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A two level interval valued neutrosophic AHP integrated TOPSIS methodology for post-earthquake fire risk assessment: An application for Istanbul

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ABSTRACT

Earthquakes are the leading natural disasters that seriously affect human life. Furthermore, earthquakes are natural disasters that have the ability to trigger a second disaster in addition to the damages they cause. From this point of view, post-earthquake fires are defined as the one of the most dangerous secondary disasters after an earthquake and often cause even more serious dangers. For this reason, government officials and relevant decision-makers should effectively determine post-earthquake fire risks and take necessary precautions. In this study, we consider the problem of determining the fire risk after an earthquake as a multi-criteria decision problem and present a two-level framework for risk assessment. The main and sub-criteria are determined by a detailed literature review and Modified Delphi method is employed to gain and consolidate expert opinions. Firstly, the importance weights of the criteria for post-earthquake fire risk problem are determined by the interval valued neutrosophic-Analytical Hierarchy Process (IVN-AHP) methodology. Then, interval valued neutrosophic TOPSIS (IVN-TOPSIS) method is used to rank the districts in Anatolian side of Istanbul according to their post-earthquake fire risks. The proposed risk assessment methodology is utilized with real life data to determine the most risky districts of Istanbul, Turkey. The result of proposed methodology is tested and validated with sensitivity analysis. A comparative analysis also is conducted to further validate the robustness and effectiveness of the proposed methodology. The proposed integrated methodology is intended to be a useful tool for risk assessment and to provide decision makers with a reliable assessment.

1. Introduction and related studies

Earthquakes are natural disasters that have the potential to trigger secondary disasters such as fires and tsunamis in addition to the serious damage they cause. From this point of view, it can be said that fires caused by earthquakes are the most dangerous secondary disasters after an earthquake [1]. Fires that break out after earthquakes can grow uncontrollably and the damage they cause can reach very serious levels. One of the most serious examples of this is the San Francisco Earthquake that occurred on April 8, 1906. It was determined that the fires that started after this earthquake caused 10 times more damage than the damage caused by the earthquake [2,3]. It is recorded that 521-burned blocks, 28,288 damaged buildings, 400 deaths and financial losses worth $400 million in the fires that lasted for 3 days. A similar disaster occurred in the Great Kanto (Tokyo) Earthquake dated September 1, 1923, known as the “greatest post-earthquake fire” in history. After the earthquake, there were 129 fire disasters, 99 of which were reported to be caused by general and chemical reasons [4]. Similarly, the fire disasters following the 1994 Northridge and 1995 Kobe earthquakes caused serious damages [5]. These disasters reveal that besides earthquakes, fires should be examined as secondary disasters after an earthquake.

When the literature on post-earthquake fires is reviewed, probabilistic prediction models and studies to estimate the location and number of potential post-earthquake ignitions come to the fore. Scawthorn et al. [6] present a model that takes into account building density and characteristics, wind speed, firefighting level and seismic intensity to determine fire risk following an earthquake spreading between low-rise

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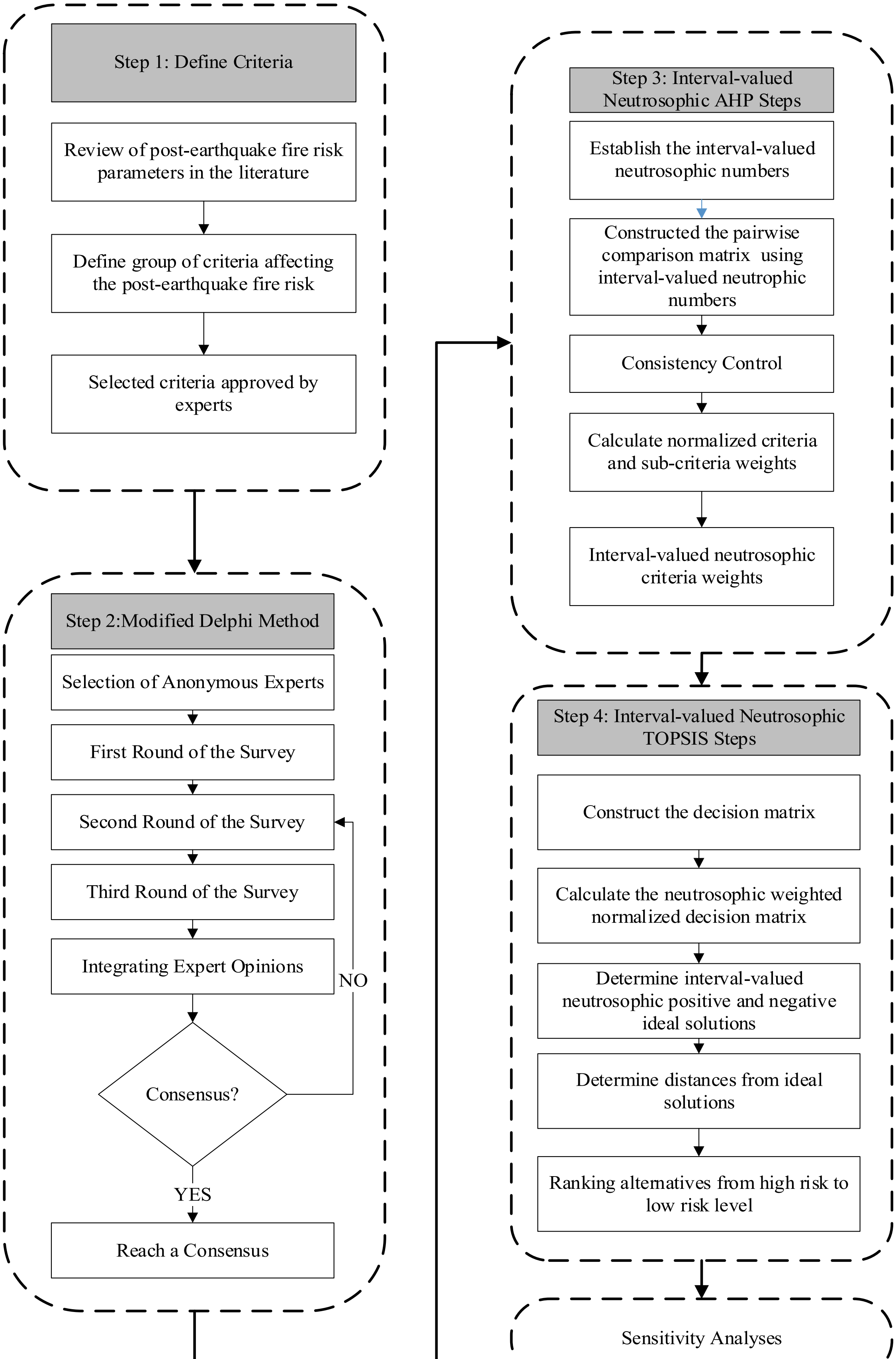

Fig. 1. The levels of the proposed methodology.

Table 1
Post-earthquake fire risk criteria and sub-criteria.

Main Criteria	Sub-Criteria	Sources
Leaks in Natural Gas and Other Gas Sources (C1)	Destroyed or Heavy Damaged Buildings Containing Natural Gas System (C11) Faults and Leaks in the Natural Gas Pipeline (C12) Leaks in Other Gases Used in Industrial Areas (C13)	[7,17, 20–22],
Electricity Sources and Electrical Devices (C2)	Short Circuit and Leaks Occurring in Completely Collapsed Buildings (C21) Malfunctions in Regional Transformers and Power Plants (C22) Heavily Damaged Buildings Heated by Electricity in the Region (C23)	[3,4,20, 23], [7,17,22, 24],
Internal Overturns Due to Shaking and Open Flame Sources (C3)	Average Distance Between Buildings (C31) Building Height (C32) Building Material Type (C33) Number of Cooking Equipment in the Buildings (C34) Population Density (C35)	[1,3,4,7], [9,18,19, 25],
Chemicals and Flammable Sources (C4)	Density of Chemical Facilities in the Region (C41) Universities or Colleges in the Region (C42) Pharmacies in the Region (C43) Areas Containing Flammable Liquids (C44)	[1,4,17, 23],
Risks Due to Delay of Intervention (C5)	Number of Firefighters Working in the Zone (C51) Faults in Water Supply Systems and Access to Resources (C52) Closed Roads Due to Completely Destroyed Buildings (C53) Fire Station Access Area (C54)	[1,9,20, 25],

wooden buildings in urban areas. Kobayashi [4] presents a prediction model for fires that may occur in future earthquakes by examining the fires that occurred after six major earthquakes in Japan, a highly active country in terms of seismicity, and the sources of these fires,. Davidson [7] focuses on statistical modelling of post-earthquake ignitions and develop generalized linear and mixed models. In addition to statistical models, simulation of post-earthquake fires with specific scenarios is also a well-studied research subject. Scawthorn [8] analyses the number of ignitions that may occur by conducting some experiments on the scenario of "a 7.8 magnitude earthquake with breeze and low humidity in November". Nishino et al. [9] calculate fire risks that may occur after an earthquake by using Monte Carlo Simulation and physics-based fire spread and evacuation simulation model together.

Multi-criteria decision-making (MCDM) models are very useful when there are multiple criteria affecting a decision and these criteria need to be evaluated together [10]. In this context, MCDM approaches are frequently used in different subjects related to natural disasters. Although there are very limited studies in the literature for post-earthquake fire risk assessment with MCDM methods. However, there are a significant number of studies using different types of models in the risk assessment of general natural disasters such as earthquakes and floods. For example, in recent years, the number of studies on flood disaster risk management with MCDM methods are increasing [11]. Orencio et al. [12] handle the vulnerability of communities living in coastal areas of the Philippines to natural disasters using Modified Delphi and AHP methods. In another study about floods risk assessment is presented by Sun et al. [11]. TOPSIS, Weighted Sum Model (WSM) and Elimination Et Choice Translation Reality (ELECTRE) methods are employed to analyze the risks at different points of the Yangtze River Delta. Jena et al. [13] examine earthquake vulnerability for Banda Aceh city by using MCDM methods AHP and VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) together. Geographical information systems (GIS) are employed to create vulnerability maps according to the risks of the regions determined by the proposed MCDM methodology. Yariyan et al. [14] analyze different dimensions of earthquake vulnerability in Sanandaj via fuzzy-AHP integrated artificial neural networks (ANN) methodology.

As mentioned before, the number of studies using MCDM methodologies to conduct post-earthquake fire risk evaluation is quite limited. Zhao et al. [1] develop a risk assessment model for potential post-earthquake fires in cities using GIS. The weights of the criteria are determined by AHP. Then, the regions examined are divided into squares and the risk of each square is calculated separately with the mathematical model. As a result, the post-earthquake fire risk map of the region is created. Lin et al. [15] determine the weights of criteria affecting post-earthquake fire risk in buildings. Four main criteria and three sub-criteria related for each main criterion are determined, and then the weights of these criteria are calculated by AHP. Firefighting equipment is determined as the most important criterion.

Considering the literature on post-earthquake fires, it is noteworthy that most of the studies consider probabilistic techniques that take into account a limited number of parameters. Post-earthquake fire risk is a type of risk includes many factors, which are uncertain in nature, coexist and it is not possible to fully calculate how and in which direction these factors affect each other. As a natural consequence of this, limited number of parameters are taken into consideration in most of the studies. This study aims to provide a broader framework for incorporating uncertain linguistic assessments in the decision-making process and to present a general risk assessment methodology for the risk of fire after an earthquake. Neutrosophic logic, a generalization of all other logics, requires more parameters for identification and thus provides more information about the problem [16].

For this purpose, a risk assessment methodology is presented using interval valued neutrosophic sets. AHP and TOPSIS are integrated with interval valued neutrosophic sets to reflect complex and uncertain human ideas into the decision-making process. Although they are quite popular methods separately, these three approaches, which are used together for the first time for post-earthquake fire risks, both represent uncertain situations well and offer a systematic tool to evaluate expert opinions, making an important contribution to the literature. Considering the performance of these approaches in scientific research, it can be said that the proposed novel methodology is an effective risk assessment approach for decision makers. In addition, since the methodology is tested with real data for Istanbul, it can be considered as a preliminary study of the measures to be taken as it and can guide experts in terms of regions and risk types that require extra attention.

In the literature, to the best of our knowledge there is no study handling post-earthquake fire risk assessment problem with MCDM methods. In this respect, the study offers a unique perspective. In addition, since it is possible to incoporate expert judgments with neutrosophic sets, which are a powerful way of expressing specificity, the proposed risk assessment methodology provides more space and freedom to experts in evaluating post-earthquake fire risks factors.

The remainder of this paper is organized as follows: Section 2 presents the proposed risk assessment methodology. In Section 3, a real case application of the proposed methodology for the Anatolian side of İstanbul is given. Section 4 presents sensitivity analysis. Comparative analysis of this study is given in Section 5. Finally, in Section 6 conclusions and suggestions for future studies are presented.

2. The proposed two level neutrosophic AHP integrated neutrosophic TOPSIS methodology

In this study, IVN-AHP and IVN-TOPSIS techniques are used together to determine post-earthquake fire risk in urban areas. In addition, expert opinions are included and consolidated in the process through the

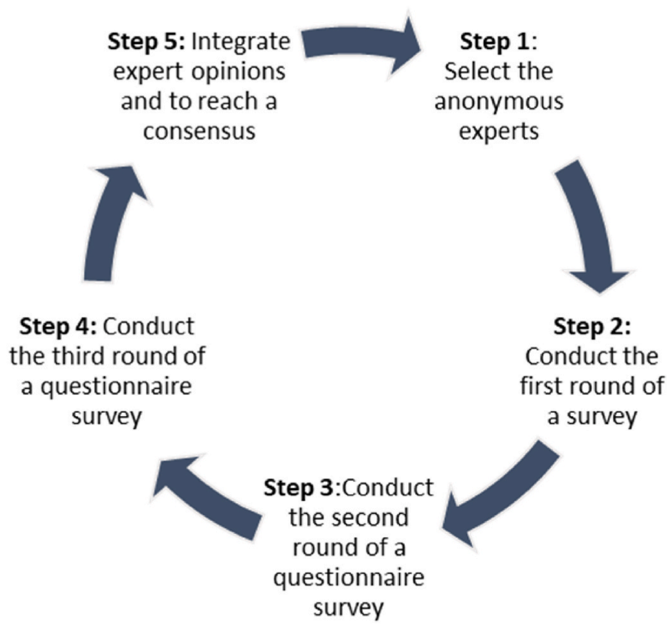

Fig. 2. The modified delphi method.

Modified Delphi method. Criteria importance weights obtained from IVN-AHP and IVN-TOPSIS are employed to rank fourteen districts in Istanbul according to their post-earthquake fire risk levels. Finally, the results are evaluated and discussed by sensitivity analysis. The steps of the proposed risk assessment methodology can be seen clearly in Fig. 1 and the levels of the proposed methodology are detailed theoretically in the following subsections.

2.1. Criteria determination

Post-earthquake fire risk assessment is a multi-dimensional and complicated decision-making problem type. The existence of many parameters to be considered makes the risk assessment process harder. To overcome this situation, we conduct a detailed literature review to identify the most appropriate criteria, especially for post-earthquake city fires. The candidate criteria obtained after this literature review are concluded in consultation with a group of experts. Five main criteria and nineteen sub-criteria are determined for risk assessment as seen in Table 1.

Leaks in Natural Gas and Other Gas Sources (C1): Gas leaks are one of the main causes of post-earthquake fires [1]. Deformations occurring in the pipelines due to the earthquake pose the risk of ignition and spread of fire [7]. Not only natural gas sources but also industrial gas sources are serious risk factors for post-earthquake fires. There are three sub-criteria depending on this main criterion. These are: Destroyed or Heavy Damaged Buildings Containing Natural Gas System (C11), Faults and Leaks in the Natural Gas Pipeline (C12), Leaks in Other Gases Used in Industrial Areas (C13).

Electricity Sources and Electrical Devices (C2): Like gas leaks, electricity sources are important risk factors, too. This risk may arise because of damages in buildings as well as because of damage to regional transformers and other electrical sources [17]. In this context, three sub-criteria are defined for electricity risk: Short Circuit and Leaks Occurring in Completely Collapsed Buildings (C21), Malfunctions in Regional Transformers and Power Plants (C22), Heavily Damaged Buildings Heated by Electricity in the Region (C23).

Internal Overturns Due to Shaking and Open Flame Sources (C3): Earthquakes can cause many topples within the buildings. Especially the overturning of open flame sources such as stoves, candles or heater is a big risk factor for post-earthquake fires [1]. However, the type of building material, and the average distances between buildings, which are critical to the growth and spread of the fire that started, should also be considered [3]. Here, population density is another sub-criterion that indirectly affects the risk of overturning and the number of cooking appliances [18]. Old and tall buildings have some disadvantages in terms of overturning due to shaking [19]. In this sense, five sub-criteria are determined as: Average Distance Between Buildings (C31), Building Height (C32), Building Material Type (C33), Number of Cooking Equipment in the Buildings (C34), Population Density (C35).

Chemicals and Flammable Sources (C4): Chemicals can be considered in the most dangerous group in terms of the area of impact they may cause. Post-eartquake ignition causes serious danger in case of splashes to chemical sources. Post-earthquake fire statistics show that chemicals are a serious risk group because of their flammability and rapid spread features [4]. For this reason, four sub-criteria are defined related with chemicals and flammable sources: Density of Chemical Facilities in the Region (K41), Universities or Colleges in the Region (C42), Pharmacies in the Region (C43) and Areas Containing Flammable Liquids (C44). Here; Universities or Colleges in the Region (C42) is added into risk assessment methodology as a sub-criterion because universities and colleges contain laboratories.

Risks Due to Delay of Intervention (C5): Timely and correct response to the fire can prevent the ignition from turning into a catastrophe [1]. Therefore, this main criterion is very important in terms of preventing spread, especially considering the limited transportation after the earthquake [20]. Four sub-criteria are defined as: Number of Firefighters Working in the Zone (C51), Faults in Water Supply Systems and Access to Resources (C52), Closed Roads Due to Completely Destroyed Buildings (C53), Fire Station Access Area (C54).

2.2. The Modified Delphi Method

The Delphi method accumulates and analyses the opinions achieved by a group of anonymous experts communicating on a particular topic in written, discussion, and feedback formats [26,27]. The method based on the sharing of knowledge, skills and ideas of the experts in the group until consensus is achieved [26,28–30]. Fig. 2 shows five main steps of the Modified Delphi method. Step 3 and Step 4 are repeated until a consensus is reached on a particular topic [31].

2.3. Neutrosophic sets and preliminaries

Many different approaches were developed to deal with uncertainty since the fuzzy theory is introduced to the literature by Zadeh [32]. Atanassov [33] presented intuitionistic fuzzy sets, which are generalization of fuzzy sets that take into account the memberships of truth and falsity. An intuitionistic fuzzy set is represented by the truth-membership function and the falsity-membership function. As a more advanced version of this approach, Smarandache [34] introduced the neutrosophic logic to handle ambiguity better. While fuzzy logic assigns uncertainty to membership variables between 0 and 1, neutrosophic logic introduces a new parameter called "uncertainty" and represents ambiguity better by carrying more information than fuzzy logic [35].

There are many studies with different variations of neutrosophic sets in the literature. Wang et al. defined the concept of a single-valued neutrosophic sets by taking the concept of neutrosophic sets from a technical point of view [36]. Thus, the neutrosophic sets, which are very useful in addressing ambiguity and uncertainty, are expanded in a strong formal framework. Single-valued neutrosophic sets are a subset of neutrosophic sets, which is a very convenient method of dealing with uncertainty and incomplete information. The necessity of taking precautions for ambiguous and incomplete information in decision-making process encourages some researchers to make different approaches. Ye proposed a new MCDM methodology based on the single-valued neutrosophic entropy, which is an extension of the cross-entropy of fuzzy sets. The supplier selection problem is solved with this novel methodology to show the applicability of the methodology [37]. Karaaslan and Hunu developed the concept of type-2 single-valued neutrosophic sets to solve the inadequacy of type-2 fuzzy and type-2 intuitionistic fuzzy sets in problems involving inconsistent data. Further, they propose some distance measurement approaches for type-2 single-valued neutrosophic sets [38]. Karaaslan and Hayat introduced new operations on two matrices by developing a single-valued neutrosophic matrix approach. In addition, they make real-life applications for a new MCDM method based on these operations [39].

Interval-valued neutrosophic sets are the other sub-set of neutrosophic sets and many types of incomplete or complete information can be included in the decision-making process using interval-valued neutrosophic sets. Aiwu et al. proposed improved aggregation rules for interval-valued neutrosophic sets and extended the generalized weighted aggregation (GWA) operator. It has been found that the proposed method preserves a lot of information and creates useful rankings for the comparative advantage matrix [40].

Karaşan et al. addressed the problem of determining and prioritizing solution alternatives in terms of sustainability for problems such as crowding and congestion, which are frequently encountered in cities, they suggest an integrated MCDM method consisting of AHP and TOPSIS under interval-valued neutrosophic environment [41]. Broumi & Smarandache defined the cosine similarity formula for interval-valued neutrosophic sets and provided a notation for use in the three-dimensional rector space. Cosine similarity is proved to be a more flexible, simple and effective method compared to the existing similarity approaches [42]. Similarly, Bolturk and Kahraman proposed IVN-AHP methodology based on cosine similarity measurement, and applied it to energy alternative selection problem and compared with similar approaches [16].

Simplified neutrosophic sets (SNNs), a subset of neutrosophic sets developed to deal with uncertainty, have been proposed to address problems with a set of specific numbers. However, SNSs have problems with some operators and comparison methods. In order to overcome these situations Peng et al. proposed new operators and comparison methods. Further, they also proposed a method for multi-criteria group decision making problems [43]. Ye introduced the concept of SNSs, a subclass of neutrosophic clusters, and defined the rules for operation of SNSs. A novel MCDM methodology was presented based on the cosine similarity measure while suggesting some addition and average operators [44].

When examining other extensions of neutrosophic sets in the literature, trapezoidal neutrosophic sets and refined neutrosophic sets are also used in many studies. Abdel Basset et al. presented a novel methodology that based on the integration of AHP into Delphi framework under the neutrosophic environment. They constructed the pairwise comparison matrix using trapezoidal neutrosophic numbers. The proposed new method was tested with real life data and its validity was demonstrated [45]. Similar studies with trapezoidal neutrosophic numbers was performed by Biswas et al. [46] and by Jana et al. [47] for multi attribute decision making problems. Gaussian Single-valued neutrosophic number (GSVNN) was proposed by Karaaslan as another generalization of neutrosophic sets [48]. With this method, it was aimed to improve the performance of traditional single valued neutrosophic sets to handle insufficient information and reflect uncertainty, while arithmetic operators for GSVNN were defined. Smarandache expanded the neutrosophic sets into a refined neutrosophic set and an improved neutrosophic logic and probability. The accuracy value T in neutrosophic sets; similarly, I and F are refined while dividing T1, T2 into subordinate types of accuracy, and a more detailed approach to uncertainty was introduced [49]. Gülistan et al. proposed the concept of neutrosophic cubic number improved generalized weighted Heronian mean operators and neutrosophic cubic number improved generalized weighted geometric Heronian mean operators [50]. Karaaslan introduce Cosine, Dice, Jaccard similarity measures for single and interval valued neutrosophic refined sets [51].

As can be seen in aforementioned studies, neutrosophic sets were employed in many studies to handle different problems that contain ambiguities. Neutrosophic sets is one of the most powerful sets to reflect the ambiguous, fuzziness and indeterminacy information in the decision making processes. Compared to fuzzy sets, neutrosophic sets provide a more advantageous and flexible tool in addressing uncertainty and indeterminacy in decision making problems. Especially in decision problems where opinions from experts are taken into consideration and linguistic evaluations are made, it gives decision-makers more freedom to express their opinions with incomplete and inconsistent information on uncertainty. Because neutrosophic sets is characterized by a truth-membership, an indeterminacy-membership, and a falsity-membership [52], while fuzzy sets focus only on membership and non-membership functions and it does not consider the indeterminacy [53]. Using neutrosophic sets in decision making problems as an effective approach to solve complex decision-making problems, especially when problems contain uncertainties and indeterminacy [54].

For the post-earthquake fire risk addressed in this study, there are many ambiguities that arise both in the nature of the problem and in the reflection of decision-makers' thoughts. In order to avoid these ambiguities, neutrosophic numbers are preferred to transfer human thoughts to mathematical expressions better. As far as we know, there is no study involving the hybridization of modified Delphi with AHP and TOPSIS methods for neutrosophic sets and their application in the risk assessment problem. The problem of post-earthquake fire risk assessment, which is an important problem regarding cities, is an issue that has not been discussed frequently in the literature before, and is increasingly important with the latest concerns in the world. Apart from mathematical modeling, which is the approach frequently used for risk assessment problems, we believe that this real-life study, which is developed by considering many conflicting criteria to evaluate different districts, will add innovation to the literature.

In this section, general information about neutrosophic sets and interval-valued neutrosophic numbers are presented. Here, $\tilde{\ddot{A}}$ shows a neutrosophic set defined in E and represented by truth-membership function T, indeterminacy-membership function I and falsity membership function F [55].

Definition 1. Let E be a universe. A neutrosophic set $\tilde{\ddot{A}}$ in E is characterized by a truth-membership function T_A, a indeterminacy-membership function I_A, and a falsity-membership function F_A [16,56].

$T_A\ (x)$, $I_A\ (x)$ *and* $F_A\ (x)$ are real standard elements of $]^-0,1[^+$.A neutrosophic set $\ddot{A}$ can be given by Equation (2.1):

$$\tilde{\ddot{A}} = \{x, (T_A\ (x), I_A\ (x),\ F_A\ (x))\ >\ : x\ \varepsilon\ E, (T_A\ (x), I_A\ (x),\ F_A\ (x)\ \varepsilon\ ]^-0, 1\ [^+)\} \tag{2.1}$$

There is no restriction on the sum of $T_A\ (x), I_A\ (x)$ *and* $F_A\ (x)$, so that $0^-\ \le\ T_A\ (x) +\ I_A\ (x) + ,\ F_A\ (x)\ \le\ 3^+$.

Definition 2. An interval valued neutrosophic set $\tilde{\ddot{N}}$ in E characterized by a truth-membership function $T_N(x)$ an indeterminacy-membership function $I_N(x)$ and a falsity-membership function $F_N(x)$ [41].

$$T_N(x) = \left[T_N^L(x), T_N^U(x)\right] \subseteq [0,1] \tag{2.2}$$

$$I_N(x) = \left[I_N^L(x), I_N^U(x)\right] \subseteq [0,1] \tag{2.3}$$

$$F_N(x) = \left[F_N^L(x), F_N^U(x)\right] \subseteq [0,1] \tag{2.4}$$

Thus $\tilde{\ddot{N}}$ can be presented as below:

$$\tilde{\ddot{N}} = \left\{\ x,\ \left[T_N^L(x), T_N^U(x)\right],\ \left[I_N^L(x), I_N^U(x)\right], \left[F_N^L(x), F_N^U(x)\right]\ x\varepsilon E\right\} \tag{2.5}$$

Definition 3. For deneutrosophication an interval valued neutrosophic number, Equation (2.6) can be used which is proposed by Bolturk et al. [55].

$$\mathfrak{D}(x) = \left(\frac{\left(T_N^L(x) + T_N^U(x)\right)}{2} + \left(I_N^U(x)\right)\left(1 - \frac{\left(I_N^L(x) + I_N^U(x)\right)}{2}\right) - \left(1 - F_N^U(x)\right)\left(\frac{F_N^L(x) + F_N^U(x)}{2}\right)\right) \tag{2.6}$$

where; $\tilde{\tilde{x}}_j = [T_x^L, T_x^U], [I_x^L, I_x^U], [F_x^L, F_x^U]$

Definition 4. Let $\widetilde{\dddot{N}}_1 = [T_{N_1}^L, T_{N_1}^U], [I_{N_1}^L, I_{N_1}^U], [F_{N_1}^L, F_{N_1}^U]$and $\widetilde{\dddot{N}}_2 = [T_{N_2}^L, T_{N_2}^U], [I_{N_2}^L, I_{N_2}^U], [F_{N_2}^L, F_{N_2}^U]$ be two interval valued neutrosophic numbers. For those two numbers some basic operations are given by Equations (2.8) – (2.15) [16,35,41,57]:

$$\widetilde{\dddot{N}}_1^{\,c} = \left[F_{N_1}^L, F_{N_1}^U\right], \left[1 - I_{N_1}^U, 1 - I_{N_1}^L\right], \left[T_{N_1}^L, T_{N_1}^U\right] \tag{2.7}$$

where $\widetilde{\dddot{N}}_1^{\,c}$ represents the complement of $\widetilde{\dddot{N}}_1$.

$$\lambda\left(\widetilde{\dddot{N}}_1\right) = \left[1 - \left(1 - T_{N_1}^L\right)^\lambda, 1 - \left(1 - T_{N_1}^U\right)^\lambda\right], \left[\left(I_{N_1}^L\right)^\lambda, \left(I_{N_1}^U\right)^\lambda\right], \left[\left(F_{N_1}^L\right)^\lambda, \left(F_{N_1}^U\right)^\lambda\right], \lambda > 0 \tag{2.8}$$

$$\left(\widetilde{\dddot{N}}_1\right)^\lambda = \left[\left(T_{N_1}^L\right)^\lambda, \left(T_{N_1}^U\right)^\lambda\right], \left[\left(I_{N_1}^L\right)^\lambda, \left(I_{N_1}^U\right)^\lambda\right], \left[1 - \left(1 - F_{N_1}^L\right)^\lambda, 1 - \left(1 - F_{N_1}^U\right)^\lambda\right], \lambda > 0 \tag{2.9}$$

$$\widetilde{\dddot{N}}_1 \subseteq \widetilde{\dddot{N}}_2 \text{ if and only if } T_{N_1}^L \leq T_{N_2}^L, T_{N_1}^U \leq T_{N_2}^U, I_{N_1}^L \geq I_{N_2}^L, I_{N_1}^U \geq I_{N_2}^U, F_{N_1}^L \geq F_{N_2}^L, F_{N_1}^U \geq F_{N_2}^U \tag{2.10}$$

$$\widetilde{\dddot{N}}_1 = \widetilde{\dddot{N}}_2 \text{ if and only if } \widetilde{\dddot{N}}_1 \subseteq \widetilde{\dddot{N}}_2 \text{ and } \widetilde{\dddot{N}}_2 \subseteq \widetilde{\dddot{N}}_1 \tag{2.11}$$

Definition 5. Let $\widetilde{\dddot{N}}_1 = [T_{N_1}^L, T_{N_1}^U], [I_{N_1}^L, I_{N_1}^U], [F_{N_1}^L, F_{N_1}^U]$is an interval valued neutrosophic number. A score function of $\widetilde{\dddot{N}}_1$ is given as follows [57]:

$$\widetilde{\dddot{N}}_1 \oplus \widetilde{\dddot{N}}_2 = \left[T_{N_1}^L + T_{N_2}^L - T_{N_1}^L T_{N_2}^L, T_{N_1}^U + T_{N_2}^U - T_{N_1}^U T_{N_2}^U\right], \left[I_{N_1}^L I_{N_2}^L, I_{N_1}^U I_{N_2}^U\right], \left[F_{N_1}^L F_{N_2}^L, F_{N_1}^U F_{N_2}^U\right] \tag{2.12}$$

$$\widetilde{\dddot{N}}_1 \otimes \widetilde{\dddot{N}}_2 = \left[T_{N_1}^L T_{N_2}^L, T_{N_1}^U T_{N_2}^U\right], \left[I_{N_1}^L + I_{N_2}^L - I_{N_1}^L T_{N_2}^L, I_{N_1}^U + I_{N_2}^U - I_{N_1}^U I_{N_2}^U\right], \left[F_{N_1}^L + F_{N_2}^L - F_{N_1}^L F_{N_2}^L, F_{N_1}^U + F_{N_2}^U - F_{N_1}^U F_{N_2}^U\right] \tag{2.13}$$

$$\widetilde{\dddot{N}}_1 \ominus \widetilde{\dddot{N}}_2 = \left[T_{N_1}^L - F_{N_2}^U, T_{N_1}^U - F_{N_2}^L\right], \left[max\left(I_{N_1}^L, I_{N_2}^L\right), max\left(I_{N_1}^U, I_{N_2}^U\right)\right], \left[F_{N_1}^L - T_{N_2}^U, F_{N_1}^U - T_{N_2}^L\right] \tag{2.14}$$

$$S\left(\widetilde{\dddot{N}}_1\right) = \frac{\left(2 + T_{N_1}^L - I_{N_1}^L - F_{N_1}^L\right) + \left(2 + T_{N_1}^U - I_{N_1}^U - F_{N_1}^U\right)}{6} \tag{2.15}$$

where $S(\widetilde{\dddot{N}}_1) \in [0, 1]$.

Definition 6. Let $\widetilde{\dddot{N}}_1 = [T_{N_1}^L, T_{N_1}^U], [I_{N_1}^L, I_{N_1}^U], [F_{N_1}^L, F_{N_1}^U]$is an interval valued neutrosophic number. An accuracy function of $\widetilde{\dddot{N}}_1$ is given as follows [57]:

$$H\left(\widetilde{\dddot{N}}_1\right) = \frac{\left(T_{N_1}^L + T_{N_1}^U\right) - \left(F_{N_1}^L + F_{N_1}^U\right)}{2} \tag{2.16}$$

where $H(\widetilde{\dddot{N}}_1) \in [-1, 1]$.

Now, based on these two functions, a comparison method for any interval valued neutrosophic numbers $\widetilde{\dddot{N}}_1$ and $\widetilde{\dddot{N}}_2$ is defined as given in Definition 7:

Definition 7. Let $\widetilde{\dddot{N}}_1$ and $\widetilde{\dddot{N}}_2$ any interval valued neutrosophic numbers. Then [58];

$$\text{i. If } S\left(\widetilde{\dddot{N}}_1\right) < S\left(\widetilde{\dddot{N}}_2\right), \text{ then } \widetilde{\dddot{N}}_1 < \widetilde{\dddot{N}}_2 \tag{2.17}$$

$$\text{ii. If } S\left(\widetilde{\dddot{N}}_1\right) > S\left(\widetilde{\dddot{N}}_2\right), \text{ then } \widetilde{\dddot{N}}_1 < \widetilde{\dddot{N}}_2 \tag{2.18}$$

$$\text{iii. If } S\left(\widetilde{\dddot{N}}_1\right) = S\left(\widetilde{\dddot{N}}_2\right), \tag{2.19}$$

$$\text{a. If } H\left(\widetilde{\dddot{N}}_1\right) < S\left(\widetilde{\dddot{N}}_2\right), \text{ then } \widetilde{\dddot{N}}_1 < \widetilde{\dddot{N}}_2 \tag{2.20}$$

Table 2
Definition and IVN scales of the linguistic variables.

Linguistic Variables	T^L	T^U	I^L	I^U	F^L	F^U
Equal Importance (EI)	0.5	0.5	0.5	0.5	0.5	0.5
Weakly More Importance (WMI)	0.5	0.6	0.35	0.45	0.4	0.5
Moderate Importance (MI)	0.55	0.65	0.3	0.4	0.35	0.45
Moderately More Importance (MMI)	0.6	0.7	0.25	0.35	0.3	0.4
Strong Importance (SI)	0.65	0.75	0.2	0.3	0.25	0.35
Strongly More Importance (SMI)	0.7	0.8	0.15	0.25	0.2	0.3
Very Strong Importance (VSI)	0.75	0.85	0.1	0.2	0.15	0.25
Very Strongly More Importance (VSMI)	0.8	0.9	0.05	0.1	0.1	0.2
Extreme Importance (EI)	0.9	0.95	0	0.05	0.05	0.15
Extremely High Importance (EHI)	0.95	1	0	0	0	0.1
Absolutely More Importance (AMI)	1	1	0	0	0	0

Table 3
Pairwise comparison of the main criteria.

	C1	C2	C3	C4	C5
C1	EI	MI	MMI	SI^C	SI
C2	MI^C	EI	MMI	SI^C	SI
C3	MMI^C	MMI^C	EI	EI	MMI
C4	SI	SI	VSMI	EI	EHI
C5	SI^C	SI^C	MMI^C	EHI^C	EI

b. If $H\left(\widetilde{\dddot{N}}_1\right) > S\left(\widetilde{\dddot{N}}_2\right)$, *then* $\widetilde{\dddot{N}}_1 < \widetilde{\dddot{N}}_2$ (2.21)

c. If $H\left(\widetilde{\dddot{N}}_1\right) = S\left(\widetilde{\dddot{N}}_2\right)$, *then* $\widetilde{\dddot{N}}_1 < \widetilde{\dddot{N}}_2$ (2.22)

Definition 8. Hamming distance between two interval valued neutrosophic numbers $\widetilde{\dddot{N}}_1$ and $\widetilde{\dddot{N}}_2$ is calculated [59]:

$$d\left(\widetilde{\dddot{N}}_1, \widetilde{\dddot{N}}_2\right) = \frac{\left(\left|T^L_{N_1} - T^L_{N_2}\right| + \left|T^U_{N_1} - T^U_{N_2}\right| + \left|I^L_{N_1} - I^L_{N_2}\right| + \left|I^U_{N_1} - I^U_{N_2}\right| + \left|F^L_{N_1} - F^L_{N_2}\right| + \left|F^U_{N_1} - F^U_{N_2}\right|\right)}{6} \tag{2.23}$$

Definition 9. Euclidian distance between two interval valued neutrosophic numbers $\widetilde{\dddot{N}}_1$ and $\widetilde{\dddot{N}}_2$ is calculated [59]:

$$d\left(\widetilde{\dddot{N}}_1, \widetilde{\dddot{N}}_2\right) = \sqrt{\frac{\left(T^L_{N_1} - T^L_{N_2}\right)^2 + \left(T^U_{N_1} - T^U_{N_2}\right)^2 + \left(I^L_{N_1} - I^L_{N_2}\right)^2 + \left(I^U_{N_1} - I^U_{N_2}\right)^2 + \left(F^L_{N_1} - F^L_{N_2}\right)^2 + +\left(F^U_{N_1} - F^U_{N_2}\right)^2}{6}} \tag{2.24}$$

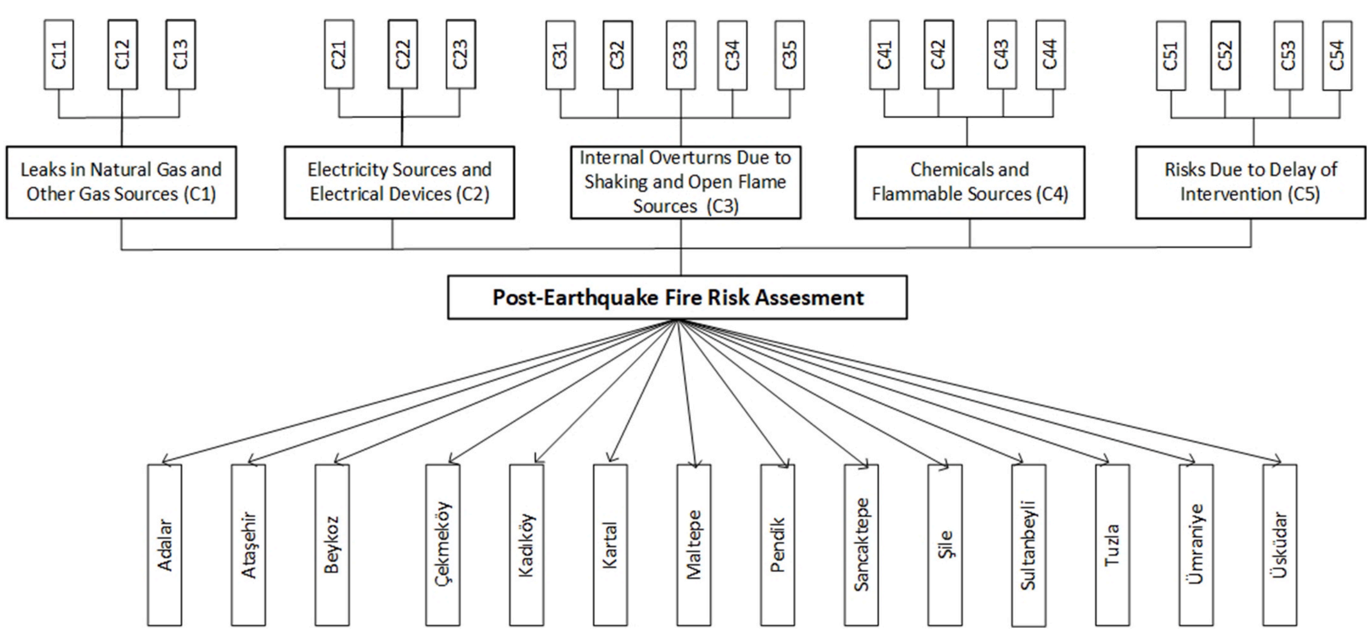

Fig. 3. Hierarchical structure of the post-earthquake fire risk assessment problem.

2.4. Interval-valued neutrosophic Analytical Hierarchy Process

AHP method, whose foundations were laid by Myers and Alpert [60] and developed and systematized by Thomas Saaty in the 1970s and brought to the literature by systematization, is based on the logic of structuring a problem in hierarchies and then evaluating the components in the hierarchy through pairwise comparisons [61]. Although AHP is a frequently used method in MCDM problems, it sometimes fails to reflect human thought. Unlike classical AHP, IVN-AHP can strongly express uncertainty with three variables (T, I and F) and integrate human thought into the decision-making process effectively. Neutrosophic AHP and IVN-AHP methodology were used in different studies such as [45,55,62]. In this study, the weights of the criteria affecting the fire risk after the earthquake are calculated by using IVN-AHP methodology. The steps of IVN-AHP is given below:

Step 1: Construct the problem in a hierarchical structure as main criteria and sub-criteria.

Step 2: Construct the pairwise comparison matrix $(\widetilde{\dddot{P}})$ by using interval-valued neutrosophic values. To check the consistency, the pairwise comparison matrix is deneutrosophicated with the help of Equation (2.6). If the deneutrosophicated pairwise comparison matrix is consistent, it can be said that the neutrosophic pairwise matrix is also consistent. The pairwise comparison matrices of criteria are given in Equation (2.25).

Step 5: All the above steps are repeated for each sub-criteria, and neutrosophic weights of the criteria are obtained.

Step 6: In order to obtain the crisp weights of the criteria, the deneutrosophication formula in Equation (2.6) is used.

2.5. Interval-valued neutrosophic TOPSIS

TOPSIS method is introduced to the literature by Hwang [64]. This method is based on the assumption that the best alternative is the closest to the positive ideal solution and the furthest to the negative ideal solution [65]. The classical TOPSIS method, like other MCDM methods, is used with many different types of fuzzy approaches to deal with uncertainty. In this study, IVN-TOPSIS method, which is an integrated version of Broumi et al. [66] and Biswas et al. [67] approaches, proposed by Karasan et al. [41] is used. After the criterion weights are calculated by IVN-AHP method, the districts are ranked in terms of post-earthquake fire risk by IVN-TOPSIS.

Step 1: The consensus neutrosophic ***decision*** matrix $(\widetilde{\dddot{X}})$ is created with the help of Modified Delphi method. Where $\widetilde{x}_{ij} = [T^L_{ij}, T^U_{ij}], [I^L_{ij}, I^U_{ij}], [F^L_{ij}, F^U_{ij}]$ shows the aggregated neutrosophic score of ith alternative with respect to jth criterion.

Step 2: Calculate the neutrosophic weighted normalized decision matrix $(\widetilde{\dddot{R}})$ by using Neutrosophic weight $(\widetilde{w}_j)$ for each criterion deter-

$$\widetilde{\dddot{P}} = \begin{bmatrix} [T^L_{11}, T^U_{11}], [I^L_{11}, I^U_{11}], [F^L_{11}, F^U_{11}] & [T^L_{12}, T^U_{12}], [I^L_{12}, I^U_{12}], [F^L_{12}, F^U_{12}] & \cdots & [T^L_{1n}, T^U_{1n}], [I^L_{1n}, I^U_{1n}], [F^L_{1n}, F^U_{1n}] \\ [T^L_{21}, T^U_{21}], [I^L_{21}, I^U_{21}], [F^L_{21}, F^U_{21}] & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ [T^L_{n1}, T^U_{n1}], [I^L_{n1}, I^U_{n1}], [F^L_{n1}, F^U_{n1}] & \cdots & \cdots & [T^L_{nn}, T^U_{nn}], [I^L_{nn}, I^U_{nn}], [F^L_{nn}, F^U_{nn}] \end{bmatrix} \tag{2.25}$$

Step 3: The importance weights of the criteria are normalized to make them comparable data and thus to rate and rank criteria [63].

mined by IVN-AHP.

Step 3: The interval valued neutrosophic positive ideal solution (IVNPIS) ;$\widetilde{\dddot{S}}^{+}$ and the interval valued neutrosophic negative ideal so-

$$\widetilde{\dddot{N}}_{ij} = \left[\frac{T^L_{kj}}{\sum_{k=1}^{n} T^U_{kj}}, \frac{T^U_{kj}}{\sum_{k=1}^{n} T^L_{kj}}\right], \left[\frac{I^L_{kj}}{\sum_{k=1}^{n} I^U_{kj}}, \frac{I^U_{kj}}{\sum_{k=1}^{n} I^L_{kj}}\right], \left[\frac{F^L_{kj}}{\sum_{k=1}^{n} F^U_{kj}}, \frac{F^U_{kj}}{\sum_{k=1}^{n} F^L_{kj}}\right] ; j = 1, 2, \ldots, n \tag{2.26}$$

Step 4: The arithmetic mean of each row is calculated to obtain the neutrosophic importance weight vector of the criteria by Equation (2.27).

lution (IVNNIS) $\widetilde{\dddot{S}}^{-}$ are calculated using Equations (2.28) and (2).29) to use in determining from ideal solutions, respectively.

$$\widetilde{\dddot{W}}_j = \left[\frac{\sum_{k=1}^{n} \frac{T^L_{1j}}{\sum_{k=1}^{n} T^U_{kj}}}{n}, \frac{\sum_{k=1}^{n} \frac{T^U_{1j}}{\sum_{k=1}^{n} T^L_{kj}}}{n}\right], \left[\frac{\sum_{k=1}^{n} \frac{I^L_{1j}}{\sum_{k=1}^{n} I^U_{kj}}}{n}, \frac{\sum_{k=1}^{n} \frac{I^U_{1j}}{\sum_{k=1}^{n} I^L_{kj}}}{n}\right], \left[\frac{\sum_{k=1}^{n} \frac{F^L_{1j}}{\sum_{k=1}^{n} F^U_{kj}}}{n}, \frac{\sum_{k=1}^{n} \frac{F^U_{1j}}{\sum_{k=1}^{n} F^L_{kj}}}{n}\right] \tag{2.27}$$

Table 4
Pairwise comparison matrix for Leaks in Natural Gas and Other Gas Sources (C1).

	C11	C12	C13
C11	EI	SI^C	MI
C12	SI	EI	VSI
C13	MI^C	VSI^C	EI

Table 5
Pairwise comparison matrix for Electricity Sources and Electrical Devices (C2).

	C21	C22	C23
C21	EI	MI^C	MI^C
C22	SI	EI	MMI
C23	MI	MMI^C	EI

Table 6
Pairwise comparison matrix for Internal Overturns Due to Shaking and Open Flame Sources (C3).

	C31	C32	C33	C34	C35
C31	EI	WMI	SI^C	MI^C	MI
C32	WMI^C	EI	VSI^C	MMI^C	WMI
C33	SI	VSI	EI	MMI	EXI
C34	MI	MMI	MMI^C	EI	VSI
C35	MI^C	WMI^C	EXI^C	VSI^C	EI

Table 7
Pairwise comparison matrix Chemicals and Flammable Sources (C4).

	C41	C42	C43	C44
C41	EI	VSI	SI	MMI
C42	VSI^C	EI	MI^C	SI^C
C43	SI^C	MI	EI	MMI^C
C44	MMI^C	SI	MMI	EI

Table 8
Pairwise comparison matrix for Risks Due to Delay of Intervention (C5).

	C51	C52	C53	C54
C51	EI	MMI^C	SMI^C	MMI^C
C52	MMI	EI	MMI^C	MI
C53	SMI	MMI	EI	SI
C54	MMI	MI^C	SI^C	EI

$$\widetilde{\dddot{S}}^{+}=\left[\max_j\left(T_j^L\right),\max_j\left(T_j^U\right)\right],\left[\min_j\left(I_j^L\right),\min_j\left(I_j^U\right)\right],\left[\min_j\left(F_j^L\right),\min_j\left(F_j^U\right)\right] \tag{2.28}$$

$$\widetilde{\dddot{S}}^{-}=\left[\min_j\left(T_j^L\right),\min_j\left(T_j^U\right)\right],\left[\max_j\left(I_j^L\right),\max_j\left(I_j^U\right)\right],\left[\max_j\left(F_j^L\right),\max_j\left(F_j^U\right)\right] \tag{2.29}$$

Step 4: The Euclidean distances of the alternatives from positive ideal solution (D_i^{PIS}) and negative ideal solution (D_i^{NIS})are calculated with the help of Equation (2.24) [65]..

Step 5: Compute revised closeness for each alternative (ε_i) by using Equation (2.30).

$$\varepsilon_i=\frac{D_i^{NIS}}{\left(D_i^{NIS}+D_i^{PIS}\right)} \tag{2.30}$$

Step 6: Rank the alternatives according to their revised closeness (greater is more risky).

3. Numerical application for anatolian side of istanbul

In this study, we focus on the problem of determining the weights of the criteria affecting the fire risk after an earthquake and ranking the Anatolian side districts of Istanbul according to the post-earthquake fire risk. Istanbul is located very close to the North Anatolian Fault Line connecting to the Marmara Sea from Izmit Gulf and is in the second-degree earthquake zone [68]. The researches carried out revealed the intensity of seismic activity and broken zones in the Marmara Sea and its surroundings, revealed that the Marmara Region is highly risky in terms of earthquakes and the severity of the damage to be experienced in a possible earthquake [69,70]. Since a possible earthquake disaster will bring fire risks with it, it is very important to analyze Istanbul in terms of post-earthquake fire risks. Therefore, Anatolian side of Istanbul province has been chosen for the numerical application of the proposed method.

The data used in this study were obtained from the reports of the "Istanbul Probable Earthquake Loss Estimates Update Project" published by the Istanbul Earthquake and Ground Investigation Directorate in June 2020 [71]. In this sense, it offers a real application for the fire risks of Istanbul after an earthquake.

Firstly, the literature is reviewed to determine the post-earthquake fire risk criteria. Then, the importance weights of each criterion for post-earthquake fire risk are obtained by using the IVN-AHP. In order to calculate the post-earthquake fire risk of fourteen districts located on the Anatolian side of Istanbul, the opinions from six experts are collected. These experts are selected from among experienced people who conducted academic research on earthquake and post-earthquake fire risks. In addition, while the majority of experts are competent in the seismic

Table 9
Pairwise comparison matrix for main criteria by interval-valued neutrosophic values.

—	C1						C2						C3					
	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U
C1	0.5	0.5	0.5	0.5	0.5	0.5	0.55	0.65	0.3	0.4	0.35	0.45	0.6	0.7	0.25	0.35	0.3	0.4
C2	0.35	0.45	0.6	0.7	0.55	0.65	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.25	0.35	0.3	0.4
C3	0.3	0.4	0.65	0.75	0.6	0.7	0.3	0.4	0.65	0.75	0.6	0.7	0.5	0.5	0.5	0.5	0.5	0.5
C4	0.65	0.75	0.2	0.3	0.25	0.35	0.65	0.75	0.2	0.3	0.25	0.35	0.8	0.9	0.05	0.1	0.1	0.2
C5	0.25	0.35	0.7	0.8	0.65	0.75	0.25	0.35	0.7	0.8	0.65	0.75	0.3	0.4	0.65	0.75	0.6	0.7

	C4						C5					
	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U
C1	0.25	0.35	0.7	0.8	0.65	0.75	0.65	0.75	0.2	0.3	0.25	0.35
C2	0.25	0.35	0.7	0.8	0.65	0.75	0.65	0.75	0.2	0.3	0.25	0.35
C3	0.1	0.2	0.9	0.95	0.8	0.9	0.6	0.7	0.25	0.35	0.3	0.4
C4	0.5	0.5	0.5	0.5	0.5	0.5	0.95	1	0	0	0	0.1
C5	0	0.1	1	1	0.95	1	0.5	0.5	0.5	0.5	0.5	0.5

Table 10
The normalized values of the pairwise comparison matrix for main criteria.

—	C1						C2						C3					
	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U
C1	0.20	0.20	0.16	0.16	0.17	0.17	0.21	0.25	0.11	0.15	0.13	0.16	0.19	0.22	0.12	0.17	0.14	0.18
C2	0.14	0.18	0.20	0.23	0.19	0.22	0.19	0.19	0.18	0.18	0.18	0.18	0.19	0.22	0.12	0.17	0.14	0.18
C3	0.12	0.16	0.21	0.25	0.20	0.24	0.11	0.15	0.24	0.27	0.22	0.25	0.16	0.16	0.24	0.24	0.23	0.23
C4	0.27	0.31	0.07	0.10	0.08	0.12	0.25	0.28	0.07	0.11	0.09	0.13	0.25	0.28	0.02	0.05	0.05	0.09
C5	0.10	0.14	0.23	0.26	0.22	0.25	0.09	0.13	0.25	0.29	0.24	0.27	0.09	0.13	0.32	0.37	0.27	0.32
	C4						**C5**											
	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U						
C1	0.17	0.23	0.17	0.20	0.17	0.19	0.18	0.20	0.14	0.21	0.15	0.21						
C2	0.17	0.23	0.17	0.20	0.17	0.19	0.18	0.20	0.14	0.21	0.15	0.21						
C3	0.07	0.13	0.22	0.23	0.21	0.23	0.16	0.19	0.17	0.24	0.18	0.24						
C4	0.33	0.33	0.12	0.12	0.13	0.13	0.26	0.27	0.00	0.00	0.00	0.06						
C5	0.00	0.07	0.25	0.25	0.24	0.26	0.14	0.14	0.34	0.34	0.29	0.29						

structure of the city of Istanbul and earthquake risks, there are also two people in the group who are competent in the field of fire and fire risks especially.

Face-to-face interviews are held with the experts. In addition, by applying Modified Delphi method, the questionnaires are answered by experts. IVN-TOPSIS method is applied after the importance weights of the criteria are calculated. The experts score fourteen districts according to the relevant criteria, and then the districts are ranked from the most risky one to the least for post-earthquake fire by IVN-TOPSIS. The methodology structure and results are analysed in detail by sensitivity analysis.

3.1. Determination of the criteria weights

The criteria, given in Table 1 and explained in Section 3.1, are evaluated by a team of six experts using the Modified Delphi method to construct pairwise comparison matrix. All experts are accepted with an equal coefficient in the evaluation process. The interval valued neutrosophic scale shown in Table 2 is used for this evaluation [41].

The symmetrical equivalents of linguistic evaluations in pairwise comparison matrices are calculated with the help of Equation (2. 8). For example, symmetrical equivalents of Strongly Importance (SI) linguistic variable can be calculated as follows:

SI = [0.65, 0.75], [0.2, 0.3], [0.25, 0.35].

SI^c = [0.25, 0.35], [1–0.3, 1–0.2], [0.75, 0.65] = [0.25, 0.35], [0.7, 0.8], [0.25, 0.35].

Step 1: The problem is constructed in a hierarchical structure of criteria and sub-criteria as given in Fig. 3.

Step 2: Pairwise comparison matrices are constructed by consolidating the evaluations gained from the experts using linguistic variables given in Table 2. The consensus of all experts on the evaluation matrices and pairwise comparison matrix for the main criteria is given in Table 3.

Then, the pairwise comparison matrices for each main criteria is created by opinions. Tables 4–8 give the sub criteria pairwise comparison matrices for the *Leaks in Natural Gas and Other Gas Sources (C1)*, *Electricity Sources and Electrical Devices (C2)*, *Internal Overturns Due to Shaking and Open Flame Sources (C3)*, *Chemicals and Flammable Sources (C4)* and *Risks Due to Delay of Intervention (C5)*, respectively.

The linguistic terms are converted the interval-valued neutrosophic values to construct pairwise comparison matrices $\widetilde{(\dddot{P})}$ according to Table 2. Table 9 gives the pairwise comparison matrices $\widetilde{(\dddot{P})}$ by using

Table 11
IVN importance weights for main criteria.

Main Criteria	T^L	T^U	I^L	I^U	F^L	F^U
C1	0.18829	0.22083	0.14115	0.17691	0.14937	0.18263
C2	0.17227	0.20543	0.16225	0.19729	0.16367	0.19643
C3	0.12415	0.15859	0.21760	0.24769	0.20609	0.23703
C4	0.27013	0.29479	0.05723	0.07594	0.06986	0.10477
C5	0.08505	0.12034	0.27857	0.30216	0.25342	0.27913

Table 12
IVN importance weights for sub-criteria.

Sub-Criteria	T^L	T^U	I^L	I^U	F^L	F^U
C11	0.26546	0.31243	0.38081	0.35353	0.31158	0.35516
C12	0.40396	0.44024	0.15050	0.20303	0.17658	0.22658
C13	0.19741	0.24732	0.40601	0.44343	0.38016	0.41825
C21	0.24484	0.28974	0.37048	0.40908	0.34558	0.38510
C22	0.35870	0.39645	0.19479	0.24407	0.21871	0.26585
C23	0.21157	0.31381	0.30197	0.34684	0.30538	0.34903
C31	0.15855	0.19135	0.18222	0.21533	0.18276	0.21424
C32	0.13225	0.16572	0.21453	0.24618	0.20561	0.23605
C33	0.25672	0.28159	0.06593	0.09557	0.08437	0.11836
C34	0.19879	0.22991	0.12345	0.15815	0.13459	0.16747
C35	0.09723	0.13141	0.25882	0.28475	0.23802	0.26387
C41	0.29615	0.32847	0.11330	0.15508	0.13364	0.17357
C42	0.13896	0.17887	0.31108	0.34348	0.28913	0.32185
C43	0.18221	0.22079	0.24817	0.28492	0.24411	0.27980
C44	0.23569	0.27187	0.17666	0.21651	0.18656	0.22477
C51	0.14775	0.18694	0.30485	0.33716	0.28343	0.31613
C52	0.22470	0.26096	0.19195	0.23063	0.20072	0.23794
C53	0.28928	0.32160	0.12178	0.16271	0.14129	0.18052
C54	0.19291	0.23049	0.23277	0.2695	0.22958	0.26540

Table 13
Local and global crisp weights for each criteria.

Main Criteria	Weight	Sub-Criteria	Local Weight	Global Weight
Leaks in Natural Gas and Other Gas Sources (C1)	**0.2207**	C11	0.314	0.0693
		C12	0.438	0.0967
		C13	0.248	0.0547
Electricity Sources and Electrical Devices (C2)	**0.2089**	C21	0.2933	0.0613
		C22	0.3916	0.0817
		C23	0.3151	0.0659
Internal Overturns Due to Shaking and Open Flame Sources (C3)	**0.1646**	C31	0.1934	0.0318
		C32	0.1714	0.0283
		C33	0.2702	0.0445
		C34	0.2268	0.0373
		C35	0.1382	0.0227
Chemicals and Flammable Sources (C4)	**0.279**	C41	0.3221	0.0898
		C42	0.1842	0.0514
		C43	0.2235	0.0624
		C44	0.2702	0.0754
Risks Due to Delay of Intervention (C5)	**0.1268**	C51	0.1925	0.0244
		C52	0.2592	0.033
		C53	0.3151	0.0399
		C54	0.2332	0.0295

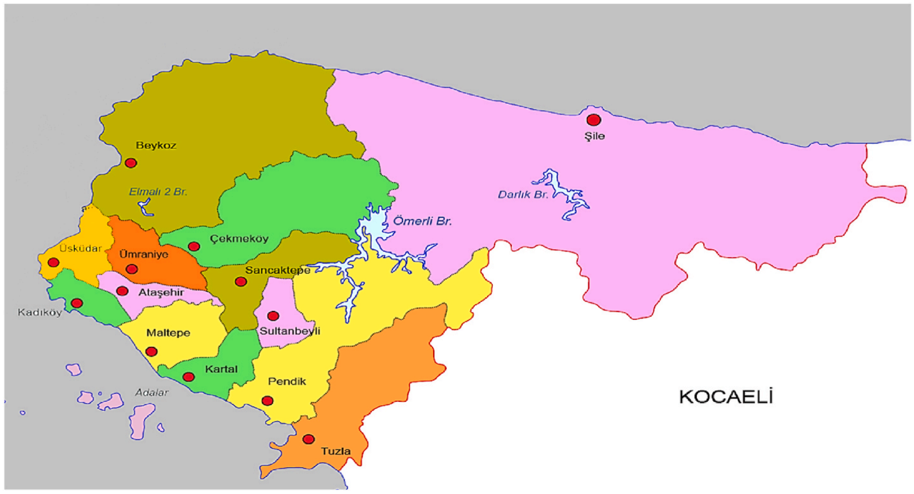

Fig. 4. The districts of the Anatolian side of İstanbul.

Table 14
Scale for scoring decision matrix.

Linguistic Variables	T^L	T^U	I^L	I^U	F^L	F^U
Certainly Low (CL)	0.05	0.2	0.4	0.6	0.85	1
Very Low (VL)	0.15	0.3	0.3	0.5	0.75	0.9
Low (L)	0.25	0.4	0.2	0.4	0.65	0.8
Below Average (BA)	0.35	0.5	0.1	0.3	0.55	0.7
Average (A)	0.45	0.6	0	0.2	0.45	0.6
Above Average (AA)	0.55	0.7	0.1	0.3	0.35	0.5
High (H)	0.65	0.8	0.2	0.4	0.25	0.4
Very High (VH)	0.75	0.9	0.3	0.5	0.15	0.3
Certainly High (CH)	0.85	1	0.4	0.6	0.05	0.2

interval-valued neutrosophic values for main criteria. Then, the pairwise comparison matrix is tested for consistency and the matrix is found as consistent.

Step 3: The importance weights of the criteria are normalized. The normalized pairwise comparison matrix for main criteria is given in Table 10.

Step 4: The neutrosophic importance weights of the main criteria are calculated and given in Table 11.

Step 5: All the above steps are repeated for each sub-criteria, and neutrosophic weights of the all sub criteria are obtained and given in Table 12.

Step 6: After obtaining the neutrosophic importance weights of the criteria, the crisp weights are calculated with the help of deneutrosophication formula in Equation (2.6). Table 13 shows the local and global importance weights of criteria.

As can be seen from Table 13, the weights of five main criteria, *Leaks in Natural Gas and Other Gas Sources (C1)*, *Electricity Sources and Electrical Devices (C2)*, *Internal Overturns Due to Shaking and Open Flame Sources (C3)*, *Chemicals and Flammable Sources (C4)* and *Risks Due to Delay of Intervention (C5)* are obtained as 0.2207, 0.2089, 0.1646, 0.2790 and

Table 15
Alternative evaluation of experts for sub-criteria.

Districts	C11	C12	C13	C21	C22	C23	C31	C32	C33	C34	C35
Adalar	AA	A	CL	CH	BA	H	H	VL	CH	A	L
Ataşehir	AA	BA	A	BA	VL	BA	CH	H	L	BA	A
Beykoz	L	BA	A	BA	VH	BA	BA	VL	H	CH	BA
Çekmeköy	VL	VL	A	CL	AA	CL	L	A	L	L	BA
Kadıköy	VH	BA	BA	AA	VL	A	CH	CH	BA	L	AA
Kartal	H	A	AA	AA	L	A	H	VH	BA	A	AA
Maltepe	CH	AA	A	AA	L	AA	H	VH	CL	L	H
Pendik	CH	VH	H	H	H	H	AA	H	H	CH	VH
Sancaktepe	BA	BA	A	L	BA	L	H	A	CL	A	AA
Şile	CL	VL	CL	CL	CH	CL	CL	CL	CH	L	VL
Sultanbeyli	BA	BA	A	BA	VL	A	CH	L	CL	A	BA
Tuzla	CH	VH	CH	CH	A	CH	BA	BA	A	BA	BA
Ümraniye	A	A	VH	BA	VL	BA	CH	AA	CL	CH	VH
Üsküdar	A	BA	A	BA	VL	BA	CH	AA	H	H	H
Districts	**C41**	**C42**	**C43**	**C44**	**C51**	**C52**	**C53**	**C54**			
Adalar	CL	CL	CL	CL	A	A	CH	H			
Ataşehir	A	AA	AA	A	VH	BA	A	H			
Beykoz	CL	A	L	L	VL	BA	BA	H			
Çekmeköy	CL	L	L	A	VH	VL	CL	CH			
Kadıköy	BA	H	CH	AA	AA	A	A	BA			
Kartal	A	CH	AA	A	AA	A	A	BA			
Maltepe	AA	AA	H	A	AA	H	VH	VH			
Pendik	AA	L	H	CH	A	VH	VH	VH			
Sancaktepe	H	CL	BA	VH	VH	A	L	VH			
Şile	CL	L	CL	VL	CL	L	CL	VH			
Sultanbeyli	A	CL	L	A	VH	H	BA	AA			
Tuzla	CH	AA	L	VH	BA	CH	CH	AA			
Ümraniye	H	L	H	H	AA	H	BA	A			
Üsküdar	CL	CH	H	AA	BA	BA	H	L			

Table 16
Neutrosophic decision matrix for the criteria C11 and C12.

Districts	C11						C12					
	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U
Adalar	0.55	0.7	0.1	0.3	0.35	0.5	0.45	0.6	0	0.2	0.45	0.6
Ataşehir	0.55	0.7	0.1	0.3	0.35	0.5	0.35	0.5	0.1	0.3	0.55	0.7
Beykoz	0.25	0.4	0.2	0.4	0.65	0.8	0.35	0.5	0.1	0.3	0.55	0.7
Çekmeköy	0.15	0.3	0.3	0.5	0.75	0.9	0.15	0.3	0.3	0.5	0.75	0.9
Kadıköy	0.75	0.9	0.3	0.5	0.15	0.3	0.35	0.5	0.1	0.3	0.55	0.7
Kartal	0.65	0.8	0.2	0.4	0.25	0.4	0.45	0.6	0	0.2	0.45	0.6
Maltepe	0.85	1	0.4	0.6	0.05	0.2	0.55	0.7	0.1	0.3	0.35	0.5
Pendik	0.85	1	0.4	0.6	0.05	0.2	0.75	0.9	0.3	0.5	0.15	0.3
Sancaktepe	0.35	0.5	0.1	0.3	0.55	0.7	0.35	0.5	0.1	0.3	0.55	0.7
Şile	0.05	0.2	0.4	0.6	0.85	1	0.15	0.3	0.3	0.5	0.75	0.9
Sultanbeyli	0.35	0.5	0.1	0.3	0.55	0.7	0.35	0.5	0.1	0.3	0.55	0.7
Tuzla	0.85	1	0.4	0.6	0.05	0.2	0.75	0.9	0.3	0.5	0.15	0.3
Ümraniye	0.45	0.6	0	0.2	0.45	0.6	0.45	0.6	0	0.2	0.45	0.6
Üsküdar	0.45	0.6	0	0.2	0.45	0.6	0.35	0.5	0.1	0.3	0.55	0.7

Table 17
Neutrosophic weighted normalized decision matrix for the criteria C11 and C12.

Districts	C11						C12					
	T^L	T^U	I^L	I^U	F^L	F^U	T^L	T^U	I^L	I^U	F^L	F^U
Adalar	0.003	0.005	0.416	0.495	0.441	0.508	0.004	0.007	0.270	0.372	0.335	0.410
Ataşehir	0.003	0.005	0.416	0.495	0.441	0.508	0.003	0.006	0.286	0.386	0.343	0.418
Beykoz	0.001	0.003	0.426	0.505	0.464	0.528	0.003	0.006	0.286	0.386	0.343	0.418
Çekmeköy	0.001	0.002	0.436	0.514	0.472	0.535	0.001	0.004	0.317	0.414	0.359	0.432
Kadıköy	0.004	0.007	0.436	0.514	0.426	0.494	0.003	0.006	0.286	0.386	0.343	0.418
Kartal	0.004	0.006	0.426	0.505	0.434	0.501	0.004	0.007	0.270	0.372	0.335	0.410
Maltepe	0.005	0.007	0.447	0.523	0.418	0.487	0.005	0.009	0.286	0.386	0.327	0.403
Pendik	0.005	0.007	0.447	0.523	0.418	0.487	0.007	0.011	0.317	0.414	0.311	0.389
Sancaktepe	0.002	0.004	0.416	0.495	0.457	0.521	0.003	0.006	0.286	0.386	0.343	0.418
Şile	0.000	0.001	0.447	0.523	0.480	0.542	0.001	0.004	0.317	0.414	0.359	0.432
Sultanbeyli	0.002	0.004	0.416	0.495	0.457	0.521	0.003	0.006	0.286	0.386	0.343	0.418
Tuzla	0.005	0.007	0.447	0.523	0.418	0.487	0.007	0.011	0.317	0.414	0.311	0.389
Ümraniye	0.002	0.004	0.406	0.486	0.449	0.515	0.004	0.007	0.270	0.372	0.335	0.410
Üsküdar	0.002	0.004	0.406	0.486	0.449	0.515	0.003	0.006	0.286	0.386	0.343	0.418

0.1268, respectively. The most important risk factor for post-earthquake fires is determined to be *Chemicals and Flammable Sources (C4)* with the rate of %27.9. In addition, *Leaks in Natural Gas and Other Gas Sources (C1)* and *Electricity Sources and Electrical Devices (C2)* are very close to each other with the criteria weights of 0.2207 and 0.2089.

When focusing on sub-criteria, it can be said that *Faults and Leaks in the Natural Gas Pipeline (C12)* is the most important risk factor with the rate of %9.968. Other risky sub-criteria are *Density of Chemical Facilities in the Region (C41)* and *Malfunctions in Regional Transformers and Power Plants (C22)* with the rate of %8.986 and %8.176, respectively. It is possible to say that the criteria that have the potential to affect a large area or mass naturally have a higher degree of importance.

Table 18
Positive and Negative ideal solutions.

Criteria	IVNPIS						IVNNIS					
	TL	TU	IL	IU	FL	FU	TL	TU	IL	IU	FL	FU
C11	0.005	0.007	0.406	0.486	0.418	0.487	0.000	0.001	0.447	0.523	0.480	0.542
C12	0.007	0.011	0.270	0.371	0.312	0.390	0.001	0.004	0.315	0.411	0.361	0.435
C13	0.004	0.006	0.490	0.561	0.476	0.536	0.000	0.001	0.533	0.600	0.527	0.582
C21	0.004	0.007	0.482	0.551	0.456	0.517	0.000	0.001	0.510	0.576	0.507	0.563
C22	0.007	0.011	0.325	0.414	0.350	0.422	0.001	0.003	0.371	0.455	0.398	0.466
C23	0.005	0.008	0.415	0.496	0.422	0.489	0.000	0.002	0.461	0.537	0.475	0.536
C31	0.000	0.001	0.400	0.464	0.439	0.496	0.002	0.003	0.370	0.437	0.356	0.420
C32	0.002	0.003	0.385	0.453	0.373	0.432	0.000	0.001	0.429	0.493	0.436	0.489
C33	0.004	0.006	0.269	0.341	0.277	0.342	0.000	0.001	0.315	0.383	0.340	0.400
C34	0.002	0.004	0.314	0.391	0.317	0.381	0.001	0.002	0.367	0.440	0.369	0.428
C35	0.001	0.002	0.420	0.483	0.406	0.459	0.000	0.001	0.455	0.516	0.452	0.502
C41	0.009	0.013	0.164	0.246	0.198	0.276	0.001	0.003	0.221	0.299	0.266	0.338
C42	0.004	0.007	0.351	0.413	0.342	0.406	0.000	0.001	0.393	0.453	0.401	0.460
C43	0.005	0.008	0.303	0.373	0.301	0.370	0.000	0.002	0.339	0.406	0.366	0.429
C44	0.006	0.009	0.224	0.304	0.248	0.324	0.000	0.002	0.285	0.361	0.325	0.394
C51	0.000	0.000	0.536	0.590	0.524	0.571	0.001	0.002	0.498	0.555	0.475	0.526
C52	0.002	0.004	0.417	0.485	0.407	0.465	0.000	0.001	0.465	0.529	0.460	0.513
C53	0.002	0.004	0.366	0.436	0.363	0.424	0.000	0.001	0.411	0.477	0.426	0.482
C54	0.000	0.001	0.486	0.545	0.483	0.537	0.001	0.003	0.446	0.508	0.429	0.487

Table 19
Distances from IVNPIS and IVNNIS.

District	D_{IVNPIS}	D_{IVNNIS}
Adalar	0.2167	0.1280
Ataşehir	0.1642	0.1809
Beykoz	0.1810	0.1577
Çekmeköy	0.2216	0.1159
Kadıköy	0.1646	0.1881
Kartal	0.1438	0.2039
Maltepe	0.1589	0.1807
Pendik	0.1593	0.2013
Sancaktepe	0.1860	0.1558
Şile	0.2455	0.0878
Sultanbeyli	0.1929	0.1516
Tuzla	0.1737	0.2082
Ümraniye	0.1776	0.1702
Üsküdar	0.1641	0.1830

Table 20
Risk ranking of districts.

Ranking	District	Score	Ranking	District	Score
1	Kartal	0.58636	**8**	Ümraniye	0.48945
2	Pendik	0.55826	**9**	Beykoz	0.46556
3	Tuzla	0.54513	**10**	Sancaktepe	0.45579
4	Kadıköy	0.53318	**11**	Sultanbeyli	0.44016
5	Maltepe	0.53208	**12**	Adalar	0.37126
6	Üsküdar	0.5272	**13**	Çekmeköy	0.34339
7	Ataşehir	0.52415	**14**	Şile	0.26339

3.2. Comparison of districts by IVN-TOPSIS

In this study, it is aimed to rank fourteen districts of the Anatolian side of İstanbul, starting with the most risky, considering the post-earthquake fire risk criteria determined based on literature review and expert opinions.

First, using the linguistic variables in Table 14 through the questionnaire, experts are asked to evaluate the districts shown in Fig. 4 by considering predetermined criteria. While making this evaluation, linguistic variables are converted into neutrosophic numbers with the help of the scale in Table 14.

Step 1: The linguistic evaluation matrix in Table 15 is obtained as a result of the experts' evaluations for the districts according to predetermined criteria.

Then the linguistic alternative evaluation matrix is converted to the neutrosophic decision matrix $(\tilde{\ddot{X}})$ by converting linguistic variables to the interval valued neutrosophic numbers. Table 16 presents the neutrosophic decision matrix for the criteria C11 and C12 as an example.

Step 2: The neutrosophic weighted normalized decision matrix $(\tilde{\ddot{R}})$ is obtained. Table 17 presents the neutrosophic weighted normalized decision matrix for the criteria C11 and C12 as an example.

Step 3: The IVNPIS and IVNNIS are determined as given in Table 18.

Step 4: The distances from IVNPIS and IVNNIS are calculated with the help of Equation (2.24) for each alternative and given in Table 19.

Step 5–6: Revised closeness (scores) for each alternative is calculated and risk ranking of fourteen districts in terms of post-earthquake fire risk are given in Table 20.

As can be seen in Table 20, the district with the highest fire risk after an earthquake is determined as Kartal. Pendik, Tuzla and Kadıköy

Table 21
Hamming distances from the IVNPIS and IVNNIS.

District	D_{IVNPIS}	D_{IVNNIS}
Adalar	0.4106	0.2303
Ataşehir	0.2894	0.3516
Beykoz	0.3392	0.3017
Çekmeköy	0.4266	0.2143
Kadıköy	0.2923	0.3486
Kartal	0.2474	0.3935
Maltepe	0.2955	0.3454
Pendik	0.2806	0.3603
Sancaktepe	0.3403	0.3006
Şile	0.4859	0.1550
Sultanbeyli	0.3488	0.2921
Tuzla	0.2852	0.3557
Ümraniye	0.3212	0.3197
Üsküdar	0.2958	0.3451

Table 22
Risk ranking of the districts according to sensitivity analysis.

Ranking	District	Score	Ranking	District	Score
1	Kartal	0.6140	**8**	Ümraniye	0.4988
2	Pendik	0.5621	**9**	Beykoz	0.4707
3	Tuzla	0.5550	**10**	Sancaktepe	0.4691
4	Ataşehir	0.5485	**11**	Sultanbeyli	0.4557
5	Kadıköy	0.5440	**12**	Adalar	0.3593
6	Maltepe	0.5389	**13**	Çekmeköy	0.3344
7	Üsküdar	0.5385	**14**	Şile	0.2419

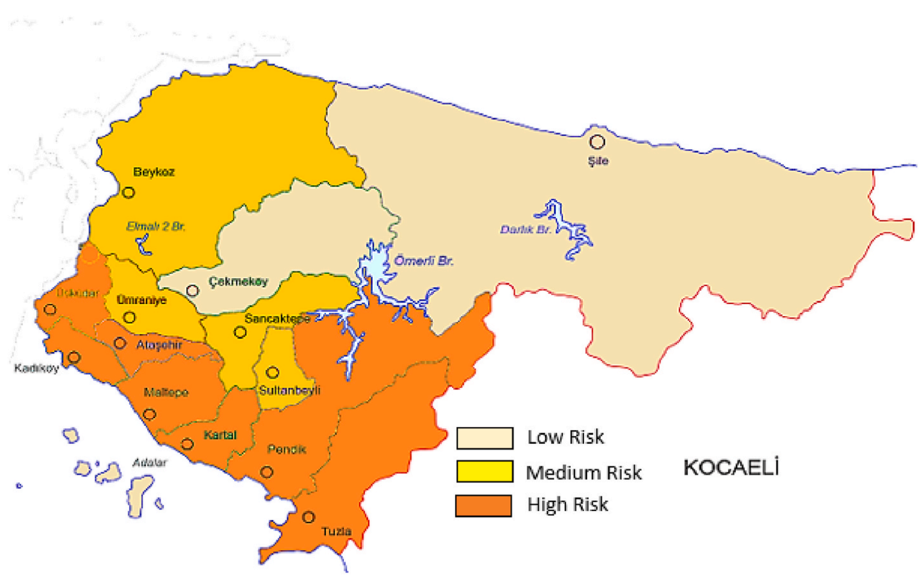

Fig. 5. Post-earthquake fire risk map.

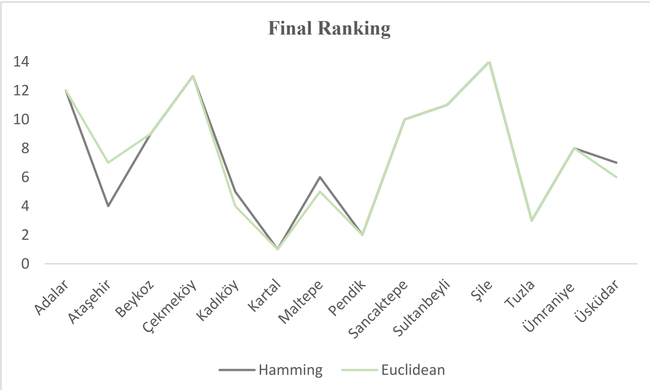

Fig. 6. Ranking of the districts for both Hamming and Euclidean distances.

Table 23
Scale for the IF-AHP evaluations.

	Interval Valued IF Number			
Linguistic Terms	μ_γ^-	μ_γ^+	ν_γ^-	ν_γ^+
Absolutely Low Importance -AL	0.1	0.25	0.65	0.75
Very Low Importance – VL	0.15	0.3	0.6	0.7
Low Importance – L	0.2	0.35	0.55	0.65
Medium Low Importance -ML	0.25	0.4	0.5	0.6
Equal Importance – EE	0.5	0.5	0.5	0.5
Medium High Importance – MH	0.5	0.6	0.25	0.4
High Importance – H	0.55	0.65	0.2	0.35
Very High Importance – VH	0.6	0.7	0.15	0.3
Absolutely High Importance – AH	0.65	0.75	0.1	0.25

Table 24
Scale for the PF-AHP evaluations.

	Interval Valued PF Number			
Linguistic Terms	μ_L	μ_U	ν_L	ν_u
Certainly Low Importance -CLI	0.00	0.00	0.90	1.00
Very Low Importance – VLI	0.10	0.2	0.8	0.9
Low Importance – LI	0.20	0.35	0.65	0.8
Below Average Importance -BAI	0.35	0.45	0.55	0.65
Equal Importance – EI	0.45	0.55	0.45	0.55
Above Average Importance – AAI	0.55	0.65	0.35	0.45
High Importance – HI	0.65	0.80	0.20	0.35
Very High Importance – VHI	0.80	0.90	0.10	0.20
Certainly High Importance – CHI	0.90	1.00	0.00	0.00

districts follow Kartal with scores close to each other. Considering that Kartal, Pendik and Tuzla districts follow each other, it seems normal that the fire risks calculated after the earthquake are close to each other. The district with the least risk is found as Şile with a score of 0.26339. In addition to having a very large area, the low population and the limited number of enterprises engaged in chemical activities support this result.

Adalar should be especially examined here. It is at the bottom of the list because it consists of islands and the buildings in this district are mainly wooden. In this case, the *Chemicals and Flammable Sources* criterion, which has the highest importance, is considered effective. The absence of chemical activity sources and the presence of very limited areas containing flammable liquids on the island are thought to significantly reduce the risk of post-earthquake fire. Fig. 5 shows the post-earthquake fire risk map of the districts according to the risk scores calculated. This map is created based on risk scores of districts.

As can be seen, the proposed two-level post-earthquake fire risk assessment method offers decision-makers or authorizes a quick assessment opportunity. It also gives an idea about the measures to be taken by setting out the criteria of high importance. By evaluating the districts according to their risks, it provides a risk map for Istanbul, which has been selected as an exemplary case and has a high earthquake risk. Thus, it gives an idea to people residing in districts with a high risk level about the fire risks after an earthquake and guides them to take precautions.

4. Sensitivity analysis

In this subsection, a sensitivity analysis is conducted to measure the effectiveness of the proposed methodology due to the changes in distance measures. For this aim, the distance measures used in Step 5 of IVN-TOPSIS are changed from Euclidean distance to Hamming distance. The Hamming distances of the alternatives from IVNPIS and IVNNIS are calculated by Equation (2.23). Table 21 shows the distance from IVNPIS and IVNNIS for each district.

Then final score of each district is calculated using Hamming distances and the districts are ranked according to the final scores. Table 22 shows the final score of each district.

According to Table 22, the most risky three districts are the same. So, it can be said that Kartal, Pendik and Tuzla are determined as most risky districts among fourteen districts. The ranking comparison of districts according to different distance measures is given in Fig. 6.

According to Fig. 6, using different distance measures can change the results therefore, it is important to select distance measure to obtain more robust results. While the distance measure is changing mutually, the ranking and risk scores of districts is changing, too. For example, by considering Maltepe, the distance measure change will cause a decrease in the final ranking of Maltepe, from 5th to 6th.

Acording results of sensitivity analysis, given in Fig. 6 and Table 22, it can be seen that the top four district are same for both Euclidian and Hamming distance measure. So, it can be said that Kartal, Tuzla, Pendik and Ataşehir are always more risky than other districts for post-earthquake fire. The safest seven districts are not changing also. Therefore Adalar, Çekmeköy and Şile are good options according their post-earthquake fire risk.

5. Comparative analysis

A comparative analysis is conducted to further validate the robustness and effectiveness of the proposed AHP methodology under neutrosophic fuzzy environment to determine criteria weights. For this

Table 25
Results of the comparative analysis.

Criteria	IVN-AHP	IF-AHP	PF-AHP	Criteria	IVN-AHP	IF-AHP	PF-AHP
C11	0.0693	0.0764	0.0470	**C35**	0.0227	0.0224	0.0068
C12	0.0967	0.1118	0.1621	**C41**	0.0898	0.0919	0.1515
C13	0.0547	0.0465	0.0302	**C42**	0.0514	0.0400	0.0501
C21	0.0613	0.0416	0.0540	**C43**	0.0624	0.0585	0.0580
C22	0.0817	0.0886	0.1123	**C44**	0.0754	0.0777	0.0737
C23	0.0659	0.0669	0.0591	**C51**	0.0244	0.0193	0.0109
C31	0.0318	0.0357	0.0153	**C52**	0.0330	0.0323	0.0259
C32	0.0283	0.0298	0.0119	**C53**	0.0399	0.0399	0.0438
C33	0.0445	0.0510	0.0455	**C54**	0.0295	0.0257	0.0177
C34	0.0373	0.0439	0.0243				

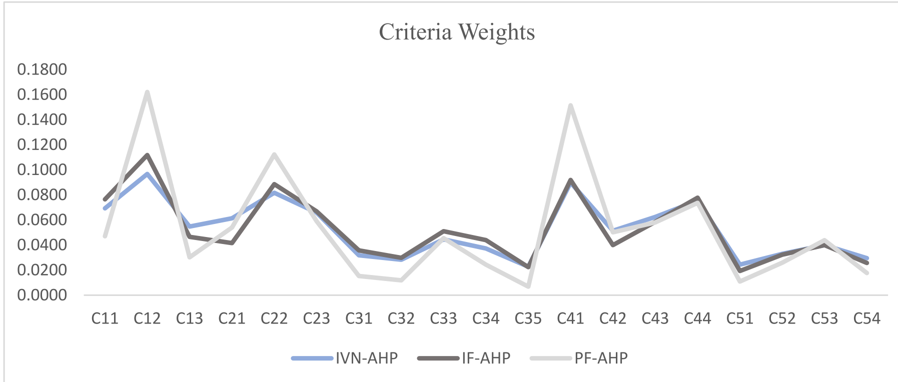

Fig. 7. The weights of the criteria for IVN-AHP, IF-AHP and PF-AHP.

purpose, the obtained criteria weights are compared with those derived by other fuzzy AHP methodologies including pythagorean fuzzy AHP (PF-AHP) and intuitionistic fuzzy AHP (IF-AHP). So the performance of IVN-AHP method is tested with both PF-AHP and IF-AHP. Both of these approaches can convert the linguistic terms into some equivalent quantitative numbers. Atanassov introduce intuitionistic fuzzy sets (IFSs) [72]. These sets are defined by membership and non-membership functions. Pythagorean Fuzzy sets (PFSs) are presented by Yager and applied to many real-life problems [73]. These sets are developed based on IFSs. PFs are also a generalization to the intuitionistic fuzzy sets and address the uncertainty in some conditions where IFSs cannot. IFSs and PFSs are defined by membership and non-membership degrees. Unlike IFSs, the sum of membership and non-membership degrees can exceed 1, but the sum of squares cannot for PFSs. Sometimes, fuzzy sets such as IFSs and PFSs cannot handle all kinds of uncertainties effectively. In fact, fuzzy sets cannot tackle with inconsistency and indetermination of decision makers perfectly [52]. Therefore, neutrosophic set, that contain a truth-membership, an indeterminacy-membership, and a falsity-membership function is employed in this study.

This section of study gives the comparison of criteria importance obtained from proposed approach with IF-AHP and PF-AHP. Tables 23 and 24 present linguistic scales for both IFSs [74] and PFSs [75], respectively.

Then we apply IF-AHP (see Ref. [74] for details) and PFAHP (see Ref. [76] for details) method to determine main and sub criteria weights. The criteria weights determined are shown in Table 25 for each criterion.

Fig. 7 demonstrates the proposed methodology results compared to those of IF-AHP and PF-AHP application.

As can be seen in Table 25 and Fig. 7, the ranking orders are the same as the result of the proposed methodology. However, taking into account of indeterminacy-membership function in the IVN-AHP that leads to can evaluate indeterminacy of information.

6. Conclusion

In this paper, the post-earthquake fire risk assessment problem is taken into account. In order to define the most important risk parameters for post-earthquake fires, six experts are interviewed and Modified Delphi Method is applied to consolidate experts' opinions. Afterward a novel two level IVN-AHP integrated IVN-TOPSIS methodology is structured and conducted. The importance weights of each criterion are determined by IVN-AHP and then, fourteen districts are ranked as alternatives according to their risk by IVN-TOPSIS.

The contributions of this study to literature and real life applications can be specified as follows: (1) neutrosophic multi criteria decision-making methods, AHP and TOPSIS, are adapted to post-earthquake fire risk assessment problem, (2) The most important criteria regarding post-earthquake fire risk are defined and classified, (3) These criteria and their sub-criteria are evaluated by the proposed methodology and the importance weights of each criteria are obtained, (4) Districts of the Anatolian side of Istanbul are ranked according to post-earthquake fire risk, (5) The validity and reliability of the proposed risk assessment method is demonstrated in a real life disaster problem, (5)The proposed risk assessment method is intended to be a useful approach for post-earthquake fire risk assessment for Istanbul and other cities, (6) To the best of our knowledge, this study is the first research conducted to evaluate post-earthquake fire risks using neutrosophic multi-criteria decision making methods, (7) It allows decision makers to make a rapid and effective assessment to address fire risks after an earthquake. In addition, according to the statistical models performed on similar issues, incomplete information can be integrated into the decision-making process through expert evaluation. In this context, a practical evaluation method is presented.

As future directions, this study can be expanded to all cities in Turkey to sort them for post-earthquake fire risks. In addition, the post-earthquake fire risk criteria considered in the proposed method can be expanded or another fuzzy multi-criteria decision making method can be included to make a more comparative assessment. Thanks to advances in neutrosophic theory, this research can make a more detailed risk assessment possible in future by taking advantage of the expandable method using n-Valued Refined Neutrosophic Logic [49] as an alternative method.

Declaration of competing interest

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

References

[1] S. Zhao, L. Xiong, R. Aizhu, Fifth Annu. IIASA-DPRI Meet, 2005, pp. 1–14.
[2] R.A. Davidson, A.M. Asce, Linear ,. Mixed … Models, 2009, pp. 351–360.
[3] A.Z. Ren, X.Y. Xie, The simulation of post-earthquake fire-prone area based on GIS, J. Fire Sci. (2004), https://doi.org/10.1177/0734904104042440.
[4] M. Kobayashi, URBAN POST-EARTHQUAKE FIRES IN JAPAN, 1985.
[5] M.R. Zolfaghari, E. Peyghaleh, G. Nasirzadeh, Fire following earthquake, intra-structure ignition modeling, J. Fire Sci. (2009), https://doi.org/10.1177/0734904108094516.
[6] C. Scawthorn, Y. Yamada, H. Iemura, A model for urban post-earthquake fire hazard, Disasters 5 (1981) 125–132, https://doi.org/10.1111/j.1467-7717.1981.tb01095.x.
[7] R.A. Davidson, Modeling postearthquake fire ignitions using generalized linear (mixed) models, J. Infrastruct. Syst. (2009), https://doi.org/10.1061/(asce)1076-0342(2009)15:4(351).
[8] C.R. Scawthorn, Fire Following Earthquake Aspects of the Southern San Andreas Fault M W 7.8 Earthquake Scenario, Earthq. Spectra, 2011, https://doi.org/10.1193/1.3574013.
[9] T. Nishino, T. Tanaka, A. Hokugo, An evaluation method for the urban post-earthquake fire risk considering multiple scenarios of fire spread and evacuation, Fire Saf. J. 54 (2012) 167–180, https://doi.org/10.1016/j.firesaf.2012.06.002.

[10] M. Aruldoss, A survey on multi criteria decision making methods and its applications, Am. J. Inf. Syst. (2013).
[11] R. Sun, Z. Gong, G. Gao, A.A. Shah, Comparative analysis of multi-criteria decision-making methods for flood disaster risk in the Yangtze River delta, Int. J. Disaster Risk Reduct (2020), https://doi.org/10.1016/j.ijdrr.2020.101768.
[12] P.M. Orencio, M. Fujii, A localized disaster-resilience index to assess coastal communities based on an analytic hierarchy process (AHP), Int. J. Disaster Risk Reduct. (2013), https://doi.org/10.1016/j.ijdrr.2012.11.006.
[13] R. Jena, B. Pradhan, G. Beydoun, Earthquake vulnerability assessment in Northern Sumatra province by using a multi-criteria decision-making model, Int. J. Disaster Risk Reduct (2020), https://doi.org/10.1016/j.ijdrr.2020.101518.
[14] P. Yariyan, H. Zabihi, I.D. Wolf, M. Karami, S. Amiriyan, Earthquake risk assessment using an integrated fuzzy analytic hierarchy process with artificial neural networks based on GIS: a case study of Sanandaj in Iran, Int. J. Disaster Risk Reduct. 50 (2020) 101705, https://doi.org/10.1016/j.ijdrr.2020.101705.
[15] H. Lin, C. Lin, J. Ko, Y. Wu, Risk Factors of Post-earthquake Fire for Constructions Using the Analytic Hierarchy Process Approach, 2017, https://doi.org/10.2991/aece-16.2017.1.
[16] E. Bolturk, C. Kahraman, A novel interval-valued neutrosophic AHP with cosine similarity measure, Soft Comput 22 (2018) 4941–4958, https://doi.org/10.1007/s00500-018-3140-y.
[17] H. Vitorino, H. Rodrigues, C. Couto, Evaluation of post-earthquake fire capacity of reinforced concrete elements, Soil Dynam. Earthq. Eng. 128 (2020) 105900, https://doi.org/10.1016/j.soildyn.2019.105900.
[18] N. Elhami Khorasani, T. Gernay, M. Garlock, Data-driven probabilistic post-earthquake fire ignition model for a community, Fire Saf. J. 94 (2017) 33–44, https://doi.org/10.1016/j.firesaf.2017.09.005.
[19] P. Farshadmanesh, J. Mohammadi, A probabilistic methodology for assessing post-earthquake fire ignition vulnerability in residential buildings, Fire Technol. 55 (2019) 1295–1318, https://doi.org/10.1007/s10694-018-0811-2.
[20] J. Li, J. Jiang, M. Li, Hazard analysis system of urban post-earthquake fire based on GIS, Acta Seismol. Sin. (2001).
[21] R. Botting, The Impact of Post-Earthquake Fire on the Urban Environment, University of Canterbury., 1998.
[22] S.S. Yildiz, H. Karaman, Post-earthquake ignition vulnerability assessment of Küçü kçekmece district, Nat. Hazards Earth Syst. Sci. 13 (2013) 3357–3368, https://doi.org/10.5194/nhess-13-3357-2013.
[23] L.T. Arumsari, I. Rosilawati, N. Kadaritna, The impact of post-earthquake fire on the urban environment, J. Pendidik. Dan Pembelajaran Kim. 53 (1998) 1689–1699.
[24] M.R. Zolfaghari, E. Peyghaleh, Fire following earthquake modelling, probabilistic ignition model for building stock, 14th World Conf. Earthq. Eng. (2008).
[25] K. Himoto, Comparative analysis of post-earthquake fires in Japan from 1995 to 2017, Fire Technol. 55 (2019) 935–961, https://doi.org/10.1007/s10694-018-00813-5.
[26] C.W. Chang, C.R. Wu, H.C. Chen, Using expert technology to select unstable slicing machine to control wafer slicing quality via fuzzy AHP, Expert Syst. Appl. 34 (2008) 2210–2220, https://doi.org/10.1016/j.eswa.2007.02.042.
[27] A.T. Gumus, Evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS methodology, Expert Syst. Appl. 36 (2009) 4067–4074, https://doi.org/10.1016/j.eswa.2008.03.013.
[28] J.W. Murry, J.O. Hammons, Delphi: a versatile methodology for conducting qualitative research, Rev. High. Educ. 18 (1995) 423–436, https://doi.org/10.1353/rhe.1995.0008.
[29] P.F. Hsu, C.R. Wu, Y.T. Li, Selection of infectious medical waste disposal firms by using the analytic hierarchy process and sensitivity analysis, Waste Manag. 28 (2008) 1386–1394, https://doi.org/10.1016/j.wasman.2007.05.016.
[30] A. Yildiz, E. Ayyildiz, A.T. Gumus, C. Ozkan, A modified balanced scorecard based hybrid pythagorean fuzzy AHP-topsis methodology for ATM site selection problem, Int. J. Inf. Technol. Decis. Making 19 (2020) 365–384, https://doi.org/10.1142/S0219622020500017.
[31] W.C. Sung, Application of Delphi method, a qualitative and quantitative analysis, to the healthcare management, J. Healthc. Manag. 2 (2001) 11–19.
[32] L.A. Zadeh, Fuzzy sets, Inf. Control 8 (1965) 338–353, https://doi.org/10.1016/S0019-9958(65)90241-X.
[33] K.T. Atanassov, Intuitionistic Fuzzy Sets, Fuzzy Sets Syst, 1986, https://doi.org/10.1016/S0165-0114(86)80034-3.
[34] F. Smarandache, Neutrosophy: Neutrosophic Probability, Set, and Logic: Analytic Synthesis & Synthetic Analysis, Rehoboth Am. Res. Press, 1998.
[35] C. Kahraman, B. Oztaysi, S. Cevik Onar, Single interval-valued neutrosophic AHP methods: performance analysis of outsourcing law firms, J. Intell. Fuzzy Syst. 38 (2020) 749–759, https://doi.org/10.3233/JIFS-179446.
[36] H. Wang, Y. Zhang, R. Sunderraman, Single valued neutrosophic sets, fuzzy sets, rough sets multivalued, Oper. Appl. (2011).
[37] J. Ye, Single valued neutrosophic cross-entropy for multicriteria decision making problems, Appl. Math. Model. (2014), https://doi.org/10.1016/j.apm.2013.07.020.
[38] F. Karaaslan, F. Hunu, Type-2 single-valued neutrosophic sets and their applications in multi-criteria group decision making based on TOPSIS method, J. Ambient Intell. Humaniz. Comput. (2020), https://doi.org/10.1007/s12652-020-01686-9.
[39] F. Karaaslan, K. Hayat, Some new operations on single-valued neutrosophic matrices and their applications in multi-criteria group decision making, Appl. Intell. (2018), https://doi.org/10.1007/s10489-018-1226-y.
[40] Z. Aiwu, D. Jianguo, G. Hongjun, Interval valued neutrosophic sets and multi-attribute decision-making based on generalized weighted aggregation operator, J. Intell. Fuzzy Syst. (2015), https://doi.org/10.3233/IFS-151973.
[41] A. Karaşan, E. Bolturk, C. Kahraman, An integrated interval-valued neutrosophic AHP and TOPSIS methodology for sustainable cities' challenges, Adv. Intell. Syst. Comput. 1029 (2020) 653–661, https://doi.org/10.1007/978-3-030-23756-1_79.
[42] S. Broumi, F. Smarandache, Cosine Similarity Measure of Interval-Valued Neutrosophic Sets, Neutrosophic Set Syst, 2014.
[43] J.J. Peng, J.Q. Wang, J. Wang, H.Y. Zhang, X.H. Chen, Simplified neutrosophic sets and their applications in multi-criteria group decision-making problems, Int. J. Syst. Sci. (2016), https://doi.org/10.1080/00207721.2014.994050.
[44] J. Ye, A multicriteria decision-making method using aggregation operators for simplified neutrosophic sets, J. Intell. Fuzzy Syst. (2014), https://doi.org/10.3233/IFS-130916.
[45] M. Abdel-Basset, M. Mohamed, A.K. Sangaiah, Neutrosophic AHP-Delphi Group decision making model based on trapezoidal neutrosophic numbers, J. Ambient Intell. Humaniz. Comput. (2018), https://doi.org/10.1007/s12652-017-0548-7.
[46] S. Pramanik Biswas, B.C. Giri, TOPSIS Strategy for Multi-Attribute Decision Making with Trapezoidal Neutrosophic Numbers, Neutrosophic Sets Syst, 2018, https://doi.org/10.5281/zenodo.1235335.
[47] C. Jana, M. Pal, F. Karaaslan, J. Wang, Trapezoidal neutrosophic aggregation operators and its application in multiple attribute decision making process, Sci. Iran. (2018), https://doi.org/10.24200/sci.2018.51136.2024.
[48] F. Karaaslan, Gaussian single-valued neutrosophic numbers and its application in multi-attribute decision making, in: Neutrosophic Sets Syst., USA, 2018, pp. 101–117.
[49] F. Smarandache, n-Valued Refined Neutrosophic Logic and its Applications to Physics, 2013.
[50] M. Gulistan, M. Mohammad, F. Karaaslan, S. Kadry, S. Khan, H.A. Wahab, Neutrosophic cubic Heronian mean operators with applications in multiple attribute group decision-making using cosine similarity functions, Int. J. Distributed Sens. Netw. 15 (2019), https://doi.org/10.1177/1550147719877613, 155014771987761.
[51] F. Karaaslan, Multicriteria decision-making method based on similarity measures under single-valued neutrosophic refined and interval neutrosophic refined environments, Int. J. Intell. Syst. 33 (2018) 928–952, https://doi.org/10.1002/int.21906.
[52] Z. peng Tian, R. xin Nie, X.K. Wang, J. qiang Wang, Single-valued neutrosophic ELECTRE II for multi-criteria group decision-making with unknown weight information, Comput. Appl. Math. 39 (2020) 224, https://doi.org/10.1007/s40314-020-01232-5.
[53] M. Abdel-Basset, G. Manogaran, A. Gamal, F. Smarandache, A hybrid approach of neutrosophic sets and DEMATEL method for developing supplier selection criteria, Des. Autom. Embed. Syst. 22 (2018) 257–278, https://doi.org/10.1007/s10617-018-9203-6.
[54] D. Karabašević, D. Stanujkić, E.K. Zavadskas, P. Stanimirović, G. Popović, B. Predić, A. Ulutaş, A novel extension of the TOPSIS method adapted for the use of single-valued neutrosophic sets and hamming distance for E-commerce development strategies selection, Symmetry (Basel). 12 (2020) 1263, https://doi.org/10.3390/sym12081263.
[55] E. Bolturk, C. Kahraman, Interval-valued neutrosophic AHP with possibility degree method, Int. J. Anal. Hierarchy Process. (2018), https://doi.org/10.13033/ijahp.v10i3.545.
[56] P. Biswas, S. Pramanik, B.C. Giri, A New Methodology for Neutrosophic Multi-Attribute Decision Making with Unknown Weight Information, Neutrosophic Sets Syst, 2014.
[57] D.-S. Xu, C. Wei, G.-W. Wei, TODIM method for single-valued neutrosophic multiple attribute decision making, Information 8 (2017) 125, https://doi.org/10.3390/info8040125.
[58] G. Tang, Approaches for Relational Multiple Attribute Decision Making with Interval Neutrosophic Numbers Based on Choquet Integral, Shandong University of Finance and Economics, 2016.
[59] J. Ye, S. Du, Some distances, similarity and entropy measures for interval-valued neutrosophic sets and their relationship, Int. J. Mach. Learn. Cybern. (2019), https://doi.org/10.1007/s13042-017-0719-z.
[60] M.I. Myers, H. James, Alpert, No title, J. Market. 32 (1968) 13–20.
[61] J. Thor, S. Ding, S. Kamaruddin, Comparison of multi criteria decision making methods from the maintenance alternative selection perspective, Int. J. Eng. Sci. (2013).
[62] A.E.D.M.R. Nouran, M. Radwan, M. Badr Senousy, Neutrosophic AHP multi criteria decision making method applied on the selection of learning management system, Int J Adv Comput Technol (IJACT) 8 (5) (2016) 95–105.
[63] N. Vafaei, R.A. Ribeiro, L.M. Camarinha-Matos, Normalization techniques for multi-criteria decision making: analytical hierarchy process case study, in: IFIP Adv. Inf. Commun. Technol., Springer New York LLC, 2016, pp. 261–268, https://doi.org/10.1007/978-3-319-31165-4_26.
[64] C.-L. Hwang, K. Yoon, Methods for Multiple Attribute Decision Making, 1981, https://doi.org/10.1007/978-3-642-48318-9_3.
[65] H. Sharma, A. Tandon, P.K. Kapur, A.G. Aggarwal, Ranking hotels using aspect ratings based sentiment classification and interval-valued neutrosophic TOPSIS, Int. J. Syst. Assur. Eng. Manag. 10 (2019) 973–983, https://doi.org/10.1007/s13198-019-00827-4.
[66] F. Broumi, S, J. Ye, Smarandache, An Extended TOPSIS Method for Multiple Attribute Decision Making Based on Interval Neutrosophic Uncertain Linguistic Variables, 2015.

[67] B.C. Biswas, P. Pramanik, S. Giri, TOPSIS Method for Multi-Attribute Group Decisionmaking under Single-Valued Neutrosophic Environment, 2016.

[68] S. Hamiyet, İstanbul Depremi Hakkında Bir Rapor Üzerine İnceleme, Ankara Üniversitesi Dil Ve Tarih-Coğrafya Fakültesi Tar. Bölümü Tar, Araştırmaları Derg., 1894, https://doi.org/10.1501/tarar_0000000097, 1996.

[69] A.D. Smith, High-resolution seismic profiling in the Sea of Marmara (northwest Turkey): late Quaternary sedimentation and sea-level changes, Geol. Soc. Am. Bull. (1995), https://doi.org/10.1130/0016-7606(1995)107<0923:HRSPIT>2.3.CO;2.

[70] T. Taymaz, H. Eyidoğan, J. Jackson, Source parameters of large earthquakes in the east Anatolian Fault zone (Turkey), Geophys. J. Int. (1991), https://doi.org/10.1111/j.1365-246X.1991.tb06328.x.

[71] İstanbul i?li olası deprem kayıp tahminlerinin güncellenmesi projesi | deprem ve zemin i?nceleme müdürlüğü (n.d.), https://depremzemin.ibb.istanbul/calismalarimiz/tamamlanmis-calismalar/istanbul-ili-olasi-deprem-kayip-tahminlerinin-guncellenmesi-projesi/. (Accessed 30 April 2021).

[72] K.T. Atanassov, Intuitionistic fuzzy sets, Physica, Heidelberg, 1999, pp. 1–137, https://doi.org/10.1007/978-3-7908-1870-3_1.

[73] R.R. Yager, Pythagorean fuzzy subsets, in: Proc. 2013 Jt. IFSA World Congr. NAFIPS Annu. Meet, IFSA/NAFIPS, 2013, pp. 57–61, https://doi.org/10.1109/IFSA-NAFIPS.2013.6608375, 2013.

[74] C. Kahraman, B. Öztayşi, S. Çevik Onar, An integrated intuitionistic fuzzy AHP and TOPSIS approach to evaluation of outsource manufacturers, J. Intell. Syst. 29 (2020) 283–297, https://doi.org/10.1515/jisys-2017-0363.

[75] E. Ayyildiz, A. Taskin Gumus, Interval-valued Pythagorean fuzzy AHP method-based supply chain performance evaluation by a new extension of SCOR model: SCOR 4.0, Complex Intell. Syst. 7 (2021) 559–576, https://doi.org/10.1007/s40747-020-00221-9.

[76] E. Ayyildiz, A. Taskin Gumus, Pythagorean fuzzy AHP based risk assessment methodology for hazardous material transportation: an application in Istanbul, Environ. Sci. Pollut. Res. (2021) 1–13, https://doi.org/10.1007/s11356-021-13223-y.