.79], [0.05, 0.21]>	<[0.6, 0.75], [0.1, 0.25]>	<[0.46, 0.62], [0.23, 0.38]>	<[0, 0.42], [0.4, 0.58]>	<[0.43, 0.58], [0.27, 0.42]>	<[0.21, 0.38], [0.46, 0.62]>	<[0.29, 0.47], [0.36, 0.53]>
C43	<[0.57, 0.72], [0.13, 0.28]>	<[0.48, 0.64], [0.21, 0.36]>	<[0.28, 0.47], [0.37, 0.53]>	<[0.32, 0.48], [0.37, 0.52]>	<[0.37, 0.53], [0.32, 0.47]>	<[0, 0.36], [0.46, 0.64]>	<[0.32, 0.48], [0.37, 0.52]>	<[0.39, 0.56], [0.28, 0.44]>	<[0.6, 0.75], [0.1, 0.25]>
C44	<[0, 0.49], [0.32, 0.51]>	<[0, 0.45], [0.37, 0.55]>	<[0.53, 0.69], [0.16, 0.31]>	<[0.54, 0.69], [0.15, 0.31]>	<[0.29, 0.45], [0.4, 0.55]>	<[0, 0.42], [0.41, 0.58]>	<[0.47, 0.62], [0.22, 0.38]>	<[0.59, 0.74], [0.11, 0.26]>	<[0.36, 0.54], [0.3, 0.46]>
C45	<[0.38, 0.53], [0.31, 0.47]>	<[0.38, 0.53], [0.31, 0.47]>	<[0.43, 0.58], [0.27, 0.42]>	<[0.43, 0.58], [0.27, 0.42]>	<[0, 0.29], [0.54, 0.71]>	<[0, 0.3], [0.53, 0.7]>	<[0.43, 0.58], [0.27, 0.42]>	<[0, 0.36], [0.46, 0.64]>	<[0.4, 0.55], [0.29, 0.45]>
C46	<[0, 0.45], [0.37, 0.55]>	<[0, 0.37], [0.47, 0.63]>	<[0.37, 0.53], [0.32, 0.47]>	<[0.36, 0.51], [0.34, 0.49]>	<[0.34, 0.49], [0.36, 0.51]>	<[0.41, 0.58], [0.26, 0.42]>	<[0.23, 0.4], [0.44, 0.6]>	<[0.25, 0.42], [0.43, 0.58]>	<[0.36, 0.51], [0.34, 0.49]>

Table 18 Weighted aggregated decision matrix

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
C11	<[0, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>
C12	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.96, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.02, 0.03], [0, 0.97]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>
C13	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0], [0.99, 1]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0], [0.99, 1]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>
C14	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>
C15	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.02], [0.96, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>
C16	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.98, 0.99]>	<[0.02, 0.02], [0.96, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.99, 0.99]>
C17	<[0.01, 0.02], [0.96, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.96, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>
C21	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.96, 0.98]>
C22	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>
C23	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.98, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.02, 0.03], [0, 0.97]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>
C24	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.02], [0.98, 0.98]>	<[0.01, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.99, 0.99]>
C25	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.96, 0.98]>	<[0.01, 0.01], [0.99, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>
C26	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.98, 0.98]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>
C31	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0], [0.99, 1]>	<[0.01, 0.02], [0.97, 0.98]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>
C32	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.02], [0.98, 0.98]>	<[0, 0.01], [0.99, 0.99]>
C41	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0], [0.99, 1]>
C42	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.02, 0.02], [0.96, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>
C43	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.02], [0.98, 0.98]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>
C44	<[0, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.02], [0.97, 0.98]>	<[0.01, 0.01], [0.98, 0.99]>
C45	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>
C46	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0, 0.01], [0.99, 0.99]>	<[0.01, 0.01], [0.98, 0.99]>

Table 19 Positive and negative ideal solutions

Criterion	IVIF positive ideal solution (O^*)	IVIF negative ideal solution (O^-)
C11	<[0, 0.006], [0.99, 0.994]>	<[0.009, 0.014], [0.979, 0.986]>
C12	<[0, 0.007], [0.989, 0.993]>	<[0.018, 0.028], [0, 0.972]>
C13	<[0, 0.004], [0.992, 0.996]>	<[0.007, 0.012], [0.982, 0.988]>
C14	<[0, 0.007], [0.988, 0.993]>	<[0.008, 0.013], [0.981, 0.987]>
C15	<[0, 0.006], [0.99, 0.994]>	<[0.014, 0.021], [0.964, 0.979]>
C16	<[0, 0.006], [0.989, 0.994]>	<[0.015, 0.023], [0.959, 0.977]>
C17	<[0.005, 0.009], [0.986, 0.991]>	<[0.015, 0.022], [0.962, 0.978]>
C21	<[0, 0.005], [0.99, 0.995]>	<[0.014, 0.021], [0.964, 0.979]>
C22	<[0.012, 0.017], [0.973, 0.983]>	<[0, 0.005], [0.991, 0.995]>
C23	<[0.018, 0.028], [0, 0.972]>	<[0, 0.007], [0.989, 0.993]>
C24	<[0.011, 0.017], [0.973, 0.983]>	<[0.005, 0.009], [0.986, 0.991]>
C25	<[0.014, 0.021], [0.964, 0.979]>	<[0.004, 0.008], [0.988, 0.992]>
C26	<[0.005, 0.009], [0.985, 0.991]>	<[0.011, 0.017], [0.973, 0.983]>
C31	<[0.011, 0.017], [0.973, 0.983]>	<[0, 0.005], [0.991, 0.995]>
C32	<[0.012, 0.018], [0.972, 0.982]>	<[0, 0.005], [0.991, 0.995]>
C41	<[0, 0.004], [0.993, 0.996]>	<[0.011, 0.017], [0.973, 0.983]>
C42	<[0, 0.007], [0.988, 0.993]>	<[0.015, 0.023], [0.957, 0.977]>
C43	<[0.014, 0.021], [0.966, 0.979]>	<[0, 0.007], [0.988, 0.993]>
C44	<[0.013, 0.02], [0.967, 0.98]>	<[0, 0.008], [0.987, 0.992]>
C45	<[0.008, 0.013], [0.98, 0.987]>	<[0, 0.005], [0.991, 0.995]>
C46	<[0.008, 0.013], [0.98, 0.987]>	<[0, 0.007], [0.989, 0.993]>

show that it will a huge effect of the *Power system security—C31* and *Traffic convenience—C32* on the evaluation of alternatives process since their weight scores are 0.145 and 0.155, respectively. It can be also said that *Operating costs—C14* and *Transportation costs—C15* are the least important criteria that will effect on evaluation process since their weight scores are 0.008 and 0.009, respectively.

The constructed linguistic decision matrix based on decision makers' evaluations is given in Table 16. The aggregated decision matrix is obtained by using Eq. (4) as shown in Table 17. The weighted aggregated decision matrix is obtained by using Eq. (13) as in Table 18.

The ideal solutions are obtained by using Eqs. (14) and (15) as shown in Table 19. The separation measures are calculated as in Table 20 as follows:

The separation measures S_j^* and S_j^- for each alternative are calculated by using Eqs. (16) and (17) as in Table 19. The final results of the problem and ranks of the alternatives are calculated by using Eq. (20) as in Table 21.

As it can be seen from Table 21, *Kadiköy Dock District—AL5* is determined as the most appropriate location for the EVs charge station with respect to criteria scores that based decision makers' opinions. *Acibadem Akasya AVM—AL4* comes after as the second best alternative. The gap between the scores of these two alternatives is very close. Charging station can be constructed one of them under the light of managerial board decision.

4.3 Sensitivity analysis

One-at-a-time sensitivity analysis based on each main criterion is performed to demonstrate effects of subcriteria on the results of IVIF-TOPSIS. To do this, we develop a pattern which is given in Table 22. We used values of 0.1, 0.5 and 1 as reference points. Simply, we assign these values to the main criteria, respectively. Then, we obtain new global weights of the subcriteria. Finally, IVIF-TOPSIS method's steps are rerun and results are obtained.

To visualize this analysis, we present the ranks of alternatives based on the test variables which are given in Fig. 5.

It can be seen that the alternative named *Kadıköy Dock District—AL5* is determined as the best alternatives among the others for all one-at-a-time sensitivity analyses. The changes in the ranks of alternatives occurred when the weight changes in criteria named *Cost—C1* and *Geography & Infrastructure—C2* are made. This concludes that our method's decisions are robust, and results are sensitive.

5 Conclusion

One of the biggest problems occurred by the industry developments and the rapid rise in human populations is the increment of the number of cars in use. As a result of this increment, the CO_2 emission rate has increased

Table 20 Separation measures of the problem

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
S_j^*									
C11	0.004	0.007	0.000	0.005	0.009	0.008	0.004	0.005	0.008
C12	0.008	0.019	0.010	0.263	0.013	0.005	0.002	0.001	0.004
C13	0.000	0.006	0.002	0.001	0.006	0.003	0.002	0.006	0.006
C14	0.001	0.007	0.006	0.007	0.007	0.006	0.007	0.003	0.007
C15	0.006	0.008	0.003	0.005	0.000	0.017	0.009	0.012	0.012
C16	0.010	0.013	0.000	0.002	0.003	0.020	0.006	0.014	0.004
C17	0.018	0.014	0.007	0.009	0.004	0.004	0.010	0.018	0.009
C21	0.015	0.007	0.011	0.009	0.007	0.001	0.004	0.005	0.018
C22	0.000	0.009	0.009	0.008	0.013	0.001	0.004	0.002	0.001
C23	0.000	0.007	0.010	0.012	0.263	0.006	0.002	0.000	0.003
C24	0.009	0.009	0.012	0.011	0.003	0.005	0.005	0.008	0.004
C25	0.010	0.005	0.005	0.005	0.002	0.008	0.017	0.004	0.013
C26	0.013	0.006	0.011	0.004	0.012	0.012	0.012	0.009	0.008
C31	0.008	0.007	0.006	0.001	0.001	0.013	0.002	0.007	0.007
C32	0.011	0.013	0.009	0.001	0.001	0.010	0.001	0.011	0.000
C41	0.005	0.002	0.003	0.002	0.005	0.012	0.004	0.000	0.002
C42	0.009	0.002	0.021	0.017	0.009	0.002	0.008	0.002	0.004
C43	0.015	0.010	0.004	0.004	0.006	0.001	0.004	0.007	0.017
C44	0.004	0.002	0.013	0.013	0.003	0.002	0.010	0.016	0.006
C45	0.006	0.006	0.008	0.008	0.001	0.001	0.008	0.001	0.007
C46	0.002	0.001	0.006	0.005	0.005	0.008	0.002	0.003	0.005
	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
S_j^-									
C11	0.004	0.002	0.009	0.004	0.000	0.001	0.005	0.004	0.001
C12	0.001	0.010	0.001	0.254	0.004	0.004	0.007	0.008	0.005
C13	0.009	0.003	0.007	0.010	0.003	0.006	0.011	0.003	0.003
C14	0.008	0.001	0.003	0.002	0.002	0.003	0.002	0.006	0.002
C15	0.003	0.001	0.005	0.004	0.009	0.008	0.000	0.003	0.003
C16	0.001	0.004	0.009	0.007	0.006	0.011	0.003	0.005	0.005
C17	0.010	0.005	0.002	0.000	0.005	0.005	0.001	0.010	0.000
C21	0.006	0.001	0.002	0.000	0.001	0.010	0.005	0.004	0.009
C22	0.009	0.000	0.000	0.001	0.004	0.010	0.005	0.007	0.008
C23	0.009	0.001	0.001	0.003	0.254	0.003	0.007	0.009	0.006
C24	0.000	0.000	0.003	0.002	0.005	0.004	0.004	0.001	0.005
C25	0.001	0.004	0.004	0.004	0.006	0.001	0.008	0.005	0.004
C26	0.004	0.003	0.002	0.005	0.003	0.003	0.004	0.000	0.001
C31	0.001	0.002	0.003	0.009	0.010	0.004	0.007	0.002	0.002
C32	0.002	0.004	0.000	0.008	0.009	0.001	0.008	0.002	0.009
C41	0.004	0.007	0.006	0.007	0.004	0.003	0.005	0.009	0.011
C42	0.001	0.007	0.012	0.008	0.000	0.007	0.001	0.007	0.005
C43	0.006	0.001	0.005	0.005	0.003	0.008	0.005	0.002	0.008
C44	0.005	0.006	0.004	0.004	0.005	0.007	0.001	0.007	0.003
C45	0.003	0.003	0.001	0.001	0.010	0.010	0.001	0.008	0.002
C46	0.006	0.008	0.003	0.004	0.004	0.001	0.007	0.006	0.004

Table 21 Final results and ranks of the alternatives

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9
S_j^*	0.155	0.159	0.159	0.390	0.368	0.140	0.120	0.132	0.144
S_j^-	0.094	0.070	0.080	0.340	0.350	0.110	0.100	0.109	0.095
C_j^*	0.378	0.311	0.350	0.470	0.480	0.440	0.450	0.452	0.396
Rank	7	9	8	2	1	5	4	3	6

Table 22 Pattern for the sensitivity analysis

Pattern	Sets with respect to main criteria			
	Set-1	Set-2	Set-3	Set-4
Test variables				
0.1	Ranks	…	…	Ranks
0.5		…	⋱	⋮
1	⋮	…	⋱	⋮

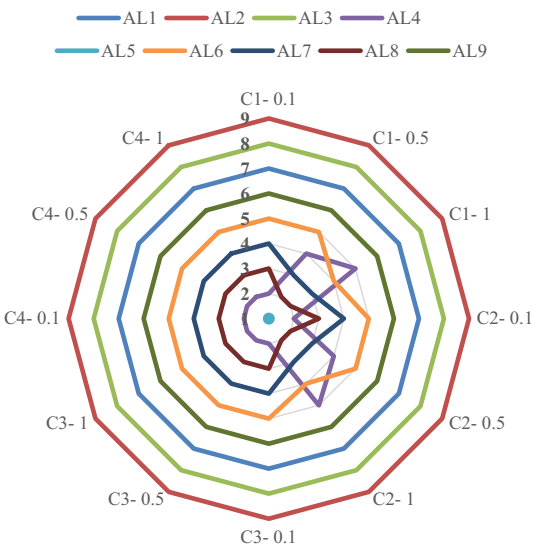


Fig. 5 Ranks of alternatives based on main criteria's weight

significantly and has caused to the global warming. Many countries have started to take precautions to endure the global warming, and one of these precautions is to promote the use of EVs. Countries that offer certain opportunities to their citizens in order to promote the use of EVs have also funded investments in this area at the same time. One of these countries, Turkey, also tries to support the investors in the context of funding investments. In this framework, an investor, who wants to take advantage of these opportunities, tries to evaluate alternative locations for the EVs charge station in the city of Istanbul, Turkey.

In this paper, an integrated intuitionistic MCDM approach composed of DEMATEL, AHP and TOPSIS methods is applied to evaluate selected alternatives to find the most appropriate location for the EV charge station. Since the selection of EVs charge station process contains many alternatives and relevant criteria, the best selection approach is considered as the MCDM methods. Many of the criteria are handled as linguistic evaluations in this selection process. Intuitionistic fuzzy sets generally deal with the problem with uncertain and vague data that generally represented with linguistic terms. In order to handle these qualitative evaluations in the selection process, we apply intuitionistic fuzzy sets.

In our application, it is determined that the selected criteria have no interdependency among themselves as a result of IF DEMATEL method since the main have a hierarchy. For further researches, using DEMATEL to reveal interdependency can be interesting for the applications that have a network instead of a hierarchy. The result of the IVIF-AHP method shows that *Power system security—C31* and *Traffic convenience—C32* subcriteria are the most effective criteria for this selection process. As a result of the IVIF-TOPSIS application, *Kadiköy Dock District—AL5* is selected as the best location to determine charging station in the Anatolian Side of the Istanbul. On the other hand, the ranks of the alternatives, *Cevahir AVM—AL1*, *Zorlu AVM—AL2* and *Metrocity AVM—AL3*, at the European Side are 7, 9 and 8, respectively. When the rankings of alternatives are taken into consideration, it can be said that the need of charging stations for the EVs in the Anatolian side of Istanbul is more important than the European side. Through the application process, one-at-a-time sensitivity analysis is illustrated to check the validation of the proposed methodology, and it is revealed that applied integrated fuzzy MCDM approach's results are robust. Thus, our proposed methodology is an evaluation process which can be used as a decision-making tool by the managers or researchers to make useful inferences, judgments and decisions for selection of EVs charging locations. Since the model considers both the quantitative and qualitative data, it is very useful for the areas that have uncertainty and indeterminacy for decision-making processes.

For future research, the proposed method can be applied for the other cities of Turkey to determine appropriate locations for charging stations of EVs. Besides, the proposed approach can be extended with other types of fuzzy

sets such as type-2, hesitant and neutrosophic sets which are usually conducted to handle uncertainty of the knowledge and indeterminacy and the obtained results can be compared with this way. By the way, these fuzzy sets can be used in MCDM methodologies to reconsider our problem and the obtained results can be compared.

Compliance with ethical standards

Conflict of interest All the authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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