International Journal of Environmental Impacts
https://www.acadlore.com/journals/IJEI

Earthquake Vulnerability Analysis Based on Fermatean Fuzzy MCDM for Reducing Uncertainties in Disaster Management

Željko Stević[1,2*], Emrah Ayhan[3], Çağlar Karamaşa[3]

[1] Department of Industrial Management Engineering, Korea University, 02841 Seoul, Korea
[2] Department of Mobile Machinery and Railway Transport, Faculty of Transport Engineering, Vilnius Gediminas Technical University, LT-10223 Vilnius, Lithuania
[3] Faculty of Economics and Administrative Sciences, Anadolu University, 26470 Eskişehir, Turkey

* Correspondence: Željko Stević (zeljko.stevic@vilniustech.lt)

Received: 11-19-2025 **Revised:** 12-17-2025 **Accepted:** 12-23-2025

Citation: Ž. Stević, E. Ayhan, and Ç. Karamaşa, "Earthquake vulnerability analysis based on Fermatean Fuzzy MCDM for reducing uncertainties in disaster management," *Int. J. Environ. Impacts.*, vol. 8, no. 6, pp. 1349–1368, 2025. https://doi.org/10.56578/ijei080620.

Abstract: Urban earthquake risk management presents a challenging problem due to rising urban density, vulnerable infrastructure, and the unpredictability of disasters. This study introduces an innovative methodological framework that combines urban resilience assessment with a Fermatean Fuzzy Set (FFs)-based Multi-Criteria Decision-Making (MCDM) methodology to analyze and improve earthquake-resilience in Turkish cities. The study identifies and prioritizes 9 criteria affecting earthquake-resilience by integrating expert perspectives from 17 specialists in disaster risk management and urbanization in Turkey. The methodology benefits from the Fermatean Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique to avoid uncertainty and to rank criteria in expert assessments, and provides a better understanding of interdependencies between resilience criteria. The findings of the study prove that the most significant determinant is the degree to which decision-makers embrace and integrate resilience thinking, which was followed by good governance mechanisms and safe residential areas as important criteria. The suggested framework of the study creates solutions for methodological deficiencies in traditional risk assessments by including uncertainty and inadequate data, while offering practical recommendations for policymakers at the same time. Therefore, this research enhances the discourse on urban resilience, because it creates a comprehensive, flexible decision-support model to inform strategic planning and disaster management in high-risk urban areas regarding earthquakes.

Keywords: Urban resilience; DEMATEL; Fermatean Fuzzy Sets; Earthquake; Governance; Risk management

1 Introduction

Urbanization is a continuous process resulting in growing urban populations and density in city centers. Due to these factors, not only access to infrastructure, jobs, and services increased, but also vulnerability to natural and anthropogenic disasters such as earthquakes, floods, energy crises, infrastructure failures, pandemics, and the effects of climate change also increased. The population and density in disaster-prone areas multiply these risks, and this causes substantial loss of life, long-term displacement, and disruption of critical infrastructures like electricity, water, communication, and healthcare. These developments underline the requirement for urban areas to increase their resilience to foresee, minimize, recover, and sustain after the detrimental impacts of disasters occur.

In reaction to the increasing number of disasters and the risks, international organizations and national governments have accelerated policies to enhance disaster risk reduction and urban resilience over the last two decades. The "Making Cities Resilient" program, which was initiated by the United Nations Office for Disaster Risk Reduction (UNDRR) in 2010, is a significant attempt in this area. The campaign portrays critical features of resilient cities, which encompass participation of all stakeholders in planning, transparent governance at the local level, efficient infrastructure, risk-informed urbanization, proactive asset safeguarding, reduction of disaster-related losses, self-sufficient response capabilities, and the swift restoration of essential services post-crisis [1].

Although there are continuing efforts, disasters continue to cause a significant burden worldwide. The 2022 World Disasters Report by the International Federation of Red Cross and Red Crescent Societies (IFRC) states that over 710 disaster occurrences occurred between 2020 and 2021, and these disasters caused nearly 30,000 deaths and affected over 220 million individuals [2]. On the other hand, climate-related catastrophes have also become the most devastating category, which was followed closely by geological and human-made disasters. The Emergency Events Database has reported several catastrophic earthquakes in recent years, including the 2010 Haiti earthquake, which resulted in 222,570 fatalities, and the 2022 Afghanistan earthquake, which caused 1,036 deaths [3].

Noto Peninsula earthquakes in Japan in January 2024 caused 213 deaths due to magnitudes between 5.0 and 7.6, so this shows the significance of sustainable urban resilience regulations [4]. Conversely, the earthquakes in Kahramanmaraş on February 6, 2023 (magnitudes 7.7 and 7.6) caused nearly 50,000 deaths and affected 11 other cities in the near region in Türkiye. Similarly, the 1999 Kocaeli earthquake resulted in more than 17,000 deaths [3, 5]. Moreover, Disaster and Emergency Management Presidency (AFAD) [6] stated that Türkiye had 22,982 natural catastrophes in 2022, including over 21,000 earthquakes, and underlines the requirement for disaster-resilient urban policy.

In light of recent disasters, urban resilience is crucial as it includes the sustainability of physical infrastructure, governance capabilities, social and political awareness, and adaptive policies that collectively enhance cities' ability to withstand and minimize the negative effects of earthquakes [7, 8]. Consequently, resilience thinking has progressively emerged as a fundamental paradigm in catastrophe risk management and sustainable urbanization.

Recent empirical research in Türkiye has utilized quantitative resilience evidence to evaluate seismic risks. For example, Askan et al. [9] contrasted the vulnerability of the Turkoglu region before and after the 2023 Kahramanmaraş earthquake. Likewise, Uzun Yüksel and Kutay Karaçor [10] used the Baseline Resilience Indicators for Communities (BRIC) framework to assess spatial, social, economic, and infrastructural aspects in Düzce City (Turkey), which experienced two consecutive earthquakes in 1999. These studies show that, although physical and infrastructural resilience have been progressively measured, criteria concerning decision-making, governance, awareness, and urban planning remain inadequately implemented in Turkish cities. Significant research has shown the multifaceted character of urban resilience. For instance, comprehensive assessments that integrate asset and catastrophe risk management with Geographic Information Systems (GIS)-based decision support systems have revealed deficiencies in methodological consistency and the incorporation of governance or policy factors [11].

This research examines Turkish cities at risk of earthquakes, which are located on active fault lines and thus face considerable seismic hazards. Therefore, it has two objectives: first, to identify the principal criteria affecting urban resilience to earthquakes in Turkish cities, and second, to offer novel policy approaches specifically designed for at-risk cities. By collecting data from expert interviews and using a fuzzy Multi-Criteria Decision-Making (MCDM) framework, this study identifies three primary determinants of resilience: (1) how local decision-makers embrace and value the concept of resilience, (2) the existing governance structures, and (3) the availability of safe residential areas. These findings provide a formulation of strategic objectives and policy recommendations that aim to enhance the adaptation capability of Turkish cities for future earthquakes.

Avoiding uncertainty is essential in the assessment of inherently uncertain situations such as earthquakes. This is because, first, data used in disaster risk analysis are often incomplete, imprecise, or based on the subjective judgments of experts. At this point, the fuzzy logic approach allows the mathematical expression of uncertain information and the more realistic incorporation of decision-makers' assessments into the model [12]. Furthermore, the Fermatean Fuzzy set approach, which was built on the classical forms of fuzzy logic, provides decision-makers with a broader range of expressive power thanks to its flexible structure based on the cubic sum of membership and dissent degrees. Thus, not only positive and negative judgments but also the dimension of indecision can be effectively modeled. With this feature, Fermatean Fuzzy methods enable more reliable and fair solutions to complex decision problems involving high uncertainty, such as earthquake risk. Fermatean Fuzzy Sets handle uncertainty and ambiguity as efficiently and flexibly as other fuzzy models [13, 14].

The next sections of this research are organized as follows: Part 2 examines the theoretical and empirical literature regarding urban resilience, with a specific focus on the Turkish setting. Part 3 delineates the study approach, encompassing the criterion selection and the implementation of Fermatean Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL). Part 4 examines the data and emphasizes the most significant factors for earthquake resilience. It also compares the results using other MCDM approaches to ensure the findings are reliable. In the final section, the study outlines the main policy insights, discusses its limitations, and suggests directions for future research.

2 Literature Review

Resilience in urban areas has been conceptualized and implemented in various disciplines such as urban planning, civil engineering, institutional governance, and disaster management. Theoretical frameworks often point out multiple fundamental dimensions, such as physical (infrastructure), social, economic, institutional, and environmental. These frameworks also underline resilience characteristics like sustainability, redundancy, adaptation, recovery, transformation, and resource efficiency. Therefore, the concept of "resilience" has developed into a multi-faceted construct, understood and used across different disciplines.

The early evaluation of "resilience" in ecological sciences can be observed in Holling's [15] fundamental work, in which he described it as a system's ability to minimize negative effects of challenges while preserving its essential functions and structural linkages. This ecological concept of resilience has also been used in climate change, disaster risk, and sustainability issues [7].

Ribeiro and Gonçalves [16] classified resilience into five interrelated dimensions: natural, economic, social, physical, and institutional. They assume that "resilience" is characterized by the capacity to endure, recover, adapt, and transform in reaction to shocks and pressures. Similarly, in urban planning, resilience is inherently connected to the concepts of sustainable development. Goal 11 of the United Nations Sustainable Development Goals (SDGs) emphasizes "sustainable cities and human settlements"; therefore, the concept is closely related to the aims of urban resilience, especially in regions under higher disaster risks [17]. In this direction, OECD defines resilient cities as those that can develop balanced growth while possessing the ability to absorb, recover from, and adapt to future shocks [8]. Therefore, resilient urban systems are ready for sudden risks and can rapidly recover and sustain operations with a minimum level of interruptions. Considering the increasing frequency and severity of natural and human-made disasters, the necessity to improve urban resilience has become an essential goal for avoiding losses and preventing crises that might transform into disasters.

2.1 Advancing Urban Resilience: Global and National Perspectives in Turkey

Recently, academic and institutional efforts have been interested in understanding and developing urban resilience. A significant initiative in this context has been organized by the UNDRR, which has played a central role in developing urbanization that is resilient against disasters. The 2010 "Making Cities Resilient" campaign underlined key principles such as proactive disaster preparedness, participatory governance, and community-based risk management [1]. This campaign created a basis for the Sendai Framework for Disaster Risk Reduction, which was adopted in the Third UN World Conference on Disaster Risk Reduction in 2015 in Sendai, Japan. The framework encourages for globally coordinated efforts to reduce disaster-related deaths and the number of people affected by 2030 [18]. Particularly, the integration of the COVID-19 pandemic into resilience discourse has broadened the scope of urban resilience, because the pandemic increased the importance of public health issues and technological risks.

In Turkey, there is increasing interest in resilience at both national and local levels. However, the empirical and city-specific studies are limited. Most of the research tends to conceptualize resilience in general terms, so the existing studies lack deep analysis for accountable, localized urban resilience planning. Although the Provincial Risk Reduction Plans (IRAP) of AFAD under the Turkish Ministry of Interior provide useful risk identification tools, they also do not include the evaluation of the comprehensive resilience capacity of cities.

A specific exception is the Esenler NAR Innovation District, which is a pilot initiative that incorporates smart technologies, sustainable urban planning, Artificial Intelligence (AI) based optimization, and participatory planning to create a resilient urban ecosystem [19]. Additionally, there has been sector-specific research in recent years. For instance, Külekçi and Vural [20] investigated the vulnerability of highway tunnels after the February 2023 earthquakes, while Kıymaz et al. [21] underlined the lack of earthquake preparedness in the national education curriculum.

Some bibliometric analyses indicate a growing scholarly interest in urban resilience. Akbaş [22] traced an upward trend in resilience-related publications within Turkey, while İrdem and Mert [23] investigated the intersection between emergency management and urban resilience, and argue that integrated approaches combining resilient infrastructure with adaptive governance mechanisms are required. Erdoğan et al. [24] evaluated resilience indicators within the legal and urban planning frameworks in İzmir-Torbalı and emphasize the challenges caused by extreme weather conditions. Similarly, Şener and Tanrıöver [8] illustrate the potential of GIS in resilience planning through a case study in the Yıldırım district of Bursa in Turkey.

In response to the increasing density and intensity of seismic disasters, Demir [25] offered a comprehensive assessment of structural damage from the 2023 Kahramanmaraş earthquakes. He identifies persistent deficiencies in building stock and institutional barriers to preparedness and infrastructure. Similarly, Sonmez et al. [26] evaluated the seismic performance of reinforced concrete structures. They found out that wall systems with appropriate reinforcement levels display a greater resilience under large drift conditions, so they provide recommendations for future building regulations. On the other hand, Tunç et al. [27] contributed comparative studies across various seismic zones in Turkey, and explain both common vulnerabilities and context-specific resilience examples.

Collectively, these findings prove that urban resilience extends far beyond physical or structural considerations. Effective governance, public awareness, regulatory framework, land-use planning, emergency response capacity, and proactive risk reduction strategies are all integral to achieving urban resilience, especially in regions under earthquake risk. However, recent studies often lack a methodological approach in capturing the causal interdependencies among resilience criteria. There is a significant gap in the application of integrated analytical frameworks, such as fuzzy logic, DEMATEL, or other MCDM methods. These methods can evaluate the complex interaction between infrastructural, institutional, socio-cultural, and governance dimensions of resilience under uncertain and complex situations.

2.2 Multi-Criteria Decision Making (MCDM) Based Studies Regarding Resilient Cities

MCDM methods are critically important in both theoretical and practical fields due to their ability to evaluate the perspectives of different stakeholders and often conflicting criteria. Focusing on a single criterion is insufficient in areas with high uncertainty and multidimensional factors, such as disaster and earthquake management. In this sense, multiple factors such as cost, safety, accessibility, social vulnerability, and environmental sustainability must be evaluated. At that point, MCDM methods provide decision-makers with a systematic and rational framework. The significance of these methods in this study is their ability to integrate both technical and social factors in measuring earthquake vulnerability, enabling more scientific selection among alternative scenarios. Thus, MCDM is not merely a methodological choice but also an inevitable tool for developing more effective and applicable policies in disaster management [28].

The use of MCDM approaches for evaluating urban resilience has recently gained significant attention. Table 1 indicates several MCDM methods, including fuzzy logic extensions such as Neutrosophic fuzzy DEMATEL [29], spherical fuzzy AHP-EDAS together with clustering methods [30], and GIS-integrated methodologies like DEMATEL-ANP [31]. These studies investigated the intrinsic complexity of resilience assessment to find out the interrelations and uncertainties among resilience criteria. This is because they provide a comprehensive framework for decision-makers to prioritize improvements across diverse urban contexts that range from earthquake-prone areas to smart city planning.

Table 1. Studies related to resilient cities by using Multi-Criteria Decision-Making (MCDM) methods

Author(s)	Methodology	Application
Şeker et al. [29]	Neutrosophic fuzzy DEMATEL	Evaluate significant relationships between factors that need to be analyzed to establish sustainable and resilient cities
Kutty et al. [30]	Spherical fuzzy AHP-EDAS- fuzzy cmeans partitioning technique	Analyze the sustainability, resilience, and liability performance of European smart cities
Jamali et al. [31]	GIS-based DEMATEL-ANP	Study the resilience of districts in Tehran towards hazards
Javari et al. [32]	GIS-based AHP-TOPSIS	Evaluate environmental resilience by the analysis of quantitative and qualitative evidence on urban settlements in Malaxer city, Iran
Mabrouk and Han [33]	Fuzzy AHP-TOPSIS-VIKOR-WSM	Assess urban resilience for identifying urban flood-exposed risky districts
Tahmasebi Birgani and Yazdandogst [34]	Adaptive AHP-Entropy-TOPSIS	Evaluate resilient-sustainable urban drainage management plans
Moghadas et al. [35]	AHP-TOPSIS	Assess urban flood resilience in Tehran, Iran
Sarmadia and Aghababaei [36]	Delphi-DEMATEL-ANP	Investigate and prioritize dimensions of the Disaster Resilient System (DRS) in urban areas

Considering these developments, there is a lack of research that uses advanced MCDM methodologies in Turkish cities that are under high seismic risk. Recent literature mostly remains descriptive or generic, without quantitative, context-specific prioritization of resilience criteria. Furthermore, there is limited attention on the Fermatean Fuzzy Sets (FFSs), which have capabilities for representing uncertainty and complexity in expert evaluations relative to traditional fuzzy sets. This comprehensive method, composed of FFS-based DEMATEL that facilitates the identification and prioritization of significant criteria influencing earthquake resilience in Turkish cities. Using these FFSs, the research can point out the intrinsic uncertainty in expert evaluations and clarify the determining fuzzy causal relationships between resilience criteria. This method helps us to determine mutually influential and cause-and-effect relationships between the criteria related to earthquake resilience, so it can rank the criteria based on significance [14].

Consequently, this study enhances Turkish urban resilience literature by evaluating seismic risk by using data-driven methods and demonstrating the benefits of FFSs in disaster risk management. Mutual relationships (causal) model related to the urban earthquake resilience based criteria are developed via Fermatean Fuzzy DEMATEL (FF-DEMATEL). To the best knowledge of the authors, causal modeling urban earthquake resilience based criteria for the Turkish cities via FF-DEMATEL has been studied for the first time in the literature. The findings are expected to inform policy-making and strategic resilience-building efforts in vulnerable urban areas.

3 Research Methodology

This part of the study explains research design, key variables, data collection methods, and analytical techniques. It emphasizes identifying influential factors and applying a new MCDM framework for both theoretical and practical assessment in disaster risk management.

3.1 Research Question and Variables

This research aims to examine the significant criteria that affect the earthquake resilience of cities in Turkey, and seek to answer the following research question: "What are the primary criteria affecting urban earthquake-resilience in Turkish cities?". Based on the literature review, 9 criteria were hypothesized to investigate the earthquake-resilience of a city (see Table 2).

Table 2 summarizes essential criteria in the literature as significant in influencing the level of earthquake-resilience in Turkish cities. Each criterion is supported by empirical or theoretical research, so the existing literature proves its significance for disaster management and long-term urban sustainability. For instance, there is strong evidence for C2 (Safe Residential Areas) and C5 (Technology-Based Smart City Applications) in many studies, which shows that there is an increasing agreement about the significance of physical safety and digital transformation in resilience. In contrast, criteria such as C8 (Attitude of Decision Makers about Earthquake Resilience) and C9 (Effects of Internal and External Migration on Earthquake Resilience) were evaluated by fewer references. This can be because these are emerging areas of interest, or these factors were insufficiently examined in Turkey. This inconsistency can be eliminated by a more focused and comprehensive empirical investigation of different criteria in a single study. The table displays the multidimensional character of urban resilience and identifies deficiencies in the literature. Therefore, future studies should investigate resilience by using integrative methodologies that identify interdependencies among these criteria.

Table 2. Criteria and their description used in the Fermatean Fuzzy DEMATEL (FF-DEMATEL) analysis

Code	Criterion	Supporting References
C1	Critical Infrastructures	Sarı et al. [19]; Alhan and Haciemiroğlu [37]
C2	Safe Residential Areas	Özden [38]; Dincer and Partigöc [39]; Sarı et al. [19]
C3	Emergency Action Plans	Erkal and Değerliyurt [40]; Dökmeci and Akduman [41]
C4	Logistics Management	Ulugergerli [42]; Tekin Temur et al. [43]
C5	Technology-Based Smart City Applications	Yaman and Çakır [44]; Selçuk and Erem [45]; Demirelli et al. [46]
C6	Governance Mechanisms	Öztürk and Demirel [47]; Aydıner and Özgür [48]
C7	Earthquake Awareness in Society	Renschler et al. [49]; Karancı et al. [50]
C8	Attitude of Decision Makers about Earthquake Resilience	Acar [51]
C9	Effects of Internal and External Migration on Earthquake Resilience	Matsuura [52]

The evaluation criteria used in this study were determined through a multi-stage process, incorporating theoretical and empirical research in the literature as well as expert opinions. In the first stage, the literature on earthquake resilience and urban vulnerability was reviewed. As a result, it was found that criteria such as governance, institutional capacity, decision-making processes, social awareness, and physical infrastructure are fundamental elements for urban resilience [19, 47, 49, 51, 53–55]. Based on these findings, a preliminary pool of criteria was created. In the second stage, these criteria were evaluated by experts experienced in disaster management and urban planning. Thus, a new set of criteria was determined by reviewing the identified criteria according to two conditions: their compatibility with the purpose of the study and their evaluability using expert-based fuzzy analysis methods [56, 57]. In the final stage, some criteria that were highly overlapping and required GIS and spatially based data were excluded from the analysis because they were incompatible with the macro-level and expert-based design of the study, and the final list of criteria was determined [53].

3.2 Data Collection

This research benefits from a qualitative data collection technique that uses expert views to investigate the key factors affecting the earthquake-resilience of Turkish cities. The data were collected through semi-structured interviews with 17 experts from various professional sectors, including public institutions, Non-Governmental Organizations (NGOs), and private-sector companies from different cities in Türkiye, namely Eskişehir, Istanbul, Denizli, Kütahya, and Ankara. Table 3 presents an overview of the experts, who were interviewed during the data collection process.

3.2.1 Expert selection

The expert evaluations in this study were obtained using a purposive sampling approach. This approach is widely used in applied studies employing mixed methods because it allows for the systematic selection of participants with in-depth knowledge of the research topic [58]. Thus, these experts were selected from individuals with at least 10 years of practical and academic expertise in diverse fields such as disaster management, earthquake risk reduction, urban and regional planning, civil engineering, and public administration. Furthermore, it was ensured that these experts had been involved in practical applications, policy development processes, or academic research in earthquake or disaster management processes. This provided interdisciplinary diversity, a balance between academics and practitioners, and diverse institutional perspectives. As a result, this approach allowed for a holistic evaluation of the criteria from both theoretical and practical perspectives.

Table 3. Profile of expert participants

No.	Profession/Title	Sector	Experience (Years)
1	Researcher/Executive	Private Sector (Hazama Ando Corporation)	40
2	Assoc. Prof./Geophysics Engineer	Public Sector (Eskisehir Technical University)	24
3	Volunteer/Psychologist	Civil Society (TUDAK-Search, Rescue and Humanitarian Aid Association)	5
4	Dr./Disaster & Urban Risk Specialist	Public Sector (Dumlupinar University)	5
5	Geological Engineer	Public Sector (AFAD)	21
6	Dr./Public Law Expert	Public Sector (Anadolu University)	5
7	Volunteer/Search & Rescue	Civil Society (GEA-Active Philosophical Culture Association)	8
8	Prof. Dr./Geotechnical & Earthquake	Public Sector (Anadolu University)	35
9	Lawyer/Volunteer	Private Sector/Civil Society (TBD)	27
10	Dr./Urban, Environmental Disasters	Public Sector (Pamukkale University)	12
11	Local Administrator (Muhtar)	Public Sector (Eskisehir Batkent Mukhtar)	25
12	Assoc. Prof./Urbanization Expert	Public Sector (Hacı Bayram Veli University)	16
13	Civil Engineer	Public Sector (Ministry of Environment, Urbanization, and Climate Change)	18
14	Prof. Dr./Disaster Risk Management	Public Sector (Anadolu University)	22
15	Volunteer/Former Municipal Member	Civil Society/Public Sector (Eskisehir City Council/Metropolitan Municipality)	20
16	Dr./Volunteer	Civil Society/Public Sector (AKUT Search and Rescue Association & Anadolu University)	5
17	Branch Manager/Engineer	Public Sector (Eskisehir Metropolitan Municipality)	10

3.2.2 Reliability of expert judgments

To increase the reliability of expert evaluations, the FFSs approach was used, which reduces uncertainty and subjective opinions by modeling them. This is because, while classical fuzzy sets address uncertainty through membership degrees [59], intuitionistic fuzzy sets examine both membership and non-membership degrees [60]. However, FFSs represent this structure in a wider field of uncertainty, capturing hesitation and indecision in expert evaluations more flexibly [13]. Within this approach, individual expert evaluations were first combined within the framework of a group decision-making approach, and these evaluations were subjected to aggregation through fuzzy numbers. Then, the influence and causality structures between the criteria were systematically revealed using the DEMATEL method, and complex relationships were modeled [61]. Furthermore, consensus-based studies typically have expert panel sizes ranging from 7 to 15 experts, rarely exceeding 30 in the literature [56, 62]. On the other hand, while Delphi-based applications may vary in number depending on the research context, the key factors are the experts' competence in their respective fields and the transparency of the processes [57]. Within this framework, the 17 expert opinions included in this study provide a reasonable methodological basis for group-based fuzzy analysis.

3.2.3 Generalizability and limitations

The findings of this study do not claim statistical generalization, as they are based on the knowledge and experience of the selected expert group. This is because expert-based consensus approaches do not aim to statistically represent the population. Instead, the main goal is to construct a decision model by structuring the knowledge of qualified experts to address an existing decision-making problem under conditions of uncertainty [56, 57]. Therefore, the findings obtained in this research should be interpreted according to the context and expert profiles. This is because the importance levels of the criteria and their causal relationships may vary according to different geographical, institutional, or socio-economic conditions. For this reason, in future research, comparative analyses with larger and more diversified expert groups for different cities or countries would further strengthen the external validity of the new results [62].

Studies on disaster risk reduction and urban resilience demonstrate that resilience indicators should be assessed not only at the administrative or institutional levels but also at the spatial scale. GIS based approaches, in particular, show that analyzing the geographical distribution of vulnerability and resilience indicators can identify areas where risk is concentrated. Such spatial analyses enable policymakers to make more effective and equitable resource allocations [53, 54]. However, another significant limitation of this study is the absence of GIS or spatial datasets in the analysis process. In future research, including GIS and spatial datasets will allow for a more detailed examination of such local differences and a geographical comparison of the criterion effects.

3.3 Data Analysis

This section consists of preliminaries related to FFSs and FF-DEMATEL, respectively.

3.3.1 Preliminaries related to Fermatean Fuzzy Sets (FFSs)

Q-rung orthopair fuzzy sets (QFS), as a general class of intuitionistic (IFS) and Pythagorean Fuzzy Sets (PFS), are proposed by Yager [63]. According to the QFS, the sum of the qth power of membership and non-membership degrees is bounded between 0 and 1. Senapati and Yager [13] called QFS as FFSs in terms of considering q = 3. Comparison related to IFS, PFS, and FFS can be seen in Figure 1.

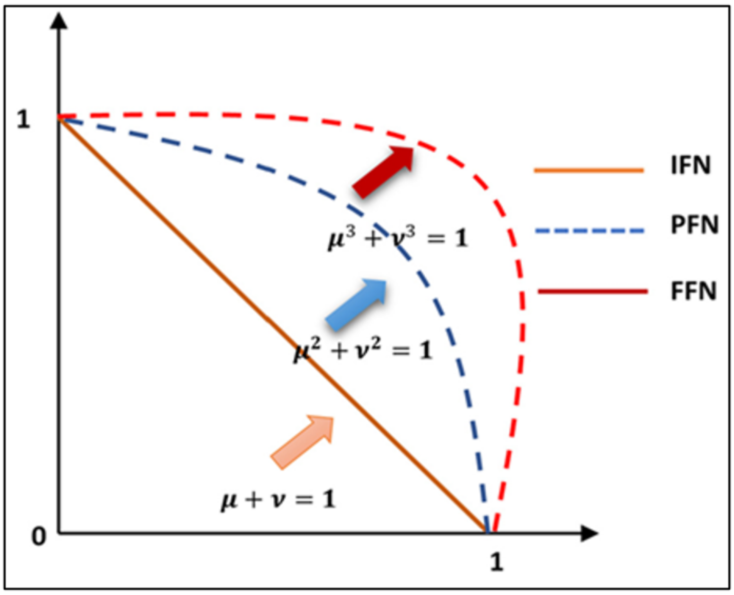

Figure 1. Comparison in terms of IFSs, PFSs, and FFSs
Source: Senapati and Yager [13]; Alkan and Kahraman [64]

According to Figure 1, while Intuitionistic Membership Degrees (IMDs) are all points under the $\mu + \upsilon \leq 1$, it is valid for Pythagorean Membership Degrees (PMDs) in terms of $\mu^2 + \upsilon^2 \leq 1$. Fermatean Membership Degrees (FMDs), which are all points under the $\mu^3 + \upsilon^3 \leq 1$ allow higher non-membership grades than IMDs and PMDs. In this way, FFSs allow Decision Makers (DMs) more flexibility and accuracy for explaining uncertainty and vagueness related to subjective evaluation of criteria as compared to triangular, IFS, and PFSs.

Consider X as a universe of discourse and a FFS K in X can be defined as an object having the form like below [13, 64]:

$$K = \{\langle x, \mu_K(x), \upsilon_K(x)\rangle : x \in X\} \tag{1}$$

where, $\mu_K(x) : X \to [0, 1]$ and $\upsilon_K(x) : X \to [0, 1]$ consist of situation

$$0 \leq (\mu_K(x))^3 + (\upsilon_K(x))^3 \leq 1 \tag{2}$$

for all $x \in X$. The membership and non-membership degrees related to the component x in the set K can be stated via $\mu_K(x)$ and $\upsilon_K(x)$ respectively.

For any FFS K and $x \in X$, the hesitancy degree can be computed as below:

$$\pi_K(x) = \sqrt[3]{1 - (\mu_K(x))^3 - (\upsilon_K(x))^3} \tag{3}$$

Consider $K = (\mu_K, \upsilon_K), K_1 = (\mu_{K_1}, \upsilon_{K_1})$ and $K_2 = (\mu_{K_2}, \upsilon_{K_2})$ as three FFSs and $\lambda > 0$. Operations related to them can be stated as follows [13, 64]:

$$K_1 \oplus K_2 = \left(\sqrt[3]{\mu_{K_1}^3 + \mu_{K_2}^3 - \mu_{K_1}^3 \mu_{K_2}^3}, \upsilon_{K_1}\upsilon_{K_2}\right) \tag{4}$$

$$K_1 \otimes K_2 = \left(\mu_{K_1}\mu_{K_2}, \sqrt[3]{\upsilon_{K_1}^3 + \upsilon_{K_2}^3 - \upsilon_{K_1}^3 \upsilon_{K_2}^3}\right) \tag{5}$$

$$\lambda K = \left(\sqrt[3]{1-(1-\mu_K^3)^\lambda}, \upsilon_K^\lambda\right), \lambda > 0 \tag{6}$$

$$K^\lambda = \left(\mu_K^\lambda, \sqrt[3]{1-(1-\upsilon_K^3)^\lambda}\right), \lambda > 0 \tag{7}$$

Assume $K_i = (\mu_{K_i}, \upsilon_{K_i})\,(i = 1, 2, \ldots, n)$ as a set of FFNs and $w = (w_1, w_2, \ldots, w_n)^T$ as a weight vector related to K_i with $\sum_{i=1}^n w_i = 1$. Besides Fermatean Fuzzy Weighted Average (FFWA) operator related to them can be written as below [64, 65]:

$$FFWA(K_1, K_2, \ldots, K_n) = \left(\sum_{i=1}^n w_i \mu_{K_i}, \sum_{i=1}^n w_i \upsilon_{K_i}\right) \tag{8}$$

3.3.2 Fermatean Fuzzy DEMATEL (FF-DEMATEL)

The DEMATEL is considered an effective tool for determining the mutual influential, cause-and-effect, and complex relationships between criteria and prioritizing them accordingly [14]. DEMATEL is applied for evaluating the mutual impact among different factors by including decision makers' pairwise comparisons to find out both indirect and direct effects [66]. FFS, which give the decision makers more freedom in subjective evaluations, provide more flexibility, efficiency, and accuracy in terms of addressing complex uncertain decision-making problems than triangular, IFS, and PFS [13]. FF-DEMATEL provides inter-dependencies and a fuzzy causal model more accurate than other methods, such as Interpretive Structural Modeling (ISM), Total Interpretive Structural Modeling (TISM), by offering a broader range of options with respect to the quantification for the power of causal relationships [14, 66].The proposed FF-DEMATEL methodology integrates quantitative information and provides a clear visual representation, eliminating the limitations of crisp DEMATEL by handling the concept of uncertainty, complexity, and ambiguity. FF-DEMATEL is considered as robust and adaptable tool for insightful research within different fields [14, 67]. Steps of Fermatean Fuzzy DEMATEL can be stated as follows [66, 68]:

Step 1. An expert decision-making group is established. A decision-making group which has expertise in earthquake resilient factors related to cities is formed, and each decision-maker (DM) in the group is denoted as DM_k, where $k = 1, 2, \ldots, K$.

Step 2. The linguistic variables related to FFs are built. All DMs in the group agree on the resilience-based criteria for this study. The criteria j can be shown as C_j, where $j = 1, 2, \ldots, n$. The evaluation of interrelationships and effect between these criteria can be handled via the linguistic variables provided in Table 4.

Table 4. Linguistic variables related to Fermatean Fuzzy Sets (FFs)

Linguistic Variable Effect Level	FF Number Membership (μ)	Non-Membership (υ)
Very Low Effect (VLE)	0.06	0.99
Low Effect (LE)	0.11	0.99
Medium Low Effect (MLE)	0.27	0.98
Medium Effect (ME)	0.44	0.95
Medium High Effect (MHE)	0.56	0.90
High Effect (HE)	0.69	0.82
Very High Effect (VHE)	0.81	0.67
Extremely High Effect (EHE)	0.92	0.51
Entirely Effect (EE)	1.00	0.00

Source: Kao et al. [69]

Step 3. The FFs direct relationship matrix is established. DM k evaluates the direct effect power of criteria i on criteria j consistent with Table 4 for obtaining the FFs direct relationship matrix $X^{(k)}$, as denoted in Eq. (9).

$$X^{(k)} = \begin{bmatrix} \left(\mu_F\left(x_{11}^{(k)}\right), v_F\left(x_{11}^{(k)}\right)\right) \left(\mu_F\left(x_{12}^{(k)}\right), v_F\left(x_{12}^{(k)}\right)\right) \\ \cdots \left(\mu_F\left(x_{1n}^{(k)}\right), v_F\left(x_{1n}^{(k)}\right)\right) \\ \left(\mu_F\left(x_{21}^{(k)}\right), v_F\left(x_{21}^{(k)}\right)\right) \left(\mu_F\left(x_{22}^{(k)}\right), v_F\left(x_{22}^{(k)}\right)\right) \\ \cdots \left(\mu_F\left(x_{2n}^{(k)}\right), v_F\left(x_{2n}^{(k)}\right)\right) \vdots \ddots \vdots \left(\mu_F\left(x_{n1}^{(k)}\right), v_F\left(x_{n1}^{(k)}\right)\right) \\ \left(\mu_F\left(x_{n2}^{(k)}\right), v_F\left(x_{n2}^{(k)}\right)\right) \cdots \left(\mu_F\left(x_{nn}^{(k)}\right), v_F\left(x_{nn}^{(k)}\right)\right) \end{bmatrix}, i = j = 1, 2, \ldots, n; k = 1, 2, \ldots, K. \tag{9}$$

where, $\mu_F\left(x_{ij}^{(k)}\right)$ and $v_F\left(x_{ij}^{(k)}\right)$ describe the membership (μ) and non-membership (v) related to the evaluations of x events respectively, in which $0 \le \mu_F\left(x_{ij}^{(k)}\right) \le 1$ and $0 \le v_F\left(x_{ij}^{(k)}\right) \le 1$. Besides, the diagonal elements of the matrix must be zero, in other words there is no self-influence between criteria $\left(\mu_F\left(x_{ii}^{(k)}\right), v_F\left(x_{ii}^{(k)}\right)\right) = 0$.

On the other hand, $0 \le \left(\mu_F\left(x_{ij}^{(k)}\right)\right)^3 + \left(v_F\left(x_{ij}^{(k)}\right)\right)^3 \le 1$. The degree of uncertainty in terms of the evaluation of DM k is computed via Eq. (10):

$$\pi_F\left(x_{ij}^{(k)}\right) = \sqrt[3]{1 - \left(\mu_F\left(x_{ij}^{(k)}\right)\right)^3 - \left(v_F\left(x_{ij}^{(k)}\right)\right)^3}, 0 \le \pi_F\left(x_{ij}^{(k)}\right) \le 1. \tag{10}$$

Step 4. The average FFs direct relationship matrix is constructed. In order to aggregate the judgments of DMs arithmetic mean is considered for obtaining the average FF direct relationship matrix B, as shown in Eq. (11).

$$B = \begin{bmatrix} \left(\mu_F(b_{11}), v_F(b_{11})\right) \left(\mu_F(b_{12}), v_F(b_{12})\right) \cdots \\ \left(\mu_F(b_{1n}), v_F(b_{1n})\right) \left(\mu_F(b_{21}), v_F(b_{21})\right) \left(\mu_F(b_{22}), v_F(b_{22})\right) \\ \cdots \left(\mu_F(b_{2n}), v_F(b_{2n})\right) \vdots \ddots \vdots \left(\mu_F(b_{n1}), v_F(b_{n1})\right) \\ \left(\mu_F(b_{n2}), v_F(b_{n2})\right) \cdots \left(\mu_F(b_{nn}), v_F(b_{nn})\right) \end{bmatrix}, i = j = 1, 2, \ldots, n. \tag{11}$$

where, $\left(\mu_F(b_{ij}), v_F(b_{ij})\right) = \frac{\sum_{k=1}^{K}\left(\mu_F\left(x_{ij}^{(k)}\right), v_F\left(x_{ij}^{(k)}\right)\right)}{k}$.

Step 5. The average FFs score function and the degree of vagueness related to the integration of DMs are computed in terms of calculation rules related to FFs score function proposed by Senapati and Yager [13]. The average FFs score function is obtained according to Eq. (12).

$$sf\left(\mu_F(b_{ij}), v_F(b_{ij})\right) = \left(\mu_F(b_{ij})\right)^3 - \left(v_F(b_{ij})\right)^3, -1 \le sf\left(\mu_F(b_{ij}), v_F(b_{ij})\right) \le 1. \tag{12}$$

The range of score function as [-1, 1] may not be intuitive for practical decison-making. In order to converge the range between 0 and 1, Eq. (13) as the FF defuzzification function (φ_{ij}) needs to be taken into the account.

$$\varphi_{ij} = 1 + sf\left(\mu_F(b_{ij}), v_F(b_{ij})\right), 0 \le \varphi_{ij} \le 1. \tag{13}$$

By using the Eqs. (12) and (13), the average FFs direct relationship matrix is converted to the initial relationship matrix which is defined in Eq. (14).

$$\varphi = \left[\varphi_{11}\varphi_{12}\cdots\varphi_{1n}\varphi_{21}\varphi_{22}\cdots\varphi_{2n}\vdots\ddots\vdots\varphi_{n1}\varphi_{n2}\cdots\varphi_{nn}\right], i = j = 1, 2, \ldots, n. \tag{14}$$

Step 6. The normalized relationship matrix is constructed. The effective relationships between criteria are determined in terms of the traditional DEMATEL method. The normalized relationship matrix is constructed by executing the normalization process as shown in Eq. (15).

$$\beta = \left[\varepsilon\cdot\varphi_{11}\varepsilon\cdot\varphi_{12}\cdots\varepsilon\cdot\varphi_{1n}\varepsilon\cdot\varphi_{21}\varepsilon\cdot\varphi_{22}\cdots\varepsilon\cdot\varphi_{2n}\vdots\ddots\vdots\varepsilon\cdot\varphi_{n1}\varepsilon\cdot\varphi_{n2}\cdots\varepsilon\cdot\varphi_{nn}\right], i = j = 1, 2, \ldots, n \tag{15}$$

where, $\varepsilon = \frac{1}{\max\left\{\sum_{j=1}^{n}\varphi_{ij}, \sum_{i=1}^{n}\varphi_{ij}\right\}}$.

Step 7. The total effect matrix is obtained. The matrix is multiplied and summed up according to Eq. (16). This process leads to the generation of total effect matrix which is presented in Eq. (17).

$$G = \beta + \beta^2 + \beta^3 + \cdots + \beta^\infty = \beta\left(I + \beta + \beta^2 + \beta^3 + \cdots + \beta^{\infty-1}\right) = \beta\left(I - \beta^\infty\right)(I - \beta)^{-1} = \beta(I - \beta)^{-1} \tag{16}$$

where, $\beta^\infty = [0]_{nxn}$, and I illustrates the identity matrix.

$$G = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nn} \end{bmatrix}, i = j = 1, 2, \ldots, n. \tag{17}$$

Step 8. The weights of the criteria are acquired and the causal diagram is generated. The elements (g_{ij}) of the total effect matrix (G) can be interpreted as the sum of the direct and indirect effect of criteria i on criteria j. Besides, the degree of effect related to criteria i, represented as r_i can be acquired via Eq. (18). Similarly, the degree of being affected related to criteria i, denoted as s_i is computed according to Eq. (19).

$$r_i = g_{11} + g_{12} + \cdots + g_{1n} = \sum_{j=1}^{n} g_{ij} \tag{18}$$

$$s_i = g_{11} + g_{21} + \cdots + g_{n1} = \left[\ \sum_{j=1}^{n} \quad g_{ij}\ \right]^{Transpose} \tag{19}$$

The total influence related to criterion i, comprising of r_i and s_i, can be identified as r_i + s_i. The effect weight related to criterion i within the evaluation system, is acquired via Eq. (20).

$$w_i = \frac{r_i + s_i}{\sum_{i=1}^{n}(r_i + s_i)} \tag{20}$$

The net effect related to criterion i is denoted by $r_i - s_i$. If $r_i - s_i$ > 0, the criterion i significantly affects other criteria. As opposed to this, if $r_i - s_i$ < 0, the criterion i is significantly affected by other criteria. The relative positions of each criterion can be drawn by considering prominence $(r_i + s_i)$ and net effect $(r_i - s_i)$ as horizontal and vertical axes of the causal diagram, respectively. The flowchart related to FF-DEMATEL is illustrated in Figure 2.

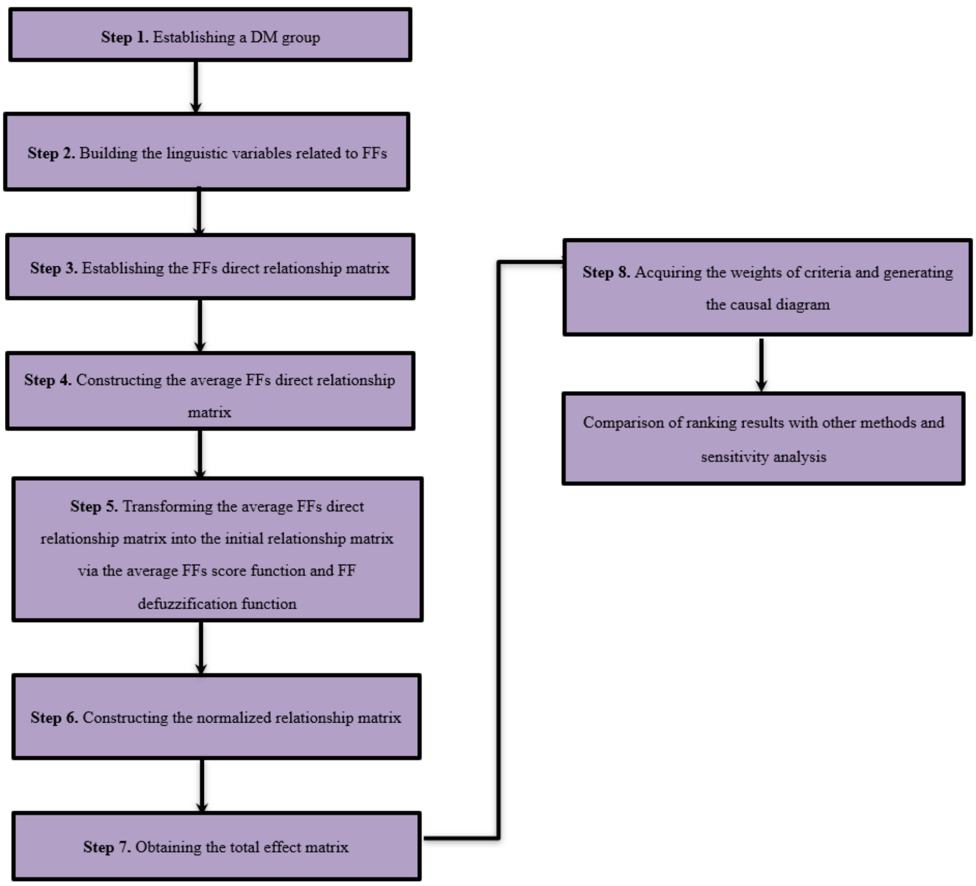

Figure 2. Framework related to Fermatean Fuzzy DEMATEL (FF-DEMATEL)

4 Findings and Discussion

The criteria that are taken into account in this study are determined based on a deep literature review and the views of the DM group. Criteria that have an impact on the resilience of the cities to the earthquake are presented in Table 5.

Table 5. Criteria affecting the resilience of cities to earthquakes

Criteria (Code)	Definition
C1 - Critical infrastructures	(e.g., electricity, water, communication, health, education, transportation)
C2 - Safe residential areas	(e.g., urbanization, legislation, assembly areas, seismic and risk maps)
C3 - Emergency action plans	(e.g., risk&crisis management, search&rescue, secondary disasters)
C4 - Logistics management	(e.g., humanitarian aid, resource distribution, and debris management)
C5 - Technology-based smart city applications	(e.g., AI, e-services, early warning&monitoring)
C6 - Governance mechanisms	(e.g., citizens, experts, NGOs, private-public sectors, international organizations)
C7 - Earthquake awareness in the society	(e.g., education, seminars, workshops, conferences)
C8 - Attitude of decision makers about earthquake resilience	(e.g., implementing resilient city policies, cooperation with all stakeholders, visionary leaders)
C9 - Effects of Internal and External Migration on Earthquake Resilience	(e.g., housing need, brain drain, urban concentration, social cohesion, in-migration, and out-migration)

The members of the DM group are all experienced related to the resilience of cities to earthquakes based duties for at least five years (see Table 3). After generating the DM group and determining the criteria related to the resilience of cities to earthquakes, the survey stage is initiated. Survey is given in the Appendix part. Pairwise comparison of criteria for all DMs is made, and the obtained FFs direct relation matrices are formed according to Eq. (9). As an example, the FFs direct relation matrix composed of linguistic variables for DM1 is presented in Table 6.

Table 6. The Fermatean Fuzzy Sets (FFs) direct relation matrix including linguistic variables according to DM1

DM1	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	EE	EE	EE	EE	EE	EE	EE	EHE
C2	EE	0	VHE	EE	EE	EE	EE	EE	EHE
C3	EE	EE	0	MHE	EE	EE	EE	EE	EHE
C4	EE	EE	EE	0	EE	EE	EE	EE	EE
C5	EE	MHE	EE	EE	0	EE	EE	MHE	MHE
C6	EE	EE	EE	EE	EE	0	EE	EE	EE
C7	EE	EE	EE	EE	EE	EE	0	EE	EE
C8	EE	EE	EE	EE	HE	EE	EE	0	EE
C9	EE	LE	EE	EE	EE	EE	EE	EE	0

The FFs' direct relation matrices for other DMs (2–17) are given in the Supplementary File. Following to this linguistic responses are converted to fuzzy values and are presented in Table 7 according to DM1.

Table 7. The Fermatean Fuzzy Sets (FFs) direct relation matrix including FF numbers according to DM1

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	([0, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([0.92, 0.51])
C2	([1, 0])	([0, 0])	([0.81, 0.67])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([0.92, 0.51])
C3	([1, 0])	([1, 0])	([0, 0])	([0.56, 0.9])	([1, 0])	([1, 0])	([1, 0])	([1,0])	([0.92, 0.51])
C4	([1, 0])	([1, 0])	([1, 0])	([0, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])
C5	([1, 0])	([0.56, 0.9])	([1, 0])	([1,0])	([0, 0])	([1, 0])	([1, 0])	([0.56, 0.9])	([0.56, 0.9])
C6	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([0, 0])	([1, 0])	([1, 0])	([1, 0])
C7	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([0, 0])	([1, 0])	([1, 0])
C8	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([0.69, 0.82])	([1, 0])	([1, 0])	([0, 0])	([1, 0])
C9	([1, 0])	([0.11, 0.99])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([1, 0])	([0, 0])

Each DM's degree of uncertainty in the evaluation is acquired by using Eq. (10). Through Eq. (11), the judgements of DMs are aggregated, and obtained average FFs direct relationship matrix is presented in Table 8.

Table 8. Average direct relationship matrix

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	([0, 0])	([0.75, 0.41])	([0.72, 0.48])	([0.77, 0.51])	([0.69, 0.48])	([0.55, 0.71])	([0.38, 0.74])	([0.60, 0.55])	([0.51, 0.77])
C2	([0.77, 0.40])	([0, 0])	([0.82, 0.48])	([0.79, 0.47])	([0.64, 0.61])	([0.62, 0.61])	([0.51, 0.65])	([0.72, 0.45])	([0.63, 0.65])
C3	([0.70, 0.53])	([0.69, 0.46])	([0, 0])	([0.76, 0.54])	([0.64, 0.67])	([0.68, 0.58])	([0.67, 0.54])	([0.68, 0.52])	([0.48, 0.82])
C4	([0.69, 0.48])	([0.67, 0.50])	([0.79, 0.44])	([0, 0])	([0.67, 0.58])	([0.65, 0.57])	([0.48, 0.76])	([0.63, 0.58])	([0.48, 0.79])
C5	([0.79, 0.36])	([0.68, 0.57])	([0.76, 0.51])	([0.80, 0.47])	([0, 0])	([0.68, 0.58])	([0.56, 0.68])	([0.60, 0.63])	([0.43, 0.87])
C6	([0.72, 0.50])	([0.65, 0.57])	([0.81, 0.44])	([0.81, 0.48])	([0.77, 0.51])	([0, 0])	([0.75, 0.52])	([0.86, 0.36])	([0.56, 0.70])
C7	([0.66, 0.58])	([0.73, 0.45])	([0.70, 0.49])	([0.69, 0.51])	([0.65, 0.64])	([0.80, 0.36])	([0, 0])	([0.81, 0.39])	([0.63, 0.53])
C8	([0.89, 0.24])	([0.90, 0.23])	([0.82, 0.35])	([0.87, 0.26])	([0.85, 0.35])	([0.91, 0.25])	([0.89, 0.30])	([0, 0])	([0.72, 0.53])
C9	([0.60, 0.62])	([0.55, 0.63])	([0.53, 0.74])	([0.62, 0.68])	([0.39, 0.85])	([0.46, 0.77])	([0.52, 0.73])	([0.52, 0.69])	([0, 0])

The FF score function is defuzzified via Eqs. (12) and (13). Following this, the average FFs direct relationship matrix is converted to the initial relationship matrix, which is given in Table 9.

Table 9. Initial relationship matrix

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	1.361	1.266	1.320	1.211	0.800	0.651	1.047	0.676
C2	1.403	0	1.441	1.399	1.039	1.005	0.852	1.277	0.976
C3	1.198	1.236	0	1.288	0.958	1.125	1.137	1.180	0.561
C4	1.229	1.177	1.418	0	1.105	1.087	0.662	1.051	0.609
C5	1.446	1.135	1.308	1.417	0	1.123	0.861	0.969	0.410
C6	1.258	1.096	1.448	1.429	1.321	0	1.293	1.604	0.819
C7	1.091	1.296	1.233	1.195	1.019	1.470	0	1.483	1.103
C8	1.708	1.717	1.507	1.654	1.582	1.737	1.695	0	1.229
C9	0.977	0.915	0.733	0.915	0.446	0.636	0.753	0.811	0

According to the normalization process, as shown in Eq. (15), the normalized relationship matrix is generated as Table 10.

Table 10. Normalized relationship matrix

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	0.106	0.098	0.102	0.094	0.062	0.050	0.081	0.052
C2	0.109	0	0.112	0.109	0.081	0.078	0.066	0.099	0.076
C3	0.093	0.096	0	0.100	0.074	0.087	0.088	0.092	0.043
C4	0.095	0.091	0.110	0	0.086	0.084	0.051	0.081	0.047
C5	0.112	0.088	0.101	0.110	0	0.087	0.067	0.075	0.031
C6	0.098	0.085	0.112	0.111	0.102	0	0.100	0.125	0.063
C7	0.085	0.101	0.096	0.093	0.079	0.114	0	0.115	0.085
C8	0.133	0.133	0.117	0.128	0.123	0.135	0.132	0	0.095
C9	0.076	0.071	0.057	0.071	0.034	0.049	0.058	0.063	0

Through Eq. (16), the total effect matrix is obtained and given in Table 11.

Table 11. Total effect matrix

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0.215	0.304	0.307	0.315	0.272	0.247	0.215	0.271	0.184
C2	0.338	0.232	0.343	0.345	0.282	0.283	0.248	0.309	0.221
C3	0.312	0.307	0.229	0.324	0.266	0.280	0.257	0.292	0.185
C4	0.304	0.293	0.319	0.223	0.266	0.268	0.218	0.274	0.181
C5	0.326	0.298	0.320	0.331	0.194	0.277	0.236	0.276	0.172
C6	0.354	0.335	0.369	0.372	0.322	0.233	0.298	0.354	0.226
C7	0.333	0.338	0.344	0.347	0.293	0.327	0.199	0.338	0.240
C8	0.437	0.427	0.428	0.443	0.386	0.401	0.365	0.293	0.288
C9	0.232	0.223	0.217	0.232	0.174	0.189	0.181	0.207	0.103

The results with respect to the FF-DEMATEL are acquired via executing the Eqs. (18) to (20) and shown in Table 12. Then the causal diagram can be plotted by considering "$r + s$ (prominence)" as the horizontal axis and "$r - s$ (net effect)" as the vertical axis, as in Figure 3. The higher the "$r + s$" value, the more significant the criterion related to the evaluation. The higher "$r - s$" shows the power of effect related to the criterion. Decision-makers can understand which criteria are effective and which are susceptible to the effect of others by using the causal diagram. Causal diagram allows the visualization of the results related to the analysis and provides DMs a clear and structured view of the influence for all criteria included. Additonally this visual depiction improves understanding by defining complicated relationships and effect levels related to different criteria [66].

Table 12. The results of the Fermatean Fuzzy DEMATEL (FF-DEMATEL)

Criteria	r	s	$r + s$ (Prominence)	$r - s$ (Net Effect)	Cause/Effect	Weight	Rank
C1	2.335	2.854	5.190	-0.519	Effect	0.112	6
C2	2.605	2.760	5.365	-0.154	Effect	0.116	3
C3	2.456	2.882	5.339	-0.425	Effect	0.115	4
C4	2.348	2.936	5.285	-0.588	Effect	0.114	5
C5	2.434	2.458	4.893	-0.023	Effect	0.106	8
C6	2.866	2.510	5.377	0.356	Cause	0.116	2
C7	2.763	2.221	4.984	0.541	Cause	0.108	7
C8	3.473	2.618	6.092	0.854	Cause	0.132	1
C9	1.762	1.804	3.567	-0.041	Effect	0.077	9

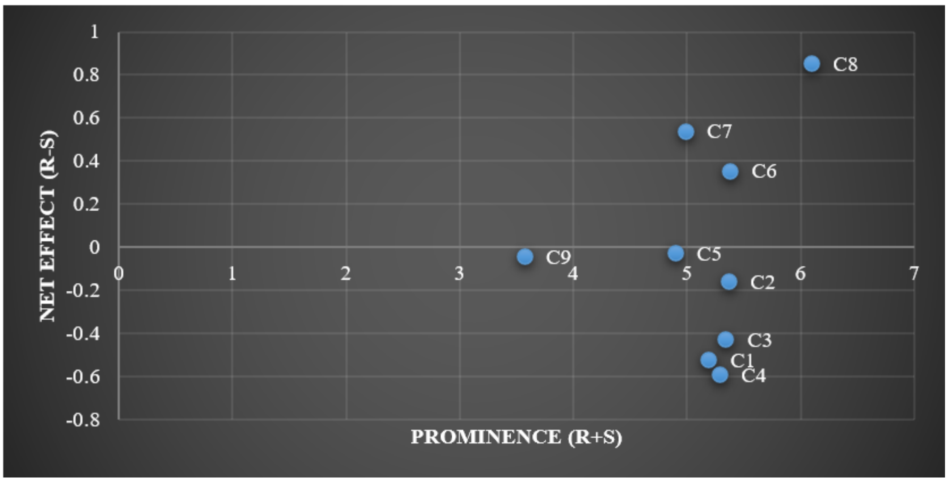

Figure 3. Causal diagram related to the resilience of Turkish cities to earthquakes

The mutual relationships between the criteria affecting the resilience of the cities are presented via the results of the FF-DEMATEL. Findings from Table 12 and Figure 3 show that three criteria (C6, C7, and C8) have a positive net effect ($r - s$) and belong to the cause group that affects other criteria. The remaining six criteria (C1, C2, C3, C4, C5, and C9) belong to the effect group due to having a negative net effect ($r - s$) value. The decreasing order of influence related to the cause group is the attitude of decision makers about earthquake resilience (C8), governance mechanisms (C6), and earthquake awareness in the society (C7), according to the resilience of Turkish cities to earthquakes. On the other hand the decreasing order of effect related to the effect group is logistics management (C4), critical infrastructures (C1), emergency action plans (C3), safe residential areas (C2), effects of internal and external migration on earthquake resilience (C9), and technology-based smart city applications (C5) in terms of the resilience of Turkish cities to earthquake. Cause group is considered the controlling factor that significantly contributes to the attainment and sustenance of the resilience of the cities to earthquakes and has an impact on the effect group. By effectively managing and enhancing these criteria, the resilience of the cities to earthquakes can be improved, too. For this purpose, these criteria are accorded to higher priority than others.

According to Table 12, while the attitude of decision makers about earthquake resilience (C8) was found as the most important criterion with the value of 0.132, the effects of internal and external migration on earthquake resilience (C9) were obtained as the least important one with the value of 0.077.

5 Sensitivity Analysis

In order to check the validity and reliability of the proposed FFS based DEMATEL methodology a sensitivity analysis is carried out. The impacts of excluding experts on the criteria ranking performance are examined. For this purpose a total of 153 scenarios were created by removing experts one by one and in pairs from the analysis. The results of the sensitivity analysis are depicted in Figure 4.

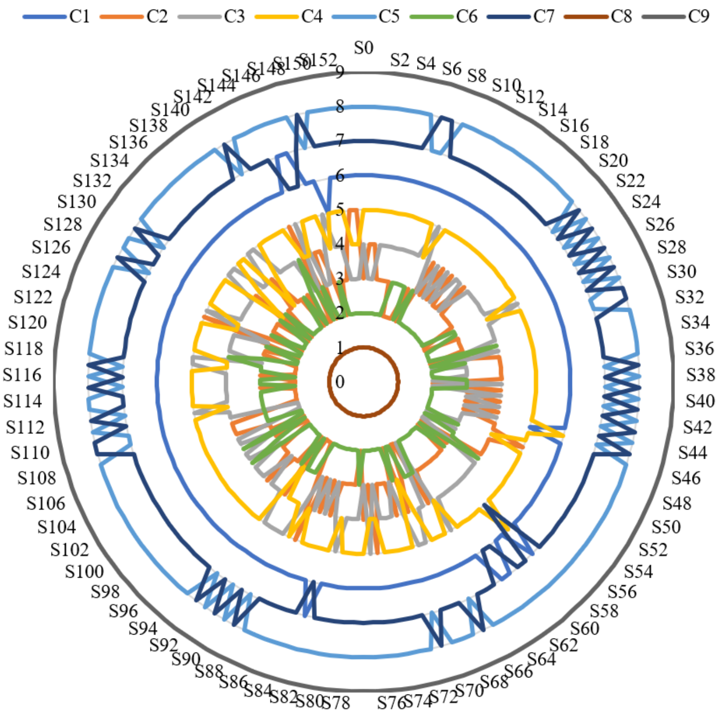

Figure 4. Ranking changes related to the criteria by removing experts

As can be seen from Figure 4, minor changes are detected with respect to the ranking of criteria in the scenarios created towards to the expert exclusion. Same ranking results have been obtained for 47 scenarios and average Spearman Rank Correlation Coefficient (SRCC) value among the acquired results of all scenarios has been found as 97.9%. C8 has remained the best criterion for all senarios, C6 has been acquired as the second-best criterion for 101 scenarios (66.01%) and C2 has been defined as the third-best criterion for 68 scenarios (44.44%). On the other hand, C9 has been found as the last criterion for all scenarios. Changes with respect to the ranking of the criteria for generated different 153 scenarios are given in Table 13.

As proposed by Ecer [70] and Ecer et al. [71], the ranking results related to the FFS based DEMATEL model and the 153 scenarios constructed were analyzed via SRCC. All correlation coefficients are greater than 0.95, exhibiting a high correlation between the ranking results of the proposed model and the ranking results of the different scenarios. The results obtained from the SRCC show that expert exclusion in different scenarios do not significantly affect the final ranking of the proposed FFS based DEMATEL approach. In general, proposed model can be handled as stable, valid, robust and less sensitive towards the expert exclusion.

Table 13. Ranking of the criteria according to the created various 153 scenarios

	1	2	3	4	5	6	7	8	9	Similarity (%)
C1	0	0	0	0	2	145	6	0	0	94.77
C2	0	42	68	36	7	0	0	0	0	44.44
C3	0	10	35	87	21	0	0	0	0	56.86
C4	0	0	4	24	123	2	0	0	0	80.39
C5	0	0	0	0	0	0	27	126	0	82.35
C6	0	101	46	6	0	0	0	0	0	66.01
C7	0	0	0	0	1	5	120	27	0	78.43
C8	153	0	0	0	0	0	0	0	0	100
C9	0	0	0	0	0	0	0	0	153	100

6 Comparison Analysis

To check the reliability of the ranking result obtained from the existing FFS-based DEMATEL methodology, a comparison analysis is made with other MCDM methods, namely FFS-based AHP and FFS-based SWARA, with regard to the SRCC values [72], and given in Table 14.

Table 14. Comparison of ranking results with other methods

Criteria	FF-DEMATEL	FF-AHP	FF-SWARA
C1	6	4	5
C2	3	5	3
C3	4	3	4
C4	5	6	6
C5	8	8	7
C6	2	2	2
C7	7	9	8
C8	1	1	1
C9	9	7	9
		SRCC = 0.85	**SRCC = 0.96**

When the values in Table 14 are considered, the average SRCC value of the FF-DEMATEL method with other MCDM techniques is obtained as 0.908. In terms of the SRCC values, a statistically significant (at 1% level) and high correlation was obtained between the FF-DEMATEL method and other MCDM techniques. The proposed FF-DEMATEL model provides consistent and reliable results when compared with other MCDM techniques.

7 Conclusion

This research improves both theoretical and practical evaluation of earthquake resilience in urban areas by combining FF-DEMATEL with expert views on Turkish cities. The findings underline the significance of “Attitude of Decision Makers regarding Earthquake Resilience” (C8), “Governance Mechanisms” (C6), and “Earthquake Awareness in Society” (C7), which were selected as the most significant causative factors influencing the earthquake-resilience level of cities. In contrast, criteria like “Logistics Management” (C4), “Emergency Action Plans” (C3), and “Critical Infrastructures” (C1) were selected as less significant factors influencing earthquake-resilience. The results show that resilience is mostly influenced by the attitude of decision-makers, governance structures, and public awareness. These factors also affect other criteria that are considered to have an influence on earthquake-resilience of cities, including critical infrastructure, emergency action plans, and logistics management. These findings confirm that resilience cannot be increased only by technical measures. These measures need to be integrated into policy implications, governance culture, democratic decision-making attitudes of decision-makers, and social awareness.

Findings regarding the “governance mechanisms” criterion show that disaster risk reduction policies should rely not only on technical capacity but also on institutional coordination, accountability, and multi-level governance structures. Similarly, the Sendai Framework for Disaster Risk Reduction underlines the importance of strong governance structures, institutional responsibilities, and stakeholder participation for disaster risk reduction. In the same direction, governance guidelines developed by the OECD also highlight the significance of institutional integrity and horizontal-vertical coordination in managing disasters and other risks. Therefore, developing a governance mechanism based on shared authority and joint decision-making processes between local and central institutions is crucial for policymakers.

Since “attitude of decision makers regarding earthquake resilience” is another important criterion, we can understand that disaster management is a cognitive and managerial process rather than a technical issue. In the OECD reports on governance in the area of risk management, it is emphasized that decision-makers can significantly reduce the social and economic impacts of disasters by implementing risk management under uncertain conditions. Therefore, decision-makers can integrate these policies into their decision-making processes by organizing regular training for senior public administrators on risk management, disaster drills, and risk assessment based on scientific data.

The third important criterion, “earthquake awareness in society,” involves strengthening societal resilience by increasing individuals’ knowledge and preparedness levels regarding disaster risks. Policies aimed at raising public awareness should be designed holistically, encompassing longer-term education policies and civil society collaborations, rather than just short-term information campaigns.

This research illustrates the unique advantages of FFS in solving decision-making and selection problems in uncertain situations, and models the causal interdependencies between several criteria influencing earthquake resilience of cities. The consistency of the findings when compared with alternative fuzzy-based approaches underlines the strength of the proposed framework. This improvement is significant for researchers in the different areas of disaster risk management because it is a reproducible framework for resilience evaluations in other high-risk areas. In addition, the research underlines a paradigm shift in policy design, which is not only based on investments in secure housing, advanced technology, and emergency logistics, but also on other factors. The study proves that these technical factors are inadequate without adaptive decision-making, transparent leadership and governance, and social awareness about earthquake-resilience. Integrating all these factors with global policy frameworks like the Sendai Framework and the SDGs of the United Nations offers governments and municipalities a significant guide for their disaster risk management strategies.

In this study, there are also some limitations, so future investigation is required. While expert evaluations provide valuable insights, comprehensive empirical data and longitudinal studies might facilitate the continuous investigation of the resilience capacity of cities over time and across various nations. In addition, in future studies, the FF-DEMATEL and weighting approaches used in this research can be integrated into GIS-based spatial analyses. For example, spatial patterns of urban resilience can be compared by applying the defined criterion weights at the neighborhood or sub-district levels. Furthermore, using spatial regression models or spatial multi-criteria decision-making techniques, the differences in relationships between criteria can be analyzed within different geographical contexts. Thus, by addressing both the administrative and spatial dimensions of urban resilience together, more powerful and applicable decision support tools can be developed for policymakers. Similarly, this research also underlines that earthquake resilience is not only about technical or infrastructure concerns, but also a systemic problem at the intersection of governance, societal awareness, and adaptive policy formulations. By integrating our recommended methodological innovation with policy-relevant findings, this study provides a framework for developing earthquake resilience in Turkish cities. It also enhances the worldwide discourse on urban resilience in regions under disaster risk.

Author Contributions

Conceptualization, Ž.S., E.A., and Ç.K.; methodology, Ž.S., E.A., and Ç.K.; data compilation, Ž.S., E.A., and Ç.K.; software, Ž.S., E.A., and Ç.K.; validation, Ž.S., E.A., and Ç.K.; formal analysis, Ž.S., E.A., and Ç.K.; investigation, Ž.S., E.A., and Ç.K.; resources, Ž.S., E.A., and Ç.K.; writing-original draft preparation, Ž.S., E.A., and Ç.K.; writing-review and editing, Ž.S., E.A., and Ç.K.; visualization, Ž.S., E.A., and Ç.K. All authors have read and agreed to the published version of the manuscript.

Informed Consent Statement

Ethical approval (No: 682031, 15/01/2024) was obtained from the Anadolu University Social and Human Sciences Scientific Research and Publication Ethics Committee for data collection.

Data Availability

Data supporting the reported results can be found in the research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] United Nations Office for Disaster Risk Reduction (UNDRR), “Making cities resilient: My city is getting ready! —Campaign kit,” 2010. https://www.undrr.org/publication/making-cities-resilient-my-city-getting-ready-campaign-kit

[2] International Federation of Red Cross and Red Crescent Societies (IFRC), “World disasters report 2022: Trust, equity and local action,” 2023. https://www.ifrc.org/sites/default/files/2023-01/2022_IFRC-WDR_EN.pdf

[3] Centre for Research on the Epidemiology of Disasters (CRED), “Earthquakes in Türkiye: A review from 1900 to today,” 2023. https://files.emdat.be/2023/09/CredCrunch72.pdf

[4] 24TV, “Japonya’daki depremlerde yašamını yitirenlerin sayısı 213’e çıktı (Death toll from Japan earthquake rises to 213),” 2024. https://www.yirmidort.tv/dunya/japonyadaki-depremlerde-yasamini-yitirenlerin-sayisi-213e-cikti-147021

[5] AFAD, “6 Şubat 2023 pazarcık-elbistan kahramanmaraş (Mw: 7.7 – Mw: 7.6) depremleri raporu (February 6, 2023 Pazarcık-Elbistan Kahramanmaraş (Mw: 7.7 – Mw: 7.6) Earthquakes Report),” 2023. https://deprem.afad.gov.tr/assets/pdf/Kahramanmara%C5%9F%20Depremi%20%20Raporu_02.06.2023.pdf

[6] AFAD, “2022 Yılı Doğa Kaynaklı Olay İstatistikleri,” 2022. https://www.afad.gov.tr/afet-istatistikleri

[7] S. E. Kavanoz, “Kentsel direnç kavramı üzerine (Urban resilience concept),” *Kent Çevre Araştırmaları Derg.*, vol. 2, no. 1, pp. 5–24, 2020.

[8] B. Şener and A. A. Tanrıöver, “Depreme dirençli şehirler: Bursa ili yıldırım ilçesi örneği (Earthquake resilient cities: The example of Yıldırım District of Bursa Province),” *Ağaç Orman Derg.*, vol. 4, no. 2, pp. 47–57, 2023. https://doi.org/10.59751/agacorman.1310296

[9] A. Askan, A. Altindal, M. F. Aydin, M. A. Erberik, M. K. Koçkar, M. Tun, M. S. Balaban, H. Uygucgil, A. Kop, S. Karimzadeh, and et al., “Assessment of urban seismic resilience of a town in eastern Türkiye: Turkoglu, Kahramanmaras, before and after 6 february 2023 M 7.8 Kahramanmaras earthquake,” *Earthquake Spectra*, vol. 41, no. 1, pp. 146–175, 2024. https://doi.org/10.1177/87552930241274715

[10] K. Uzun Yüksel and E. L. Kutay Karaçor, “A model proposal for disaster resilient neighborhoods: Düzce City case,” *City Territ Archit*, vol. 12, no. 30, pp. 1–18, 2025. https://doi.org/10.1186/s40410-025-00280-w

[11] S. M. Rezvani, M. J. Falcão, D. Komljenovic, and N. M. de Almeida, “A systematic literature review on urban resilience enabled with asset and disaster risk management approaches and GIS-based decision support tools,” *Appl. Sci.*, vol. 13, no. 4, p. 2223, 2023. https://doi.org/10.3390/app13042223

[12] M. Baydaş, S. Turgay, M. K. Ömeroğlu, A. Aydin, G. Baydaş, Ž. Stević, E. E. Başar, M. İnci, and M. Selçuk, “A refined fuzzy MARCOS approach with quasi-D-overlap functions for intuitive, consistent, and flexible sensor selection in IoT-based healthcare systems,” *Mathematics*, vol. 13, no. 15, p. 2530, 2025. https://doi.org/10.3390/math13152530

[13] T. Senapati and R. R. Yager, “Fermatean fuzzy sets,” *J. Ambient Intell. Hum. Comput.*, vol. 11, no. 2, pp. 663–674, 2020. https://doi.org/10.1007/s12652-019-01377-0

[14] M. Akhtar and M. Asim, “Fuzzy causal model of enterprise flexibility dimensions using Fermatean fuzzy DEMATEL: A case study of the Indian pharmaceutical industry,” *Benchmarking*, vol. 32, no. 4, pp. 1338–1359, 2024. https://doi.org/10.1108/BIJ-07-2023-0462

[15] C. S. Holling, “Resilience and stability of ecological systems,” *Annu. Rev. Ecol. Syst.*, vol. 4, pp. 1–23, 1973.

[16] P. J. G. Ribeiro and L. A. P. J. Gonçalves, “Urban resilience: A conceptual framework,” *Sustain. Cities Soc.*, vol. 50, p. 101625, 2019. https://doi.org/10.1016/j.scs.2019.101625

[17] United Nations Environment Programme (UNEP), “Sustainable Cities,” 2024. https://www.unep.org/regions/asia-and-pacific/regional-initiatives/supporting-resource-efficiency/sustainable-cities

[18] United Nations Office for Disaster Risk Reduction (UNDRR), “Monitoring the Sendai Framework,” 2023. https://www.undrr.org/implementing-sendai-framework/monitoring-sendai-framework

[19] E. Sarı, S. P. Öztürk, and İ. As, “Geleceğin dirençli kenti: Esenler NAR inovasyon bölgesi,” *Çevre Şehir İklim Derg.*, vol. 1, no. 2, pp. 119–146, 2022.

[20] G. Külekçi and A. Vural, “Kahramanmaraş ilindeki depremler sonrası karayolu tünellerinin güçlendirilmesi: Yeraltı boşlukları ve deprem etkisi incelemesi,” *AS-Proceedings*, vol. 1, no. 1, pp. 79–82, 2023.

[21] M. S. Kıymaz, O. Ahat, M. Turan, and S. Arslan, “Türkçe ders kitaplarında deprem hazırlığı üzerine bir inceleme,” *Çocuk Edebiyat Dil Eğit. Derg.*, vol. 6, no. 1, pp. 16–36, 2023. https://doi.org/10.47935/ceded.1275179

[22] İ. Akbaş, “Dirençlilik ve dirençli kent yaklaşımında yeni eğilimler: Bibliyometrik bir analiz,” *Nevşehir HBV Üniv. Sos. Bilim. Enst. Derg.*, vol. 13, no. 3, pp. 1866–1889, 2023. https://doi.org/10.30783/nevsosbilen.1302930

[23] İ. İrdem and E. Mert, “Deprem, dirençli şehir ve acil afet yönetimi: Türkiye örneği,” *Kamu Yönetimi Polit. Derg.*, vol. 4, no. 2, pp. 241–276, 2023. https://doi.org/10.58658/kaypod.1319821

[24] G. Erdoğan, S. Simsar, Ö. Kor, G. Kardoğan, Y. D. Kaya, B. Gündoğdu, and C. Parıltı, “Dirençli şehirler tasarlamak: Uygulama kılavuzu arayışı, İzmir–Torbalı örneği,” *Çevre Şehir İklim Derg.*, vol. 1, no. 2, pp. 165–202, 2022.

[25] A. Demir, “Post-earthquake structural damage assessment, lessons learned, and addressing objections following the 2023 Kahramanmaraş, Turkey earthquakes,” *Bull. Earthq. Eng.*, vol. 23, pp. 1107–1127, 2025. https://doi.org/10.1007/s10518-024-02092-8

[26] E. Sonmez, M. Eryilmaz Yildirim, M. F. Aydin, and F. B. Koroglu, “Seismic performance assessment of

structural systems in the aftermath of the 2023 Kahramanmaraş earthquakes: Observations and fragility analyses," *Earthquake Spectra*, vol. 41, no. 1, pp. 198–218, 2024. https://doi.org/10.1177/87552930241287541

[27] G. Tunç, H. C. Mertol, and T. Akış, "Lessons learned from four recent Turkish earthquakes: Sivrice–Elazığ, Aegean sea, and dual Kahramanmaraş," *Nat. Hazards*, vol. 120, pp. 12 341–12 373, 2024. https://doi.org/10.1007/s11069-024-06687-x

[28] M. Baydaş, O. E. Elma, and Ž. Stević, "Proposal of an innovative MCDA evaluation methodology: Knowledge discovery through rank reversal, standard deviation, and relationship with stock return," *Financ. Innov.*, vol. 10, no. 1, p. 4, 2024. https://doi.org/10.1186/s40854-023-00526-x

[29] Ş. Şeker, N. Aydın, and U. R. Tuzkaya, "What is needed to design sustainable and resilient cities: Neutrosophic fuzzy-based DEMATEL for designing cities," *Int. J. Disaster Risk Reduct.*, vol. 108, p. 104569, 2024. https://doi.org/10.1016/j.ijdrr.2024.104569

[30] A. A. Kutty, M. Küçükvar, N. C. Onat, B. Ayvaz, and G. M. Abdella, "Measuring sustainability, resilience and livability performance of European smart cities: A novel fuzzy expert-based multi-criteria decision support model," *Cities*, vol. 137, p. 104293, 2023. https://doi.org/10.1016/j.cities.2023.104293

[31] A. Jamali, M. Robati, H. Nikoomaram, F. Farsad, and H. Aghamohammadi, "Urban resilience assessment using hybrid MCDM model based on DEMATEL-ANP method," *J. Indian Soc. Remote Sens.*, vol. 51, pp. 893–915, 2023. https://doi.org/10.1007/s12524-023-01670-8

[32] M. Javari, M. Saghaei, and F. F. Jazi, "Analyzing the resilience of urban settlements using multiple-criteria decision-making models: Case study of Malayer city," *Sustain. Environ.*, vol. 7, no. 1, pp. 1–15, 2021. https://doi.org/10.1080/27658511.2021.1889083

[33] M. Mabrouk and H. Han, "Urban resilience assessment: A multicriteria approach for identifying urban flood-exposed risky districts using MCDM tools," *Int. J. Disaster Risk Reduct.*, vol. 91, p. 103684, 2023. https://doi.org/10.1016/j.ijdrr.2023.103684

[34] Y. Tahmasebi Birgani and F. Yazdandoost, "An integrated framework to evaluate resilient-sustainable urban drainage management plans using a combined-adaptive MCDM technique," *Water Resour. Manag.*, vol. 32, pp. 2817–2835, 2018. https://doi.org/10.1007/s11269-018-1960-2

[35] M. Moghadas, A. Asadzadeh, A. Vafeidis, A. Fekete, and T. Kötter, "A multi-criteria approach for assessing urban flood resilience in Tehran, Iran," *Int. J. Disaster Risk Reduct.*, vol. 35, p. 101069, 2019. https://doi.org/10.1016/j.ijdrr.2019.101069

[36] H. Sarmadia and S. Aghababaei, "Prioritizing the components of the disaster resilient system using DEMATEL and ANP for urban areas," *Environ. Sci. Sustain. Dev.*, vol. 8, no. 4, pp. 52–66, 2023. https://doi.org/10.21625/essd.v8i4.973

[37] C. Alhan and M. Hacıemiroğlu, "Dirençli şehirler için depreme dayanıklı yapı tasarımında sismik izolasyon," *Çevre Şehir İklim Derg.*, vol. 2, no. 4, pp. 96–127, 2023.

[38] P. Özden, "Türkiye'de kentsel dönüşümün uygulanabilirliği üzerine düşünceler," *İstanbul Üniv. Siyasal Bilg. Fak. Derg.*, vol. 36, pp. 215–233, 2006.

[39] C. Dinçer and N. Partigöç, "CBS tabanlı afet risk analizi: Denizli ili örneği," *Geomatik*, vol. 9, no. 1, pp. 27–44, 2024. https://doi.org/10.29128/geomatik.1261051

[40] T. Erkal and M. Değerliyurt, "Türkiye'de afet yönetimi," *Doğu Coğrafya Derg.*, vol. 14, no. 22, pp. 147–164, 2009.

[41] A. H. Dökmeci and Ö. Akduman, "Doğal olayların tetiklediği KBRN-p tehlikesi ve riski: Türkiye örneği," *Doğal Afetler ve Çevre Dergisi*, vol. 8, no. 1, pp. 165–177, 2022. https://doi.org/10.21324/dacd.979583

[42] F. G. Ulugergerli, "Afet tedarik zinciri yönetimi: Nitel bir araştırma," *Dirençlilik Dergisi*, vol. 5, no. 1, pp. 1–20, 2021. https://doi.org/10.32569/resilience.817225

[43] G. Tekin Temur, Y. Turgut, A. Yılmaz, Ş. Arslan, and A. Camcı, "Deprem sonrası planlamaya yönelik lojistik ağ tasarımı: Ümraniye bölgesinde farklı deprem senaryoları için bir uygulama," *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi*, vol. 25, no. 1, pp. 98–105, 2019.

[44] M. Yaman and E. Çakır, "Dijitalleşen dünyada akıllı afet ve acil durum uygulamaları," *İnsan ve Toplum Bilimleri Araştırmaları Dergisi*, vol. 7, no. 2, pp. 1124–1138, 2018. https://doi.org/10.15869/itobiad.399043

[45] E. Selçuk and M. Erem, "Deprem öncesi hazırlık ve deprem anında yapılması gerekenler," *TOTBİD Dergisi*, vol. 21, no. 3, pp. 249–252, 2022. https://doi.org/10.5578/totbid.dergisi.2022.33

[46] E. Demirelli, H. İ. Solak, and İ. Tiryakioğlu, "Makine öğrenmesi algoritmaları ile deprem katalogları kullanılarak deprem tahmini," *Gümüşhane Üniversitesi Fen Bilimleri Dergisi*, vol. 13, no. 4, pp. 979–989, 2023. https://doi.org/10.17714/gumusfenbil.1268504

[47] N. K. Öztürk and Ö. Demirel, "Çok paydaşlı iş birliği ve dirençli kent açısından montreal şehri," *Ekonomi ve Yönetim Araştırmaları Dergisi*, vol. 10, no. 2, pp. 24–44, 2021.

[48] T. Aydıner and H. Özgür, “Yönetişim ve doğal afetler: Türkiye’de doğal afet yönetişimi ne kadar ve hangi biçimde mümkün?” in *Kamu Yönetiminde Değişim KAYFOR XII Bildiriler Kitabı*. Türkiye Süleymancılar Birliği and Adnan Menderes Üniversitesi, 2014, pp. 395–404.

[49] C. S. Renschler, A. Frazier, L. Arendt, G. P. Cimellaro, A. M. Reinhorn, and M. Bruneau, “A framework for defining and measuring resilience at the community scale: The PEOPLES resilience framework,” National Institute of Standards and Technology, 2010. http://peoplesresilience.org/wp-content/uploads/2013/07/NIST_GCR_10-930.pdf

[50] A. N. Karançı, B. Akşıt, and G. Dirik, “Impact of a community disaster awareness training program in Turkey: Does it influence hazard-related cognitions and preparedness behaviors?” *Soc. Behav. Pers.*, vol. 33, no. 3, pp. 243–258, 2005. https://doi.org/10.2224/sbp.2005.33.3.243

[51] M. Acar, “Kamu personel sisteminde değişim tartışmalarına bir katkı: 5-S reform çerçevesi,” *Kamu Yönetimi ve Politikaları Dergisi*, vol. 2, no. 1, pp. 11–34, 2021.

[52] H. Matsuura, “Level of disaster resilience and migration patterns in Japanese and foreign residents,” in *Integrated Research on Disaster Risks: Disaster Risk Reduction*. Cham: Springer, 2021, pp. 137–155. https://doi.org/10.1007/978-3-030-55563-4_8

[53] S. L. Cutter, L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb, “A place-based model for understanding community resilience to natural disasters,” *Glob. Environ. Chang.*, vol. 18, no. 4, pp. 598–606, 2008. https://doi.org/10.1016/j.gloenvcha.2008.07.013

[54] United Nations Office for Disaster Risk Reduction (UNDRR), “Sendai framework for disaster risk reduction 2015–2030,” 2015. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

[55] Organisation for Economic Co-operation and Development (OECD), “Recommendation of the council on the governance of critical risks,” 2014. https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0405

[56] C. C. Hsu and B. A. Sandford, “The Delphi technique: Making sense of consensus,” *Pract. Assess., Res. Eval.*, vol. 12, no. 1, p. 10, 2007. https://doi.org/10.7275/pdz9-th90

[57] G. J. Skulmoski, F. T. Hartman, and J. Krahn, “The Delphi method for graduate research,” *J. Inf. Technol. Educ. Res.*, vol. 6, pp. 1–21, 2007. https://doi.org/10.28945/199

[58] L. A. Palinkas, S. M. Horwitz, C. A. Green, J. P. Wisdom, N. Duan, and K. Hoagwood, “Purposeful sampling for qualitative data collection and analysis in mixed-method implementation research,” *Admin. Policy Ment. Health Ment. Health Serv. Res.*, vol. 42, no. 5, pp. 533–544, 2015. https://doi.org/10.1007/s10488-013-0528-y

[59] L. A. Zadeh, “Fuzzy sets,” *Inf. Control*, vol. 8, no. 3, pp. 338–353, 1965. https://doi.org/10.1016/S0019-9958(65)90241-X

[60] K. T. Atanassov, “Intuitionistic fuzzy sets,” *Fuzzy Sets Syst.*, vol. 20, no. 1, pp. 87–96, 1986. https://doi.org/10.1016/S0165-0114(86)80034-3

[61] E. Fontela and A. Gabus, “The DEMATEL Observer,” Battelle Geneva Research Center, Geneva, 1976. https://www.scirp.org/reference/referencespapers?referenceid=1847241

[62] V. Naisola-Ruiter, “The Delphi technique: A tutorial,” *Res. Hosp. Manag.*, vol. 12, no. 1, pp. 91–97, 2022. https://doi.org/10.1080/22243534.2022.2080942

[63] R. R. Yager, “Generalized orthopair fuzzy sets,” *IEEE Trans. Fuzzy Syst.*, vol. 25, no. 5, pp. 1222–1230, 2017. https://doi.org/10.1109/TFUZZ.2016.2604005

[64] N. Alkan and C. Kahraman, “Prioritization of supply chain digital transformation strategies using multi-expert Fermatean fuzzy analytic hierarchy process,” *Informatica*, vol. 34, no. 1, pp. 1–33, 2023. https://doi.org/10.15388/22-INFOR493

[65] T. Senapati and R. Yager, “Fermatean fuzzy weighted averaging/geometric operators and its application in multi-criteria decision-making methods,” *Eng. Appl. Artif. Intell.*, vol. 85, pp. 112–121, 2019. https://doi.org/10.1016/j.engappai.2019.05.012

[66] H. W. Lo, H. W. Chan, J. W. Lin, and S. W. Lin, “Evaluating the interrelationships of Industrial 5.0 development factors using an integration approach of Fermatean fuzzy logic,” *J. Oper. Intell.*, vol. 2, no. 1, pp. 95–113, 2024. https://doi.org/10.31181/jopi21202416

[67] S. Golui, B. S. Mahapatra, and G. S. Mahapatra, “A new correlation-based measure on Fermatean fuzzy applied on multi-criteria decision making for electric vehicle selection,” *Expert Syst. Appl.*, vol. 237, p. 121605, 2024. https://doi.org/10.1016/j.eswa.2023.121605

[68] H. C. Huang, C. N. Huang, H. W. Lo, and T. M. Thai, “Exploring the mutual influence relationships of international airport resilience factors from the perspective of aviation safety: Using Fermatean fuzzy DEMATEL approach,” *Axioms*, vol. 12, no. 11, p. 1009, 2023. https://doi.org/10.3390/axioms12111009

[69] F. C. Kao, S. C. Huang, and H. W. Lo, “A rough-Fermatean DEMATEL approach for sustainable development evaluation for the manufacturing industry,” *Int. J. Fuzzy Syst.*, vol. 24, no. 7, pp. 3244–3264, 2022. https:

//doi.org/10.1007/s40815-022-01334-8
[70] F. Ecer, "Sustainability assessment of existing onshore wind plants in the context of triple bottom line: A best-worst method (BWM) based MCDM framework," *Environ. Sci. Pollut. Res.*, vol. 28, no. 16, pp. 19 677–19 693, 2021. https://doi.org/10.1007/s11356-020-11940-4
[71] F. Ecer, D. Pamucar, S. H. Zolfani, and M. K. Eshkalag, "Sustainability assessment of OPEC countries: Application of a multiple attribute decision making tool," *J. Clean. Prod.*, vol. 241, p. 118324, 2019. https://doi.org/10.1016/j.jclepro.2019.118324
[72] Z. Wang, M. Baydaş, Ž. Stević, A. Özçil, S. A. Irfan, Z. Wu, and G. P. Rangaiah, "Comparison of fuzzy and crisp decision matrices: An evaluation on PROBID and sPROBID multi-criteria decision-making methods," *Demonstr. Math.*, vol. 56, no. 1, p. 20230117, 2023. https://doi.org/10.1515/dema-2023-0117

Appendix

Determining the Importance Levels and Interactions of Criteria Affecting Earthquake Resilience

The purpose of the survey form in this section is to analyze the degree of interaction between criteria affecting Eskişehir's earthquake resilience and determine their level of importance by using Fermatean Fuzzy DEMATEL. In order to complete this survey, please follow the instructions below.

Importance Degrees

The scale that will be used related to the evaluation is shown as below:

Numerical Level	Symbolic Counterpart	Linguistic Variable	Description
1	VLE	Very Low Effect	One criterion has a very low effect on the emergence of another criterion
2	LE	Low Effect	One criterion has a low effect on the emergence of another criterion
3	MLE	Medium Low Effect	One criterion has a medium low effect on the emergence of another criterion
4	ME	Medium Effect	One criterion has a medium effect on the emergence of another criterion
5	MHE	Medium High Effect	One criterion has a medium high effect on the emergence of another criterion
6	HE	High Effect	One criterion has a high effect on the emergence of another criterion
7	VHE	Very High Effect	One criterion has a very high effect on the emergence of another criterion
8	EHE	Extremely High Effect	One criterion has an extremely high effect on the emergence of another criterion
9	**EE**	**Entirely Effect**	One criterion has an entirely effect on the emergence of another criterion

Sample evaluation:

If criterion C1 (Critical Infrastructures) has a very low effect (VLE) on criterion C2 (Safe Residential Areas), then 1 needs to be written in the cell where C1 and C2 intersect in the matrix below.

The degree to which the criteria in the row (in terms of the Cause) affect the criteria in the column (in terms of the Effect) forms the basis of the evaluation logic.