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A DEMATEL-based approach of multi-criteria evaluation for urban fire and emergency facilities

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With the increasing complexity of rapidly growing urban environments and the interactions of humans and socioeconomic and political systems, the global urgency for applying sustainable risk management planning strategies, comprehensively for urban fire risk reduction activities, becomes increasingly evident in most fire-prone megacities worldwide such as Istanbul. The current research aims to examine the complex interrelationships and levels of influence among the criteria previously determined for optimally selecting new urban infrastructure for fire and emergency services in Istanbul as part of the fire risk mitigation planning efforts applying the multi-criteria decision analysis method of the Decision-Making Trial and Evaluation Laboratory (DEMATEL). Useful insights were generated from the study by constructing an intelligible structural model visually in the form of a *digraph* involving analysis of causal relationships among criteria and their directional influences, as well as corresponding degrees of strength. The findings reveal that high population density is the most critical criterion followed by the density of hazardous materials criterion in effectively planning new urban facilities for fire and emergency services, thus significantly influencing and impacting all the other criteria, while the distance-to-earthquake risk criterion does not influence any other criteria and consequently is not essential in the planning procedure. The DEMATEL model results were validated in terms of levels of criteria significance using previous studies and shown to be in high correlation. In this regard, these contextual relationships established would contribute toward an integrated fire risk mitigation planning policy formulation in urban environments through the engagement of all decision-makers across various backgrounds and disciplines such as urban and city planners, engineers, emergency and risk managers and administrators, socioeconomic and environmental experts, fire service industry practitioners, and local community leaders.

KEYWORDS

Decision-Making Trial and Evaluation Laboratory (DEMATEL), geographic information system (GIS), multi-criteria decision analysis (MCDA), urban emergency facility planning, fire station

Highlights

- The Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique is proposed to model the complex interrelationships of criteria previously determined for optimally selecting new facilities for fire and emergency services in Istanbul as part of the fire risk mitigation planning efforts.

- Useful insights were generated in the form of a *digraph* involving causal relationship evaluations among criteria and their directional influences, as well as corresponding degrees of strength.
- The findings reveal that high population density and the density of hazardous materials criteria, within the cause group, are the most significant criteria and therefore need to be prioritized to effectively plan new urban infrastructure for fire and emergency services, while the distance-to-earthquake risk criterion does not influence any other criteria and is consequently not essential in the planning procedure.
- The DEMATEL model outcomes were validated in terms of levels of criteria significance using previous studies and shown to be in high correlation.
- In this regard, these contextual relationships established would contribute toward an integrated fire risk mitigation planning policy formulation in urban environments through the engagement of all decision-makers across all levels and disciplines.

1. Introduction and background

The growing scale of urban fire risk especially in the megacities of the world such as Istanbul in Turkey arises largely because of the confluence of various contemporary developmental and demographic trends that include accelerated urbanization, rising urban populations and migration to cities, and socioeconomic factors, such as inequalities. Increasing urban development pressure brings about an expansion in built-up and urban settlement areas, often without adequate and comprehensive urban planning policies and regulations. As a result of increased human activities and interactions, these places are increasingly exposed to fire risk, particularly in vulnerable communities with limited adaptive capacity, such as inhabitants without land ownership and new migrants (Mtani and Mbuya, 2018; UN Office for Disaster Risk Reduction, 2019). To improve decision-making, a better comprehension of these relationships and interconnections as part of the complexities of human systems and urban dynamics functioning across different levels, actors, stakeholders, sectors, and disciplines is needed to mitigate fire hazard risk in urban populations. The sustainable development gains will, to a great extent, be impeded in most parts of the world by failing to effectively manage these fire risk and disaster prevention strategies, threatening the functionality of global society (UN Office for Disaster Risk Reduction, 2019).

The Hyogo Framework for Action 2005–2015, which was enacted in 2005, recognizes the established link between disaster risk reduction (DRR) and sustainable development. DRR is recognized as an intersectoral issue of urgency that affects sustainable development at all levels within this framework. In a broad sense, the Millennium Development Goals, which emerged from the United Nations Millennium Summit in 2000, recognized the importance of safety (which includes protection against fire risks and disasters) in urban environments. Goal 11 of the Sustainable Development Goals aims to make cities and human habitations more equitable, secure, resilient, and sustainable by instituting unified multilevel planning strategies for comprehensive disaster risk management in conformity with the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015). The Sendai Framework was endorsed by governments all over the world in 2015 as the replacement mechanism for the Hyogo Framework for Action to deal with more extensive issues connected to the spectrum of risks and hazards. It provides clarity on the policy direction for relevant stakeholders such as governments and citizens to mitigate associated technological hazards and risks such as fires. The Sendai Framework establishes the connecting fabric for the 2030 Agenda for Sustainable Development, the Paris Agreement, the New Urban Agenda, the Addis Ababa Action Agenda, and the Agenda for Humanity in terms of logically formulating the link between DRR and enhancing resilience (UN Office for Disaster Risk Reduction, 2019).

Against this backdrop, fire risk and emergency planning within the spatial scale of the urban environment is an interconnected and complex decision-making procedure involving multiple criteria, as well as stakeholder participation of a transdisciplinary nature (Erden, 2012; Nyimbili and Erden, 2018). In the context of urban emergency planning and fire risk mitigation, the present research suggests the implementation of the multi-criteria decision analysis (MCDM) technique based on the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to evaluate the interdependencies of the criteria necessary for the optimal planning of new urban fire emergency facilities in Istanbul, Turkey.

The DEMATEL method was developed by the Geneva Research Center of the Battelle Memorial Institute (Gabus and Fontela, 1973, 1976) to solve complex global issues involving structural relationships in complex systems (Wu, 2008). The DEMATEL method was utilized in this research to analyze the interrelations among the assessment criteria for the urban emergency facility site selection process, thereby building the causal relationship diagram and digraph. The fundamental research question to be addressed in this article is how the criteria for the selection of new urban fire stations are interrelated and their relative significance in the planning process.

Prevailing studies have reaffirmed the benefits of the application of the DEMATEL technique, which is among the top 20 most popular and cited MCDA methods in the last decade (Taherdoost and Madanchian, 2023). For instance, Lin and Wu (2008) suggested that DEMATEL is the most appropriate approach in causal analyses for supporting decision-makers in separating the examined criteria of a system into cause and effect groups, thereby assisting in determining the criteria of highest influence. The DEMATEL approach, according to Lin et al. (2011), can be used to resolve causal relationship concerns for essential skills for a successful design service within the semiconductor industry of integrated circuits. Li et al. (2014) explored the use of the DEMATEL technique in emergency management to uncover crucial success variables. Azizi et al. (2014) evaluated suitable site conditions for setting up a wind power plant in Iran using a DEMATEL combined model in a GIS environment. Furthermore, Chen (2016) used DEMATEL to improve the quality assessment for the airline industry in Taiwan in the long run to build a long-term competitive advantage. The interrelationships and impacts among the evaluation criteria were examined in order to give airlines a guideline for the assessment and improvement of service quality. For successful disaster preparation, Trivedi (2018) suggested using DEMATEL to analyze complicated interrelationships between drivers of shelter location selection. By examining the interdependence between the major risk variables of Sponge City Public–Private Partnership in the setting of China, Zhang et al. (2019) used the DEMATEL approach to analyze them. DEMATEL was used by Altuntas and Gok (2021) to help governments make efficient quarantine measures in the wake of the COVID-19 pandemic, which had a direct impact on the hospitality business. The major essential hospitality sector criterion assessed in their study was interregional travel flow between areas in Turkey for local tourism. DEMATEL was used to examine direct and indirect interrelationships among Turkey's regions, as well as travel information, to provide practical solutions for assisting policymakers in making effective quarantine decisions during the pandemic while minimizing the impact on the tourism and hospitality industries. Additionally, the DEMATEL technique was used in a comparative evaluation study in the field of sustainable transport incorporating Ratio Estimation in Magnitudes or deciBells to Rate Alternatives which are Non-DominaTed (REMBRANDT) and VIekriterijumsko KOmpromisno Rangiranje (VIKOR) methods (Broniewicz and Ogrodnik, 2021); an analysis of factors affecting the resilience of a subway system in disaster mitigation (Bu et al., 2023); a hybrid GIS-based framework to model flood susceptibility in large ungauged areas without hydrological data (Sahraei et al., 2022); zoning areas at risk of flash floods using a combined GIS-based analytic network process (ANP) and satellite imagery (Taherizadeh et al., 2023); and in resolving a supplier selection problem (Rahman et al., 2021). In Pakistan, Shah et al. (2021) introduced a decision support framework to assess and rank waste-to-energy options in the aftermath of the COVID-19 pandemic. By using fuzzy DEMATEL, they unveiled the inherent interdependencies among decision criteria. Das et al. (2021) utilized the DEMATEL approach to examine the factors influencing supply chain networks to build resilience in response to the emergence of the COVID-19 pandemic.

It is evident from the literature that there are numerous effective MCDM techniques that have been developed for addressing a wide range of group decision-making (GDM) real-world challenges (Sotoudeh-Anvari, 2022), prompting the examination of DEMATEL against these methods to reveal its strengths and limitations. The comparison encompasses widely used MCDM techniques such as the analytic hierarchy process (AHP), gray relational analysis (GRA), the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), VIKOR, ELECTRE (Elimination Et Choix Traduisant la REalité), fuzzy set theory (FST), linear programming technique for multidimensional analysis of preference (LINMAP), the best–worst method (BWM), PROMETHEE (preference ranking organization method for enrichment evaluations), and ANP. Each of the technique's underlying principles is assessed as well as their limitations.

AHP involves hierarchy-based goal distribution and impact assessment on goal achievement. It provides a clear framework for decision-making and can handle both quantitative and qualitative data. AHP, however, does not explicitly capture interdependence among criteria or feedback loops in a visual manner and it may not effectively represent causal relationships between criteria. GRA evaluates the similarity and correlation between sequences of data based on gray relational coefficients while DEMATEL focuses on revealing the inner relationships and influence dynamics among decision criteria.

VIKOR employs a ranking index derived from "closeness" to the ideal solution through linear normalization but may not capture causal relationships as directly as DEMATEL. TOPSIS selects alternatives closest to the ideal and farthest from the negative-ideal solution. It is effective for finding the best compromise among alternatives though may not reveal direct causal relationships among criteria. ELECTRE, an outranking MCDM approach, identifies optimal actions based on the multi-attribute utility theory (Si et al., 2018; Broniewicz and Ogrodnik, 2021). Conversely, it may not explicitly reveal the underlying causal links between criteria. FST deals with uncertainty and vagueness in decision-making, allowing for flexible modeling of preferences and can handle imprecise data. Its weakness, however, is that it might not explicitly represent causal relationships or feedback loops. LINMAP transforms ordinal preference statements into numerical values using linear programming, although it may not emphasize causal relationships. BWM is a straightforward approach that identifies the best and worst criteria relative to each other and helps assess the significance of criteria through a simple ranking process. Even so, BWM does not explicitly reveal causal relationships or interdependencies among criteria. It might not fully capture complex interactions in decision-making. PROMETHEE ranks alternatives based on preference functions and pairwise comparisons. It considers the criteria's importance, captures preference relations among alternatives, offers valuable insights into ranking alternatives, and can handle multiple criteria. Nonetheless, PROMETHEE's focus is on ranking alternatives rather than exploring relationships between criteria. ANP extends AHP to model dependencies among elements within the hierarchy, allowing for more complex relationships. It considers both the influence and dependence relationships between criteria. ANP is suitable for capturing feedback and interdependencies, but its complexity may require more data and expertise, which is impractical in most situations.

Each of these MCDM techniques has its own unique features and applications. It has to be noted that there is no universal MCDA approach capable of addressing all decision problems (Kalbar and Das, 2020; Taherdoost and Madanchian, 2023). As emphasized by Dožić (2019), the choice of the method and suitability of each MCDM technique relies on the specific nature of the decision problem at hand, the availability of pertinent data, the complexity of the relationships involved, and the preferences of the decision-makers. The potential limitations of the DEMATEL may be that it does not incorporate aspiration levels (as in GRA and VIKOR) or yield partial ranking orders (as in ELECTRE) and that it ranks interdependent alternatives, potentially neglecting other criteria (Si et al., 2018; Broniewicz and Ogrodnik, 2021; Sahraei et al., 2022). Despite these potential weaknesses, in comparing these MCDA methods with DEMATEL, it is evident that DEMATEL excels in capturing in-depth causal relationships and interdependencies among criteria. The construction of a digraph and influence-relation map (IRM) facilitates a visual representation of these relationships, enhancing the understanding of complex interactions, a distinct feature and benefit of using the DEMATEL method. While other methods like AHP, TOPSIS, ANP, and others offer their own strengths, DEMATEL's unique ability to unravel cause-and-effect connections provides a valuable tool for decision-makers dealing with intricate urban planning and risk mitigation challenges as is hoped to be demonstrated in this research.

In this study, the DEMATEL approach was used to plan the locations of the new fire emergency facilities in Istanbul, which were previously determined from prior works (Nyimbili and Erden, 2020a,b,c, 2021). These criteria under evaluation are *high population density* (HPD), *proximity to main roads* (PMR), *distance from existing fire stations* (DEF), the *density of hazardous materials* (DHM), *wooden building density* (WBD), and *distance to earthquake risk* (DER). However, the MCDM methods coupled with GIS, such as AHP, fuzzy AHP, entropy AHP, and BWM utilized from previous studies are unable to determine the dependence, feedback, and inter-relationships among the criteria involved. Therefore, the current article presents a unique research opportunity as it, on the first occasion, explores the use of the DEMATEL technique to overcome these limitations. In DEMATEL, an assumption is made that all criteria are *mutually dependent* and *influence other* criteria. On this account, the significance of this study is that it establishes the importance and causal relationships among the criteria which are modeled visually in the form of a digraph and thereby determines the most influential criteria to be considered for the urban emergency facility site selection process. The research outcome will contribute substantially toward policy formulation for effective and comprehensive planning of urban emergency facilities and fire risk mitigation strategies for Istanbul, Turkey. For instance, in optimizing and targeting resource allocation, identifying the most critical criteria implies that resources, such as fire stations and equipment, can be strategically allocated to areas with these characteristics. Policies can therefore be formulated to prioritize resource allocation based on the potential impact of these factors on fire risk. The research can also influence policy related to zoning and land-use planning, as well as building codes and regulations, where urban planning policies can incorporate the research findings by zoning areas with the most influential criteria for specific types of land uses. These areas would require review and enhancement of existing standards requiring stricter fire-resistant building codes and fire safety regulations that are tailored to Istanbul's unique urban characteristics and vulnerabilities to minimize the potential for rapid fire spread and risk. The research outcomes emphasize the importance of data-driven decision-making. Policies can encourage the collection and maintenance of up-to-date data on population density, hazardous material storage, and other critical criteria to support effective planning and risk assessment. Furthermore, the research underscores the need for collaboration among professionals from various disciplines such as urban planners, engineers, experts in environmental issues, disaster and risk management, social scientists, GIS specialists, geologists and seismologists, community representatives, policymakers, and decision-makers from various government agencies. Policies can therefore be designed to facilitate cross-disciplinary coordination and cooperation, ensuring a holistic approach to fire risk reduction, which can be integrated into broader disaster management plans and guide the formulation of strategies that account for fire risks when responding to other types of disasters, such as earthquakes or floods.

The following is how the rest of the article is structured: Section 2 gives an insight into the present fire risk condition in Istanbul, Turkey. Section 3 outlines the research method and the construction of the DEMATEL model. A brief description of the criteria affecting the planning of the new urban emergency facilities is also expressed. The implementation of the DEMATEL model is elaborated in Section 4 while the results of the findings and model validation from previous studies are discussed in Section 5. Finally, the concluding remarks and implications of the study are articulated in Section 6.

2. Current fire risk status in Istanbul

The World Bank estimates that, globally, 55% of the population resides in urban regions presently. It is estimated that by 2050, the urban population will more than double its current size (World Bank, 2020). Istanbul, straddling Europe and Asia is one of the megacities of the world having a population of 15,462,452 (constituting 18.49% of Turkey's population) as of 2020 (TUIK, 2020) and is the commercial capital of Turkey accounting for more than a third of the gross domestic product. The number of people living in Turkey's urban regions has risen steadily throughout the years, from 38.9% in 1971 to 76.1% in 2020, with an average annual growth rate of 1.38% (United Nations Population Division, 2020). This upsurge in the urban population resulting in the growing demand for increased access to socioeconomic and infrastructure services has given rise to rapid urbanization challenges such as exposure and vulnerability to urban fire risk. It is vital to have enough coverage of fire and emergency facilities in urban areas to limit the risks of present and future fire hazard situations. Figure 1 shows the population density, as well as the spatial distribution of existing fire and emergency facilities, in Istanbul Province.

As inferred, most of the existing emergency facilities are clustered around the densely populated regions of the predominantly built-up and industrialized zones of Istanbul with a high exposure to urban fire risk. Urban fires can be dangerous to people, essential infrastructure, and the environment, resulting in injuries and deaths, as well as economic loss and pollution. Urban fires generally fall under the technological hazard cluster and can be triggered by natural (e.g., lightning strikes) and human-made activities (e.g., arson) emanating from technological or industrial situations such as accidents, unsafe operations, and damage to infrastructure (UN Office for Disaster Risk Reduction, 2019, 2020). Fires may also arise from secondary effects of natural hazard impacts, such as earthquakes, for example, the 1999 Kocaeli earthquake (AIGM, 1999), with devastating consequences due to structural and infrastructure damage. Large industries, warehouses, petroleum refineries, and electrical and gas utility lines are among the most vulnerable facilities (ISMEP, 2009). According to the Istanbul Metropolitan Municipality's (IMM, 2016) annual report, the number of fires reported in Istanbul has been rising, with response times exceeding 5 min.

In this view, the present fire risk status was analyzed from the latest statistics acquired from the IMM Fire Brigade Department

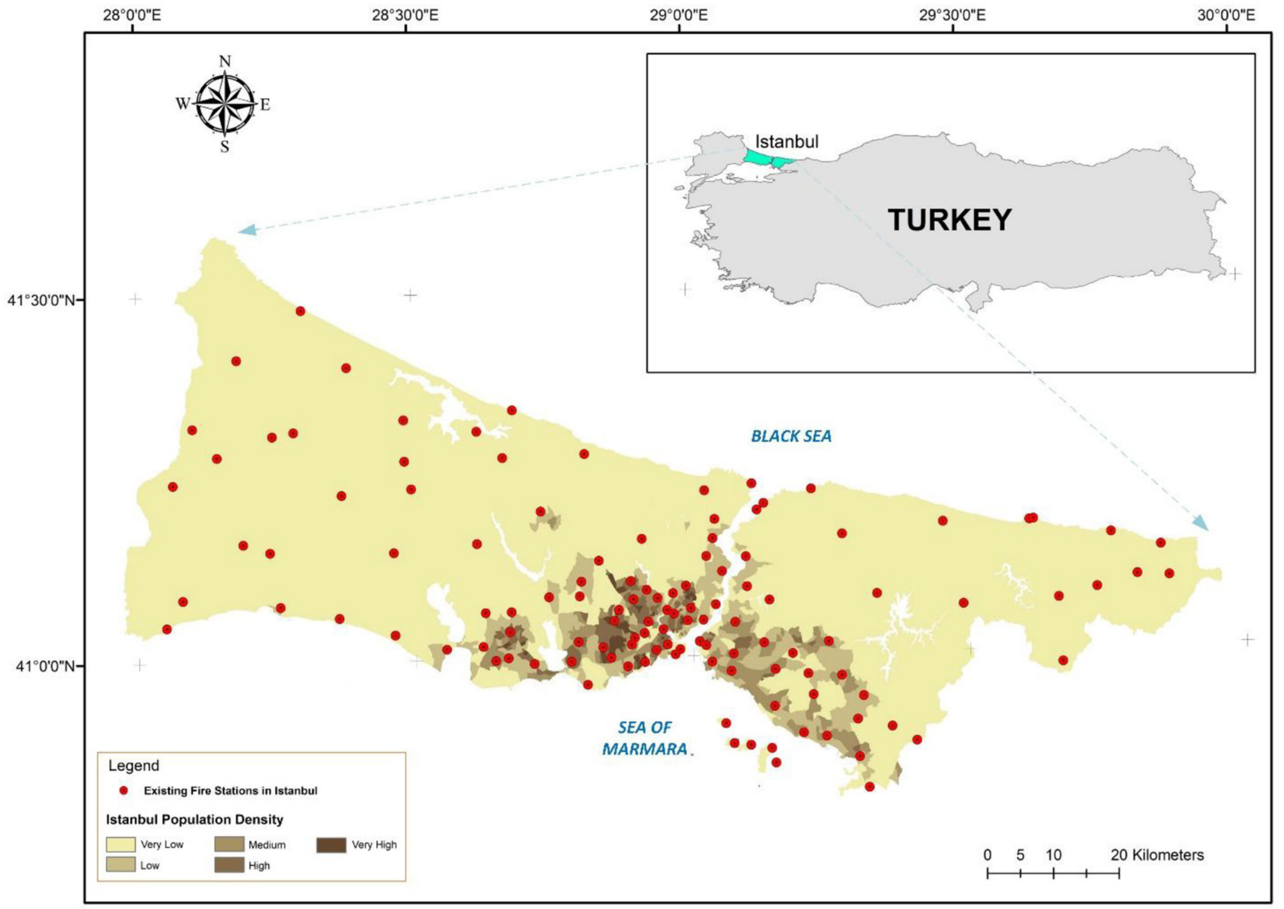

FIGURE 1
Case study of Istanbul Province showing existing fire stations and population density for 2020. Source: Nyimbili and Erden (2020c).

(IMM Fire Department, 2020) for 2020 considering the causes of fires and the number of incidences. The results are presented in Table 1.

As shown in Table 1, the sources and causes of the urban fires were generalized into 11 classes that included cigarettes, electrical (electrical contact, electricity, electrical appliances, electrical conduit box, transformer, overhead lines), children playing with fire (spark splash, candle tipping, flash fire and fire suspicion), intentional (deliberate), unknown, chimney and stove, increased heat/blaze, cooker hood/hoover and gas cooker, natural gas explosion (chemical substance fire, liquefied petroleum gas (LPG) explosion, gasoline flares/fuel oil for vehicles (LPG vehicle and fuel oil), and lightning). The total number of fire incidents registered for Istanbul in 2020 was 20,586. The highest number of cases were from cigarettes, with 8,022 (39.0%), followed by electrical causes, with 5,420 (26.3%). Children playing with fire-related causes also represented quite a high number with 1,946 (9.5%), as well as intentional/deliberate and unknown causes of fire incidences accounting for 1,553 (7.5%) and 1,444 (7.0%) cases, respectively. The lowest number of incidences were recorded from lightning causes with only 10 (0.1%) cases, closely followed by gasoline flares/fuel oil/LPG for vehicle causes with 57 (0.3%) and natural gas/LPG explosions with 87 (0.4%) cases.

From the fire statistics examined, it can be observed that a high number of fire occurrences was largely related to energy consumption (electricity usage) and human activities such as smoking (cigarettes) and children playing with fire/flash fires.

The urgent need for additional urban emergency facilities is underlined in light of Istanbul's current fire risk condition. The subsequent section, therefore, presents a conceptual framework for the DEMATEL technique being used to examine the interrelationships and levels of influence among the criteria, briefly described therein, that are deemed necessary for the planning procedure.

3. Research methodology

The selection of new urban emergency facilities and fire station sites in Istanbul is a complex problem involving multiple criteria as well as a thorough procedure for evaluating many alternatives to arrive at an optimal solution.

In this article, within the structuring and construction stage of the research methodology, the decision goal is well defined and the MCDA method of DEMATEL (Gabus and Fontela, 1973, 1976) was

TABLE 1 Causes of fire and number of incidents in Istanbul for 2020.

Causes of fire	Number of incidents	Percentage
Cigarettes	8,022	39.0
Electricity, electric conduit box, overhead lines, transformer, refrigerator	5,420	26.3
Children playing with fire, spark splash, candle tipping, flash fire, suspicion of fire	1,946	9.5
Intentional/on purpose, sabotage (deliberate)	1,553	7.5
Indeterminable/undetected (unknown)	1,444	7.0
Chimney, stove	901	4.4
Increased heat/blaze	868	4.2
Cooker hood, gas cooker	278	1.4
Natural gas explosion, chemical substance fire, LPG explosion, explosion	87	0.4
Gasoline flares/fuel oil for vehicles, fuel oil, LPG vehicle	57	0.3
Lightning	10	0.1
Total	**20,586**	

LPG, liquefied petroleum gas.

selected as the most suited to resolve the complexity related to the multiple evaluations of interrelated criteria.

Based on a comprehensive literature search and previous studies (Erden and Coskun, 2010; Nyimbili and Erden, 2020b,c, 2021), the relevant criteria for the development of new metropolitan emergency departments were determined to create a structural model. Thereafter, using the GDM approach, a committee of experts was selected from which an aggregate of their assessments using a 5-point comparison scale of the DEMATEL method was captured. The acquired information reflected the decision-makers' preference judgments of the criteria influences and interrelationships. The expert panel that was assembled was composed of 19 specialists, each possessing over a decade of pertinent experience in disaster and emergency management, as well as risk planning disciplines. These experts were selected from academic, professional, and industry spheres, all having been involved in disaster and emergency planning project activities in Istanbul, including others with Federal Emergency Management Agency certifications, alongside seasoned fire brigade practitioners that consisted of firefighters, research and planning coordinators, and supervision personnel. The detailed summary profile of the experts engaged, as well as their corresponding weights, is further provided in Nyimbili and Erden (2020c).

The criteria interactions and interrelations were then evaluated using the DEMATEL method during the assessment stage to construct a causal diagram and a digraph. Transforming the criteria's complex causal interrelation into a visible structural representation was made possible by using the constructed causal diagrams that provide useful insight, thereby enabling effective problem-solving and decision-making by identifying and distinguishing the cause-and-effect criteria under evaluation (Tzeng and Huang, 2011).

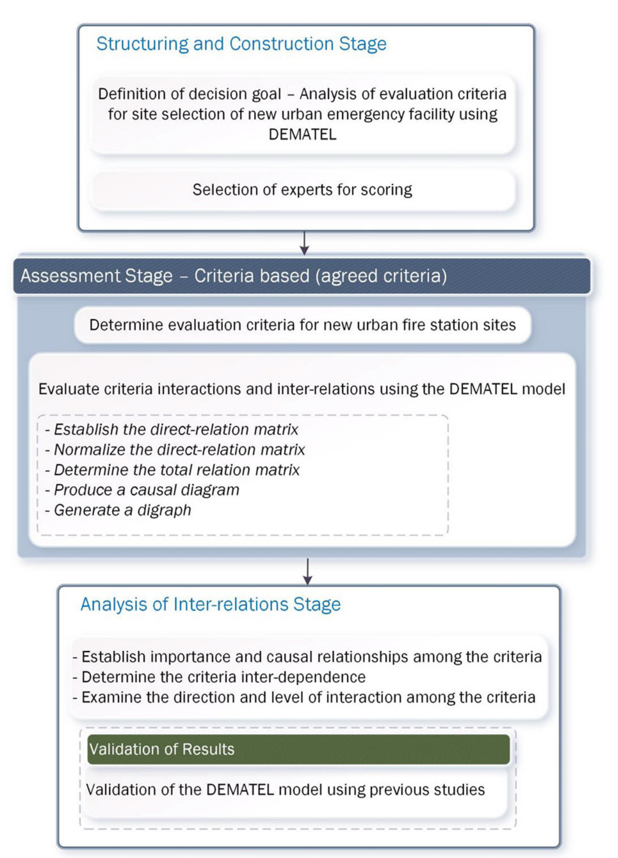

FIGURE 2
Proposed Decision-Making Trial and Evaluation Laboratory (DEMATEL) framework.

Finally, during the analysis of the interrelations stage, the criteria's significance, causal linkages, interdependence, and direction, as well as the level of interaction, were investigated. Consequently, validation of the DEMATEL model result was conducted by comparing the results from previous studies to generate further insights. Figure 2 provides the overall framework applied in this research.

3.1. DEMATEL

The technique of DEMATEL (Gabus and Fontela, 1973, 1976) was developed to resolve intricate problems connected with multiple interrelated criteria using a structural modeling approach.

The DEMATEL method comprehensively constructs and analyzes a structural model using directed graphs or *digraphs* visually to segregate multiple criteria into cause-and-effect groups that enable the capture of causal relationships between criteria. The generated *influence map* supports the analysis of intertwined cluster problems to visualize the directed criteria relationships and specify the level of interactivity between criteria (Tzeng and Huang, 2011).

TABLE 2 Comparison scale of the Decision-Making Trial and Evaluation Laboratory method.

Numerical		Definition
0	$\Longrightarrow$	No influence
1	$\Longrightarrow$	Low influence
2	$\Longrightarrow$	Medium influence
3	$\Longrightarrow$	High influence
4	$\Longrightarrow$	Very high influence

By using DEMATEL in this study, quantitative extraction of the interrelationship between evaluation criteria for selecting new urban emergency facility sites is taken into account. In this regard, both direct and indirect influences among multiple criteria are considered (Tzeng and Huang, 2011; Dey et al., 2012). Over the years, the DEMATEL method has been widely used to handle a variety of complex practical decision-making challenges, such as in aviation safety assessments (Liou et al., 2007), supplier selection (Dey et al., 2012), urban rail transit projects (Yuan et al., 2015), landfill site selection (Kharat et al., 2016), adaptive reuse of culturally significant industrial structures (Vardopoulos, 2019) and recovery solutions for ecotourism centers amid the COVID-19 outbreak (Hosseini et al., 2021). The DEMATEL model construction procedure is broken down into the following stages.

3.1.1. Stage 1: calculate the average initial direct-relation matrix [A] using scores

The DEMATEL method's comparison scale must be built in order to measure the relationship between criteria i and j, according to the four influential levels varying from 0 (*no impact*) to 4 (*very high influence*) as shown in Table 2.

Using the comparison scale, a panel of representative experts is asked to determine their view of the direct effect that each element i exerts on each other element j, as shown by a_{ij}. The influence of a particular criterion over itself is 0, and therefore, all the diagonal elements will be 0. Following the collection of these sets of direct matrices from the experts, an average matrix **A** is created, with each element representing the mean of the corresponding elements in the experts' direct matrices (in the case of GDM).

The kth expert assigns an integer rating x_{ij}^{k} that represents the degree of influence that criterion i has on criterion j.

Equation 1 calculates the $n \times n$ matrix **A** by taking the average of the individual expert's scores:

$$Matrix\ \mathbf{A}\ (mean\ initial\ direct - relation\ matrix) = [a_{ij}] \quad (1)$$

$$a_{ij} = \frac{1}{H} \sum_{k=1}^{H} x_{ij}^{k}, \quad (2)$$

where H, total number of experts and k, number of respondents surveyed.

3.1.2. Stage 2: normalizing the direct-relation (or direct-influence) matrix

The normalized direct-influence (or direct-relation) matrix, **D**, is computed using Eqs (2), (3) based on the direct-relation matrix, **A**.

Let

$$S = max\left(\max_{1 \le i \le n} \sum\nolimits_{j=1}^{n} a_{ij},\ \max_{1 \le j \le n} \sum\nolimits_{i=1}^{n} a_{ij}\right) \quad (3)$$

then,

$$\mathbf{D}\ (the\ direct - influence\ matrix) = \frac{\mathbf{A}}{\mathbf{S}}. \quad (4)$$

The direct impact that criterion i has on the other criteria is represented by the sum of each row j of matrix **A**; $max(\max_{1 \le i \le n} \sum_{j=1}^{n} a_{ij},\ \max_{1 \le j \le n} \sum_{i=1}^{n} a_{ij})$ depicts the direct impact on others.

3.1.3. Stage 3: calculate the total-relation matrix

The total-relation matrix (**T**) implies the total-influence matrix. The total-relation matrix, **T**, is computed using Equation 4 after producing the normalized direct-relation matrix, **D**.

$$\mathbf{T} = \mathbf{D}\,(I - \mathbf{D})^{-1}, \quad (5)$$

where I, identity matrix.

3.1.4. Stage 4: producing a causal diagram

In the total-influence matrix, **T**, the sum of rows and columns are represented individually as vectors **D** and **R**, respectively. "*Prominence*," the horizontal axis vector (**D** + **R**), is created by adding **D** to **R**, which denotes the criterion's importance. Similarly, the vertical axis (**D** − **R**), termed "*Relation*," is created by subtracting **R** from **D** and can be used to separate criteria into *causal* and *effect groups*. From the foregoing statements, if (**D** − **R**) is positive, the criterion belongs to the *causal group*, and if (**D** − **R**) is negative, the criterion belongs to the *effect group*. As a result, the *causal diagram* may be obtained by mapping the (**D** + **R**, **D** − **R**) data set.

Then,

$$\mathbf{T} = [t_{ij}]_{nxn} \quad i, j = 1,\ 2,\ \ldots, n; \quad (6)$$

$$\mathbf{D} = [D_i]_{nx1} = \left(\sum\nolimits_{j=1}^{n} t_{ij}\right)_{nx1}; \quad (7)$$

$$\mathbf{R} = [R_j]'_{nx1} = \left(\sum\nolimits_{i=1}^{n} t_{ij}\right)'_{1xn}, \quad (8)$$

where transposition is indicated by the *superscript apostrophe*.

If D_i is the sum of the ith row of matrix **T**, then D_i is the sum of all the other criteria's direct and indirect impacts of criterion i. Furthermore, if R_j is the sum of the jth column of matrix **T**, then R_j is the sum of all the other elements' direct and indirect impacts on j.

Additionally, note that when $j = i$ (i.e., the sum of the row and column aggregates); $(D_i + R_i)$ yields an index of the intensity of the given and received influences. That is, it illustrates how much criterion i impacts or is impacted by criterion j. Also, if $(D_i + R_i)$ is positive, criterion i influences other criteria, whereas if it is negative, criterion i is influenced by the other criteria (Liou et al., 2007; Yang et al., 2008; Chen, 2016). In other words, $(D_i + R_i)$ represents the significance of criterion i whereas $(D_i - R_i)$ denotes the net impact of criterion i (Altuntas and Gok, 2021).

3.1.5. Stage 5: confirm the threshold value (α), obtain an inner-dependence matrix, and generate a digraph showing causal relations

To filter the minor effects given in matrix **T**, it is required to select a threshold value, α, which is derived based on calculating the mean elements in matrix **T** or the representative experts' judgments (Yang et al., 2008; Chen, 2016; Altuntas and Gok, 2021). This final stage is necessary to identify the relationship structure of the most important variables. Each criterion t_{ij} offers information about how criterion factor i influences j, according to matrix **T**. A threshold value for each criterion's influence intensity is required to reduce the complexity of the IRM. If an element's influence level in matrix **T** exceeds the threshold value, α, that element is included in the final IRM (Liou et al., 2007; Yang et al., 2008). In an *inner-dependence matrix*, only the criteria whose impact in matrix **T** are larger than the threshold value will be displayed (Lin et al., 2011).

3.2. Criteria affecting the planning of new urban emergency facilities

Existing studies have analyzed six criteria when deciding where to build new emergency centers in cities. These criteria were screened after a comprehensive evaluation process from previous studies as suggested by Erden and Coskun (2010) and Nyimbili and Erden (2020a,b,c, 2021). The developed criteria encompass social, built, accessibility, and risk and safety dimensions as shown in Table 3.

Brief operational definitions of the criteria most influential for selecting new urban facility sites are described in the following subsections.

3.2.1. HPD

Fires are more likely to occur in densely populated urban community areas, culminating in a greater impact. The high concentration of people, unfitting structural characteristics of urban property, and unsound human behavioral practices exacerbate the conflagration and fire risk potential (Abrassart et al., 2021). This includes unsafe energy consumption usage, such as electricity, gas, and so on by communities, especially in overcrowded settlements, where residents lack the capacity to carry out quick intervention measures to combat fires that have already ignited and fire trucks and emergency equipment have limited access to building structures due to a failure to comply with planning regulations (Mtani and Mbuya, 2018).

TABLE 3 **Factors affecting the planning of new urban emergency facilities.**

Dimensions	Criteria	Description
Social	HPD	Densely populated areas are at risk of fires
Built	WBD	Old wooden building structures within built-up areas pose a huge risk of the spread of fire
Accessibility	DEF	Fire stations and emergency facilities should be located away from the already serviced areas
	PMR	Accessibility of emergency facilities to the main road and transportation routes is essential in enabling faster response to fire incidences
Risk and safety	DHM	Hazardous materials in industrial facilities and warehouses that include LPG, pressured gases, oil stations, etc. increase the risk of fires and explosions
	DER	Planning of emergency facilities away from areas prone to earthquakes prevents infrastructural and structural damage in the event of a disaster

HPD, high population density; WBD, wooden building density; DEF, distance from existing fire stations; PMR, proximity to main roads; DHM, density of hazardous materials; DER, distance-to-earthquake risk; LPG, liquefied petroleum gas.

3.2.2. WBD

Istanbul city has had a rich cultural heritage since the Byzantine period and is composed of old wooden building architecture that significantly increases the risk of the spread of fire and large urban conflagrations. In the built-up regions with a high density of wood building inventory, the potential for risk of urban fires is higher, hence the need to prioritize the siting of fire and emergency facilities in these locations.

3.2.3. DEF

New urban emergency facilities should be planned away from the existing emergency and fire facilities to ensure optimization and avoid overlap of the service coverage areas. A fire response time of within 5 min is considered in the new service coverage analysis while taking the drive time, topology, and road traffic conditions on the main road networks into account.

3.2.4. PMR

In urban areas, especially in congested central business districts and high building-density areas with poorly planned city infrastructure, narrow roads limit access by fire engines and firefighting equipment. This scenario significantly increases the fire risk and impedes rescue and evacuation efforts with delays in emergency response times. Therefore, new urban emergency facilities should be sited near main-road transportation networks, free from crowded areas, for easier access to fire incidences and improving emergency response times.

3.2.5. DHM

One of the major sources of ignitions is oil and gas refineries and industrial and warehouse facilities, comprising petroleum, compressed gases, and chemical spills that are highly combustible, thereby increasing the risk of large flames, blasts, and propagation. New emergency facilities must therefore be prioritized in these high fire risk areas that have a high density of hazardous materials.

3.2.6. DER

The large metropolitan area of Istanbul that predominantly constitutes densely spaced building structures has historically been subjected to large conflagrations, arising from fires following earthquake occurrences since it is situated in an earthquake risk zone (Scawthorn, 2021). The last such huge fire caused massive destruction to a larger part of the Fener district in 1941 (Ansal et al., 2003). Post-earthquake fires, therefore, pose a significant hazard risk. The resultant ignitions from shaking in the event of large earthquakes lead to multiple simultaneous catastrophic conflagrations and massive damage to infrastructure (Scawthorn, 2021). Zones of high seismicity within Istanbul should consequently be avoided when planning new urban emergency facilities, and locations farther away from these high-risk areas should be preferred. Additionally, during an earthquake occurrence, damage to communication and road transportation routes will impede access to emergency sites by fire trucks and emergency vehicles.

After screening and determination of these criteria, a committee of experts through a consultative procedure provided their linguistic assessments of the direct relations among criteria for optimal planning of new urban emergency facility locations using the DEMATEL technique as clarified in the following section.

4. Implementation of the DEMATEL approach

In the implementation of the DEMATEL model, a committee of experts with emergency facility and disaster planning experience was consulted to assess the association between paired criteria that influence the optimal planning of urban emergency facilities in Istanbul. The experts provided their judgment of the interaction between each of the pair of criteria. By doing so, the linguistic assessments of direct relations among criteria were obtained.

As the result of this evaluation, the DEMATEL method's comparison scale (Table 2) was used to produce an *average direct-relation matrix*, **A**, which was obtained as the preliminary data of the analysis. The direct-relation matrix, **A**, computed for the panel of experts is shown in Table 4.

Normalization of the direct-relation matrix was performed using Equations 2 and 3 to generate the *normalized direct-relation matrix*, **D**. Table 5 summarizes the findings.

The total-influence matrix, **T**, is then calculated using Equation 4 as presented in Table 6.

The total and net impacts for each criterion were calculated using the total-influence matrix and are given in Table 7.

Table 7 was used to retrieve, order, and tabulate the influencing impact of D_i, the influenced impact of R_i, the level of significance $(D_i + R_i)$, and the causal degree $(D_i - R_i)$ values.

A data set of $(D_i + R_i,\ D_i - R_i)$ was mapped to construct the cause-and-effect diagram (causal diagram) using $\boldsymbol{D}$ and $\boldsymbol{R}$. With $(D_i + R_i)$ as the horizontal (x-)axis and $(D_i - R_i)$ as the vertical (y-)axis, the digraph was displayed in Figure 3.

From Figure 3, the causal diagram articulates the interaction between the criteria and could be a useful tool in making decisions. To filter out certain minor impacts in practice, the threshold value in this research, $\alpha = \mathbf{0.1773}$, was derived from the mean of the elements in the matrix. The relationships in the total influence matrix, **T**, that goes beyond the threshold value are bolded and presented in Table 8.

These results from Table 8 were used to show the IRM via a digraph, with the direction of arrows representing the inter-criteria influence in Figure 4.

The subsequent section discusses the research results of the criteria influences and inter-criteria analyses as well as the DEMATEL model validation for the best choice of urban fire and emergency facilities in Istanbul.

5. Results and discussion

5.1. Key results and findings

Further insights into analyses of the criteria interactions were generated by identifying the most important relationships among the criteria. From Table 8, which shows the relations exceeding the threshold limit of influence of **0.1773**, some inferences can be made. Out of the six criteria, high population density (HPD) has a significant influence on four other criteria; PMR, DEF, DHM and WBD each have a significant influence on three other criteria. Therefore, these four criteria are the most influential contributors to the best choice of location options for facilities of fire and emergency services in cities. Conversely, DER does not significantly influence any other criteria. Based on the influence that each criterion has on others, an IRM or influence map was created that describes how each criterion interacts with the other criteria (Ogrodnik, 2018; Rahman et al., 2021).

The causal diagram (Figure 3) shows the x-axis $(D_i + R_i)$ that represents the criterion's measure of influence while the y-axis $(D_i - R_i)$ represents the magnitude of a criterion's influence from other criteria or the intensity of the effect. Both these values characterize the criteria interrelationships. The impact on other criteria is represented by the D_i factor, whereas the impact from other criteria is represented by the R_i value (Broniewicz and Ogrodnik, 2021). All these variables should be considered when identifying and determining the critical criteria in the planning of urban emergency facilities. According to the causal diagram in Figure 3, when the criterion is situated above the horizontal axis, the $(D_i - R_i)$ value is *positive*, implying that the effect of this particular criterion exerted on the other criteria is greater than that received from the others. The value of the influential impact D_i is larger than the value of the affected impact R_i (Zou et al., 2022). Therefore, the criterion is a net causer and, in turn, is categorized in the *cause cluster*. In contrast, when the $(D_i - R_i)$ value is *negative*, the criterion is

TABLE 4 Average direct-relation matrix for the experts.

Criteria	C_1 (HPD)	C_2 (PMR)	C_3 (DEF)	C_4 (DHM)	C_5 (WBD)	C_6 (DER)
C_1 (HPD)	0	2	3	2	3	0
C_2 (PMR)	2	0	2.5	1.5	0	0
C_3 (DEF)	2	2	0	1	1.5	0
C_4 (DHM)	2	2	1.5	0	1	1
C_5 (WBD)	1	2	2.5	1	0	0.5
C_6 (DER)	1	1	1	1	1	0

HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk.

TABLE 5 Normalization of the direct-relation matrix.

Criteria	C_1 (HPD)	C_2 (PMR)	C_3 (DEF)	C_4 (DHM)	C_5 (WBD)	C_6 (DER)
C_1 (HPD)	0	0.2	0.3	0.2	0.3	0
C_2 (PMR)	0.2	0	0.25	0.15	0	0
C_3 (DEF)	0.2	0.2	0	0.1	0.15	0
C_4 (DHM)	0.2	0.2	0.15	0	0.1	0.1
C_5 (WBD)	0.1	0.2	0.25	0.1	0	0.05
C_6 (DER)	0.1	0.1	0.1	0.1	0.1	0

HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk.

TABLE 6 The total-influence matrix.

Criteria	C_1 (HPD)	C_2 (PMR)	C_3 (DEF)	C_4 (DHM)	C_5 (WBD)	C_6 (DER)	D_i
C_1 (HPD)	0	0.3039	0.4559	0.3039	0.4559	0	**1.5195**
C_2 (PMR)	0.3039	0	0.3799	0.2279	0	0	**0.9117**
C_3 (DEF)	0.3039	0.3039	0	0.1520	0.2279	0	**0.9877**
C_4 (DHM)	0.3039	0.3039	0.2279	0	0.1520	0.1520	**1.1396**
C_5 (WBD)	0.1520	0.3039	0.3799	0.1520	0	0.0760	**1.0637**
C_6 (DER)	0.1520	0.1520	0.1520	0.1520	0.1520	0	**0.7598**
R_i	**1.2156**	**1.3676**	**1.5955**	**0.9877**	**0.9877**	**0.2279**	

HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk. Bold values indicate sum of rows and columns signifying D_i & R_i values respectively.

regarded as a net receiver and subsequently classified in the *effect cluster* (Raut et al., 2011; Xia et al., 2015; Rahman et al., 2021; Ortíz-Barrios et al., 2023). Overall, the effect criteria are affected by the cause criteria, thus directly influencing them in the planning of new urban fire facilities.

Furthermore, the inter-criteria effect is represented by the orientation of the arrows as depicted in Figure 4, which illustrates these linkages among criteria in the modified version of the diagram without the **D** and **R** values (Figure 5).

It can be observed from Figure 5 that HPD has the most influence on all other criteria, whereas PMR and DEF are impacted by a lot of other criteria. The interrelationships among the various criteria for optimally selecting fire stations and urban emergency facilities in Istanbul were analyzed in this study. From Table 7 and the generated digraph presented in Figures 3, 4, the criteria's cause and effect linkages have been revealed. Based on Figures 4, 5, the causal criteria, in terms of their levels of significance, can be ordered as HPD ≻ DHM ≻ WBD ≻ DER. By further discussing the cause-and-effect directional arrows from the digraph in Figures 4, 5, HPD and DHM have mutual interactions where either one of the criteria will affect the other. Concurrently, mutual influences occur between the pairs of "HPD and DEF" and "HPD and PMR." However, PMR and DEF are net receivers and are both influenced by four criteria. The PMR criterion is influenced by the HPD, DHM, DEF, and WBD criteria, while the DEF criterion is influenced by the HPD, DHM, WBD, and PMR criteria. By comparison, HPD and DHM are net causes and thus affect four (DHM, WBD, PMR, DEF) and three (HPD, PMR, DEF) criteria, respectively. That is, the HPD criterion is the most essential in selecting an urban fire facility preceded by the DHM criterion. Notably, the DER criterion is neither influenced nor influences any other criteria. Furthermore, the HPD is at the peak of the

TABLE 7 Total effects and net effects for each criterion.

Criteria	D_i	R_i	D_i+R_i	D_i-R_i	Identity
C_1 (HPD)	1.5563	1.3834	2.9396	0.1729	Cause
C_2 (PMR)	0.8646	1.5563	2.4209	**−0.6917**	Effect
C_3 (DEF)	1.0375	1.5563	2.5938	**−0.5188**	Effect
C_4 (DHM)	1.2104	0.8646	2.0750	0.3458	Cause
C_5 (WBD)	1.0375	1.0375	2.0750	0.0000	Cause
C_6 (DER)	0.8646	0.1729	1.0375	0.6917	Cause

HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk. Bold values indicate an effect value.

causative group, inferring that it is the most critical parameter considered in urban emergency facility planning. The density of the population is higher in areas with close access to main roads, existing fire stations, industrialized areas with a lot of factories, and settlements with wooden buildings and is thus influenced by the relevant criteria. DHM is the second-most important criterion in the causal class, and it has a huge impact on the other population and closeness variables because highly industrialized regions with a higher concentration of hazardous products from factories have a large population and easy access to major road networks. The other least influential criteria in the causal group are WBD and DER.

The criteria in the effect group are PMR and DEF. These criteria are the most affected by the other criteria and the most influenced. Distances and access to the main road network are significantly affected by the population density, closeness to existing fire stations, presence of settlement areas with wooden buildings, and highly industrial zones/factories. DEF is largely influenced by the population, hazardous material density in factories/industrial facilities, access to the main road networks, and the presence of old historical buildings made of wood.

From the analyses of the most essential criteria within the causal cluster, it can be inferred that these criteria have a direct impact on the rest of the criteria and their performance can directly affect the planning objective of selecting new urban fire facilities. Correspondingly, it is difficult to move the cause cluster criteria as opposed to the effect cluster criteria (Hori and Shimizu, 1999). Moreover, when contrasted to the effect criteria, the cause criteria are considered to be the most underlying and stable (Vardopoulos, 2019), affecting the integral planning model, and therefore should be given more special attention by assigning them a higher priority (Wu and Chang, 2015). While the DEMATEL analysis has provided valuable insights into the interrelationships among the criteria, there are certain limitations that should be acknowledged. Different experts may provide different judgments, introducing subjectivity into the results and leading to potential variations in the outcomes. The other weakness of the study could be limited data variability, as the research relies on data specific to Istanbul. The findings might not be directly applicable to other urban areas with different demographic, geographic, and socioeconomic characteristics. In this view, some potential avenues for future research include exploring dynamic changes in these relationships over time, considering factors like urban growth and population shifts, as well as incorporating uncertainty analysis techniques, that can enhance the robustness of the findings. Methods such as the Monte Carlo simulation can be used to account for uncertainty in expert judgments and data.

The research findings hold significant implications for urban fire risk reduction planning, especially in megacities like Istanbul. By identifying the critical criteria that influence the selection of urban fire and emergency facilities, the research contributes to the development of evidence-based policies and strategies that can enhance public safety and emergency response effectiveness.

Moreover, the insights gained from this research can serve as a valuable resource for interdisciplinary collaboration among urban planners, emergency services managers, risk assessment experts, and policymakers. This collaboration can lead to the formulation of holistic, well-informed policies that address the complex challenges associated with urban fire risk in densely populated environments. The results of the DEMATEL analysis can therefore be validated using previous studies as described in the following sub-section.

5.2. Validation of model results from previous studies

Our DEMATEL analysis unveiled intricate cause-and-effect relationships within the decision criteria, shedding light on the complex dynamics influencing urban emergency facility planning and fire risk mitigation strategies. These insights resonate with the work of Trivedi (2018), who employed a similar DEMATEL approach to comprehend the interdependencies in shelter site selection for disaster response and preparedness decision-making. Our study further extends this notion by examining these relationships in the context of urban emergency facility selection for a specific urban setting, Istanbul. The findings of this research have several significant implications for urban fire risk mitigation planning. The research identifies critical criteria influencing the optimal location selection for fire and emergency facilities in Istanbul, such as HPD, DHM, PMR, and DEF. These critical criteria should guide decision-makers in allocating resources and developing policies. Further, the influence map generated from the DEMATEL analysis indicates the hierarchy of cause-and-effect relationships among criteria. This can aid in setting priorities for policy formulation and resource allocation, with HPD and DHM emerging as the most influential criteria. In addition, the interrelationship analysis underscores the need for a holistic approach to decision-making. Policies that address the identified cause criteria, particularly HPD and DHM, will likely have a greater impact on the overall effectiveness of fire risk mitigation efforts.

The validation of the DEMATEL model results using previous studies conducted by Nyimbili and Erden (2020b,c, 2021) enhances the credibility of the findings. The consistent alignment between the DEMATEL analysis results and the outcomes from other MCDM techniques, such as GIS-based fuzzy AHP, entropy AHP, and GDM, as well as the BWM (Rezaei, 2015), reinforces the robustness of the identified critical criteria for the appropriate selection of new urban fire and emergency infrastructure needed to reduce fire response time to under 5 min. Using the six evaluation criteria established from the screening process, the relevant criteria weights were determined, from which the subsequent preference rankings were identified as shown in Table 9.

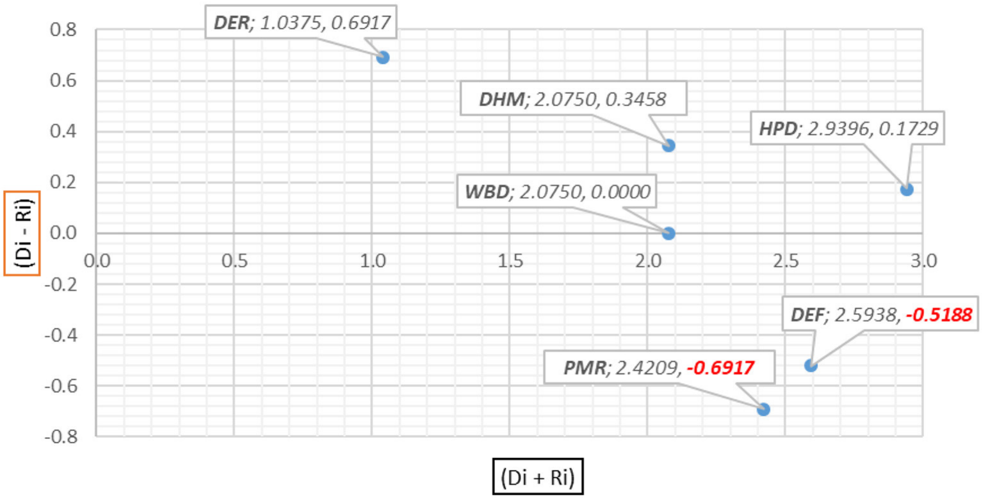

FIGURE 3
Causal diagram showing causal and effect relations among criteria. HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk.

TABLE 8 Total-influence matrix with relations exceeding the threshold value.

Criteria	C_1 (HPD)	C_2 (PMR)	C_3 (DEF)	C_4 (DHM)	C_5 (WBD)	C_6 (DER)
C_1 (HPD)	0	**0.3039**	**0.4559**	**0.3039**	**0.4559**	0
C_2 (PMR)	**0.3039**	0	**0.3799**	**0.2279**	0	0
C_3 (DEF)	**0.3039**	**0.3039**	0	0.1520	**0.2279**	0
C_4 (DHM)	**0.3039**	**0.3039**	**0.2279**	0	0.1520	0.1520
C_5 (WBD)	0.1520	**0.3039**	**0.3799**	0.1520	0	0.0760
C_6 (DER)	0.1520	0.1520	0.1520	0.1520	0.1520	0

HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk. Bold values indicate the highest value.

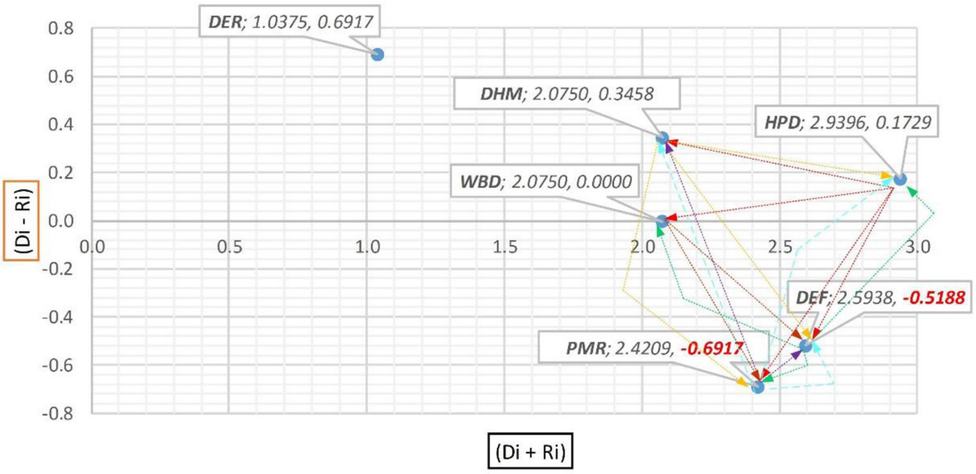

FIGURE 4
Digraph showing the significant relationships in terms of linkages among criteria. HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk.

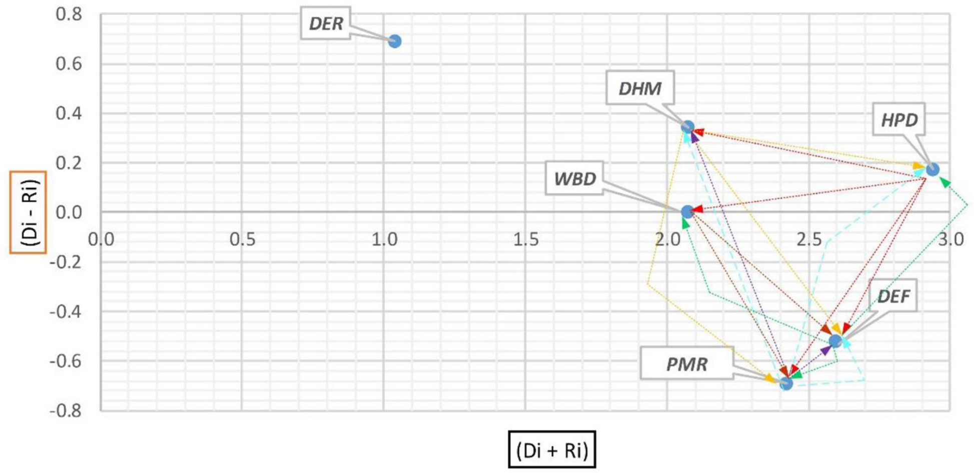

FIGURE 5
Digraph showing linkages among criteria (without D and R values). HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk.

The results from the MCDM techniques implemented in previous research (Nyimbili and Erden, 2020b,c, 2021) correlate well with the DEMATEL analysis findings. From all the MCDA methods examined, it can be observed that the most important and influential criteria for optimal planning of new urban emergency infrastructure across all groups of decision-makers are the DHM and HPD. These two criteria are ranked at the top of the causal group while the least important criterion evaluated is DER, which is also the lowest ranked in the causal group according to the findings of the DEMATEL analyses, therefore, validating the model. The validation process demonstrates a consensus regarding the importance of DHM and HPD as top-ranking criteria. This convergence of the most significant criteria across the different MCDA methods, therefore, strengthens the argument for the significance of these criteria in urban fire risk reduction planning.

Comparing our results, the research aligns with the conclusion of Trivedi (2018): that understanding these interconnections is crucial for effective emergency facility planning. Our findings further demonstrate that, in line with Trivedi (2018), urban density and accessibility significantly influence the distribution of emergency facilities. This insight corroborates the notion that optimal placement should consider not only fire risk but also ease of access. The studies by Abdeen et al. (2021), Ortíz-Barrios et al. (2023), and Taherizadeh et al. (2023) also support our findings, highlighting the importance of stakeholder collaboration in aligning emergency facility placement decisions with community needs for effectiveness in disaster mitigation, preparedness, and response planning.

TABLE 9 Criteria rankings and importance by preference ordering from previous studies for Decision-Making Trial and Evaluation Laboratory model variation.

MCDM technique	DM group	Criteria rankings and importance by preference ordering
AHP	Both academicians and practitioners	DHM ≻ HPD ≻ PMR ≻ WBD ≻ DEF ≻ DER
FAHP	Both academicians and practitioners	DHM ≻ HPD ≻ PMR ≻ WBD ≻ DEF ≻ DER
Entropy-AHP	Both academicians and practitioners	HPD ≻ DHM ≻ PMR ≻ WBD ≻ DEF ≻ DER
BWM	Both academicians and practitioners	DHM ≻ HPD ≻ PMR ≻ DEF ≻ WBD ≻ DER
BWM (GDM approach)	Academicians only	DHM ≻ HPD ≻ PMR ≻ DEF ≻ WBD ≻ DER
	Practitioners only	HPD ≻ DHM ≻ PMR ≻ WBD ≻ DEF ≻ DER

MCDM, multi-criteria decision analysis; DM, decision maker; AHP, analytic hierarchy process; FAHP, fuzzy analytic hierarchy process; BWM, best–worst method; GDM, group decision-making; HPD, high population density; PMR, proximity to main roads; DEF, distance from existing fire stations; DHM, density of hazardous materials; WBD, wooden building density; DER, distance-to-earthquake risk.

6. Concluding remarks

In essence, this research set out to apply the method of DEMATEL to assess the complex interrelationships among the criteria deemed essential for planning new facilities for fire and emergency services in Istanbul city, Turkey.

The high fire risk situation prevalent in Istanbul is largely caused by the rising urban population and increasing demand for access to socioeconomic and infrastructural services, thereby underscoring the need for adequate planning of emergency and fire protection services.

Based on previous studies, the suitable criteria for the optimal planning of emergency facilities were comprehensively examined. The expert preferences of the criteria influences were acquired using the GDM approach of the DEMATEL technique. The criteria interactions and the cause-and-effect group interrelationships were subsequently evaluated to generate a diagram of causality and consequence aside from a *digraph* to visually illustrate the causal linkages using directional arrows.

The results of the study suggest that the HPD and the DHM criteria are at the top of the causal group implying that they are the most influential and significant for suitably planning urban emergency facilities. These criteria should be given the highest priority in the planning process. The optimal selection of a suitable site must be located in areas with a high population density and is likely to be close to the main road network infrastructure (PMR), where there are existing fire and emergency facilities (DEF), in highly industrialized zones with a high density of hazardous materials from factories (DHM), and settlement areas made up of a high density of wooden building structures (WBD). The HPD criterion is therefore affected by these previously discussed criteria. The DHM criterion is ranked second within the causal group and has a considerable effect on the HPD and PMR criteria. In highly industrialized areas with a large number of factories and warehouses, DHM is high. These areas also have large population densities (HPD) and have good access to the main road and transportation networks (PMR). The effect group criteria are the most affected and influenced by the other criteria and consist of PMR and DEF.

The DEMATEL model results presented in this article, with regard to the criteria importance levels have therefore been validated using previous studies that utilized other MCDM methods, such as AHP, fuzzy AHP, entropy AHP, and BWM.

The contribution of this research is that the complexity of the interrelationships and interdependence of the criteria required for planning new emergency facilities in megacities and urban environments has been modeled using the MCDM method of DEMATEL. Linkages among the criteria have been established, and these criteria have been clustered into the cause-and-effect groups in terms of their levels of influence, priority, and how they impact directly or indirectly on the entire emergency planning and fire risk mitigation process. The research outcomes have an immense practical benefit to policymakers at both local and national levels toward enhancing the integrated planning of fire risk reduction and mitigation strategies with a special focus on rapidly growing urban areas and megacities besides Istanbul that are facing similar challenges.

In conclusion, this research has made significant contributions to policy development in the realm of fire risk reduction and emergency facility planning for rapidly growing megacities like Istanbul. The application of the DEMATEL method to assess the intricate interrelationships among critical criteria for urban emergency facilities has yielded insights with direct policy implications such as providing decision-makers with a comprehensive understanding of the critical criteria influencing the optimal location selection for fire and emergency facilities. By identifying HPD and DHM as top-priority criteria, the research aids in informed decision-making, enabling authorities to allocate resources efficiently and effectively.

Additionally, the prioritization of criteria through the DEMATEL analysis, placing HPD and DHM at the forefront, offers a clear road map for policy development. These findings can guide policymakers in formulating strategies that align with the most influential factors driving fire risk mitigation and emergency facility planning. Furthermore, the research outcomes guide resource allocation for fire protection and emergency services. Policies can be crafted to ensure that areas with high population densities, industrial activity, and hazardous materials concentrations receive greater attention, leading to enhanced emergency response capabilities. This research also contributes to formulating policy related to urban planning integration. The emphasis on criteria interactions and their hierarchical relationships underscores the need for integrated urban planning. The research findings advocate for policies that integrate fire risk reduction considerations into broader urban development strategies, fostering safer and more resilient cities.

Stakeholder engagement is another contribution to policy that is strongly emphasized in literature within the broader context of urban planning. The complexity of fire risk mitigation planning, as revealed in this research, emphasizes the need for multistakeholder engagement and communication. Policies can encourage collaboration among urban planners, emergency service providers, industry stakeholders, and communities, ensuring a holistic approach to risk reduction.

The research further establishes the intricate links between criteria that contribute to effective fire risk reduction. Policies derived from these findings can integrate fire risk mitigation with broader disaster management strategies, enhancing overall preparedness and response capabilities and focusing on vulnerability reduction and resilience building that align with the principles of sustainable development. Policies influenced by the research outcomes therefore can contribute to the creation of more sustainable and secure urban environments, minimizing the adverse impacts of fire emergencies.

While this study has contributed valuable insights into the complex interrelationships of criteria for urban emergency facility planning, it is important to acknowledge its limitations in relation to the decision problem under examination and consider avenues for future research that can build upon the findings. This study focused on the specific context of Istanbul; thus, the findings may not be directly applicable to other cities with distinct demographic, geographic, and socioeconomic characteristics. Future research should explore how the identified interrelationships vary across different urban settings. Also, in this study, experts' judgment was relied on for the pairwise comparisons in the DEMATEL analysis. The inherent subjectivity of these judgments introduces a level of uncertainty in the results. Incorporating a broader range of experts, employing sensitivity analysis techniques, and using FST can enhance the reliability of the findings. In practice, a combination of other MCDM methods is recommended as well to gain a more comprehensive view of the decision problem.

Building on the static nature of this study, future research could delve into dynamic analyses that consider the evolving nature of urban environments. Exploring how interrelationships change over time due to factors like population growth, economic shifts, and policy changes can offer deeper insights. While the validation against previous studies enhances credibility, future research could also undertake quantitative validation using empirical data from real-world emergency responses. Comparing the predicted outcomes with actual emergency events could validate the model's effectiveness. Another future research direction is to perform a cross-cultural analysis. Exploring how cultural factors influence criteria interrelationships could provide a broader understanding of the dynamics. Comparative studies across cities with different cultural contexts could shed light on the role of culture in shaping urban emergency facility planning. The study further recommends that a long-term resilience analysis be done. An investigation of the long-term impact of the identified critical criteria on urban resilience can provide insights into how emergency facility planning influences a city's overall ability to withstand and recover from various hazards.

In essence, this research has bridged the gap between theory and practical policy implementation by illuminating the interplay of criteria in urban fire risk reduction and emergency facility planning. The contributions made by this study have the potential to reshape policy agendas, enhance the effectiveness of fire risk mitigation strategies, and contribute to the overall safety and resilience of rapidly growing cities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PN: conceptualization, data curation, methodology, software, visualization, writing—original draft preparation, investigation, writing—review and editing, resources, and formal analysis. TE: conceptualization, methodology, validation, formal analysis, resources, writing—review and editing, project administration, and supervision. EM: writing—review and editing, resources, and project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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