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A Hybrid Approach Integrating Entropy-AHP and GIS for Suitability Assessment of Urban Emergency Facilities

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Abstract: Globalization has become a major issue of focus as rapid urban populations and urbanization effects are on the rise. A critical need arises for effective urban planning for Istanbul in relation to the use of a hybrid approach integrating AHP-Entropy and GIS for emergency facility planning. In this paper, the combination of AHP and Entropy methods was used for evaluating criterion weights subjectively and objectively. These techniques were utilized with regard to the assessment of suitable areas for planning new urban emergency facilities for Istanbul province which experiences increasing urban fire-related emergencies. AHP and Entropy have been used to evaluate the weights of determined criteria from expert preference judgments and GIS for processing, analysis and visualization of the model result in the form of a suitability map for new urban emergency facilities. Validation of the model was performed on the criteria with the strongest influence in the decision outcome and spatially visualized using the sensitivity analysis (SA) method of one-at-a-time (OAT). From the findings, it was estimated that 28.1% of the project area, accounting for a third of it, is likely to be exposed to the risk of urban fires and therefore immediate planning of new urban emergency facilities is recommended for adequate fire service coverage and protection.

Keywords: geographic information system (GIS); analytical hierarchy process (AHP); entropy; emergency facilities; multi-criteria decision making (MCDM); sensitivity analysis

1. Introduction

The phenomena of technological development, globalization, population growth and their effects have given rise to urbanization. The growth and expansion of cities have been accentuated by the rise in population and migration to urban regions [1]. This prevalence has also brought about the growing concern and potential risk of fires causing loss of lives and property damage, consequently posing a threat to urban societies.

Istanbul is regarded as a regional economic, cultural and historic hub in the Euro-Asian region. It is the most urbanized province of Turkey inhabited by more than 15 million people, representing almost 20% of the country's population [2]. Concurrently, there has been a high and recurrent rise in the number of fire incidences experienced in Istanbul. More than 58,000 fire occurrences having an average response time exceeding five minutes have been reported by the Istanbul Metropolitan Municipality Department of Fire Brigade [3]. Fire incidences mainly arise from careless actions or misuse of hazardous, flammable or explosive material and after strong earthquake eventualities [4] which cause infrastructural damage, with the most vulnerable facilities being large industrial and oil plants, electrical and gas lines [5]. Against this background, this study aims to suggest a GIS-based multi-criteria decision analysis (MCDA) methodology for assessing the feasibility of planning additional urban fire and emergency facility locations by reducing the fire response time to within five minutes for a case study region of Istanbul. Thereby, mitigating fire impacts and risks leads to an improvement in fire safety and protection services as part of emergency preparedness and response planning action.

MCDA methods were developed to resolve complex problems that have many criteria to be considered, incorporating a broad range of opinions among stakeholders and conflicting goals in the process of making decisions. The common goal is to systematically select the most optimal planning decision outcome that transcends the shortcomings of the unstructured individual or group decision-makers, among many available alternatives based on varied criteria [6,7]. The selection of new urban fire facility sites represents a spatial, complex planning problem that requires a thorough and careful analysis of numerous criteria and the involvement of multidisciplinary teams across different planning functions. Many MCDA methods exist and are more commonly used such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [8], Analytical Hierarchy Process (AHP) [9], ELimination and Choice Expressing REality (ELECTRE) [10,11], CRiteria Importance Through Intercriteria Correlation (CRITIC) [12], Multi-Attribute Utility Theory (MAUT) [13], Simple Multi-Attribute Rating Technique (SMART) [14,15], Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) [16,17]. The key aspects of any MCDA problem require decision-makers' (DMs) or experts' judgements for appraising feasible alternatives based on multiple, conflicting and incompatible criteria [18]. Numerous spatial decisions often involve more than one DM as opposed to a single DM in a group decision-making (GDM) process. This is undertaken to enhance the quality of the decision-making endeavor as well as to minimize possible conflicts by building a higher degree of consensus. Elements of geographic decision alternatives involve the course of action to be taken and the location which can either be defined implicitly or explicitly, depending on the selected GIS data models [19,20]. Site and facility selection, location-allocation and land-use suitability problems are representative of explicitly spatial alternatives, such as in [21].

Processes for addressing spatial multi-criteria problems are premised on three fundamental concepts which form the foundation of GIS-MCDA approaches. These spatial decision support procedures include standardization, the weighting of criteria and decision rules. Standardization or value scaling procedures convert raw data of the criteria under evaluation to units that can be compared. Criteria can be assigned values that indicate their level of importance relative to the other criteria under review and subsequently used by the relevant MCDA method in the evaluation of the decision alternatives [22]. The methods for criterion weight assessment can be categorized into global and local techniques. Local weighting methods account for the spatial heterogeneity of DM preferences, whereas global methods assume that the DMs' preferences are spatially homogeneous and therefore a single weight is allocated to each criterion. Global weighting methods consist of rating, ranking, pairwise comparisons (e.g., AHP) and Entropy techniques [18]. The criterion weighting process involving rating, ranking and pairwise comparison [20] methods is done subjectively, relying on the experts' judgements. The Entropy-based technique, on the other hand, assigns weights objectively by mathematical determination of initial criterion value information [8] and therefore does not necessitate DMs to specify their preferences in relation to the evaluation criteria [18].

Within this context, Entropy-based GIS-MCDA methods have been suggested to consider objective weighting approaches. These procedures evaluate criteria weights by use of mathematical models without the involvement of DM preferences which would bring subjectivity in the judgement information, affecting the final decision outcome [23]. Very few Entropy-based criteria weighting methods have been utilized for GIS-MCDA applications [18]. Zheng et al. [24] and Li et al. [25] proposed use of this criteria weighting method as GIS-based weighted linear combination (WLC) and TOPSIS modules, respectively. Further, it has been suggested that GIS-MCDA methods should incorporate both subjective and objective criterion weighting techniques [26].

In the present study, a GIS-MCDA hybrid approach utilizing the AHP, combined with Entropy technique has been recommended for assessing ideal locations of urban emergency facilities in Istanbul. GIS is proposed to be used as a spatial decision support tool for analysis and visualization of outputs in the form of raster suitability maps, therefore enhancing the quality of the planning decision. GIS analytical approaches have been utilized in many natural disaster and emergency-related research areas. A study by Lin et al. [27] explored the use of a data mining technology applying an integrative self-organizing data (ISODATA) analysis and maximum likelihood (ISO-Maximum) clustering algorithm in a GIS environment to assess flash flood risk in Guangdong Province in China. The clustering algorithm was used to efficiently obtain flood risk classification results where deficiency of data exists leading to the production of the risk clustering map and final flash flood hazard, vulnerability and risk maps. García-Ayllón, Tomás and Ródenas [28] used geostatistical analysis tools in a post-earthquake evaluation of seismic damage indicators for Lorca city in Spain. Bivariate GIS assessment was utilized to show a spatial statistical correlation of the distribution of the earthquake variables using geo-process and geostatistical tools in ESRI ArcGIS software. The geostatistical functions of Global Moran's I, Anselin Local Moran's I and Getis-Ord Gi were used to analyze the degree of spatial autocorrelation, the cluster and outliers and the segmentation of cold and hot spots, respectively. An optimized hot spot analysis (OHSA) using the Getis-Ord Gi statistic in GIS interface was implemented by Lu et al. [29] for analyzing incremental spatial autocorrelation in landslide surface detection and risk studies across the Volterra area of Italy. Maqsoom et al. [30] applied the DRASTIC index function of the ArcGIS platform for modelling the groundwater susceptibility risk and vulnerability to contamination in Gilgit Baltistan City, Pakistan. In their study, a map removal sensitivity analysis using the raster math tool in GIS was also performed to analyze the model sensitivity.

In the literature, to the best of the authors' knowledge, there has been no study conducted within the fields of the emergency and fire facility planning that utilized the proposed model, worldwide. This, therefore, offers a unique research opportunity to be explored. In recent years, several studies related to the use of AHP and GIS for urban fire station facility selection have been reviewed [21,31–40]. Many influencing factors can be considered for the location of new urban emergency facilities. For instance, Wang [35] proposed the use of combined GIS, AHP and fuzzy evaluation methods for optimizing the locations of new fire stations in China by considering four selection factors such as social services, transit time, environmental geography and cost of fire station construction, as well as operation. Chaudhary et al. [32] assessed the population density, distance from roads, distance from rivers and land cover which included built-up areas to be ideal criteria for fire station suitability zone mapping using AHP and GIS in Kathmandu Metropolitan City in Nepal. Dong et al. [37] attributed the complex layout of urban geography and increasing urban developments that included factories and warehouses as the main source of fire risks in Linyi city in China. The constraints of emergency facility planning layout incorporated drive time and road traffic conditions, the shortest path to the major fire risk and demand points, fire risk emergency rescue considering a response time of five minutes, and capital costs. Population density and socio-economic criteria that included proximity from multi-story residential areas, health centers, commercial and shopping malls and public parks were considered by Wahab and Khayyatet [34] in their suitability analysis study, integrating AHP and GIS approaches to select optimum sites for new fire departments in Erbil City, Iraq. Other researchers such as Lai et al. [33] selected the population density, road distance to the nearest fire station and building loss criteria for layout planning of fire stations using GIS and AHP in Beijing, China. Habibi, Lotfi and Koohsari [38] considered the population density, accessibility, distance to high fire risk areas and plot sizes criteria for selection of fire stations utilizing the AHP, GIS and index overlay (IO) model in Tehran, Iran. Tali et al. [39] proposed a location-allocation model for locating fire stations in the urban area of Mysore, India. They used the existing road network, location of existing fire stations, land use/land cover map for identifying available sites and fire incident data as the most essential criteria in the model analysis. The service area and location analysis were performed using the network analysis function in the ArcGIS software.

In a recent study by Uddin and Warnitchai [40] applied to Dhaka in Bangladesh, the main criteria of elements at risk, fire hazard, spatial and geological settings were evaluated for optimizing the location of new urban fire station facilities. These included assessed sub-criteria such as the density of population, residential and commercial buildings, critical facilities, fire hazard from an earthquake, the average distance from critical facilities, connectivity and accessibility via major roads, soil amplification factor and liquefaction susceptibility for earthquake vulnerability analysis. From the studies reviewed, the common factors considered to be essential for selecting ideal sites for fire stations in urban regions were identified and incorporated in our research. These included population density (HPD), proximity to arterial and main roads (PMR), distance to existing fire stations (DEF) and density of hazardous material facilities (DHM). Determination of ideal criteria is based on suitability to the prevailing local conditions of the study region, expert knowledge and availability of data. Accordingly, our proposed research procedure adopted additional selection factors such as the density of wooden buildings (WBD) and, since Istanbul lies in a seismically active and fault zone, the distance to areas prone to earthquake risk (DER) criterion was also taken into account as similarly considered in the research by Uddin and Warnitchai [40]. The criteria identified and adopted for use in our study encompassed social/demographic, built environment, risk/safety aspects as well as the influence of spatial variability. Therefore, our proposed criteria incorporated in this research were comprehensive and critical for evaluating the best decision outcome. Further, the incorporation of the Entropy-based weighting method eliminates possible uncertainty of the expert judgements in the subjectively evaluated criteria weighting process of the AHP. This arises from several circumstances that include imprecise information, lack of expert knowledge and experience and the limited capacity of the DM for accurately allocating precise weights to the criteria, also attributed to the intangible nature of the criteria [41,42].

The proposed hybrid AHP-Entropy model, using a combinative weighting approach, considers both subjective and objective weighted procedures and is adopted to yield more accurate criteria weight results as recommended by some researchers [43–46]. Furthermore, this study enhances the AHP-Entropy model by use of sensitivity analysis (SA) which examines the dependency of model output on changes of input criteria weights within a spatial domain. A generic SA approach, utilizing the one-at-a-time (OAT) procedure is applied by changing one factor at a time while keeping others fixed, to observe criteria weight sensitivity which can subsequently be visualized relative to the model problem. The SA helps minimize uncertainty in the multi-criteria decision approach and tests the robustness of the proposed hybrid MCDA model, ensuring its stability for validation. The involvement of nineteen DMs, including both academic professionals and fire brigade practitioners, enhanced the decision-making process, ensuring more comprehensive and reliable model results.

The rest of the research paper is structured as follows. Section 2 describes the study area, data collection and research methodologies utilized, such as AHP, Entropy, integrated AHP-Entropy and GIS analyses that include model validation using spatial sensitivity analysis (SA). The study results are presented in Section 3, which illustrates the outputs of the GIS modelling procedures in the form of raster criteria map layers, final urban fire facility suitability raster map and simulations of SA outputs. The discussion and conclusions of the key research results drawn from this study are given in Sections 4 and 5, respectively.

2. Materials and Methods

2.1. Study Area

The case study region of Istanbul province has the largest population in Turkey of about 15,519,267 as of 2019 [2], and is the country's economic, cultural and historic center. Its landmass straddles Europe and Asia between the Sea of Marmara and the Black Sea, separated by the Bosphorus strait. Istanbul province spans an estimated area of 5, 343.22 km^2 and lies approximately between the latitudes 40°44′42′′ N to 41°35′59′′ N and longitudes 27°58′04′′ E to 29°54′58′′ E (Figure 1).

Istanbul is comprised of 39 districts, of which 25 districts are situated on the European side, representing a population of 10,067,617 and 14 are on the Asian side, having a third of the total population with 5,451,650 people. A detailed map of the metropolitan area showing the population density relative to the districts of Istanbul and the spatial distribution of the existing emergency service stations is shown in Figure 2. As can be observed, a larger concentration of the existing emergency facilities is situated in the most densely populated regions correlating to higher population density values. These areas have a high hazard zone rating with a large potential for fire risk as a result of urban developments and expansion, socio-economic and industrial and trading activities, tourist centers, clustered urban housing and multi-story residential areas, etc. The increasing demand for fire protection services takes into account the potential impact on communities, such as damage to property and infrastructure, loss of lives, revenue and livelihoods.

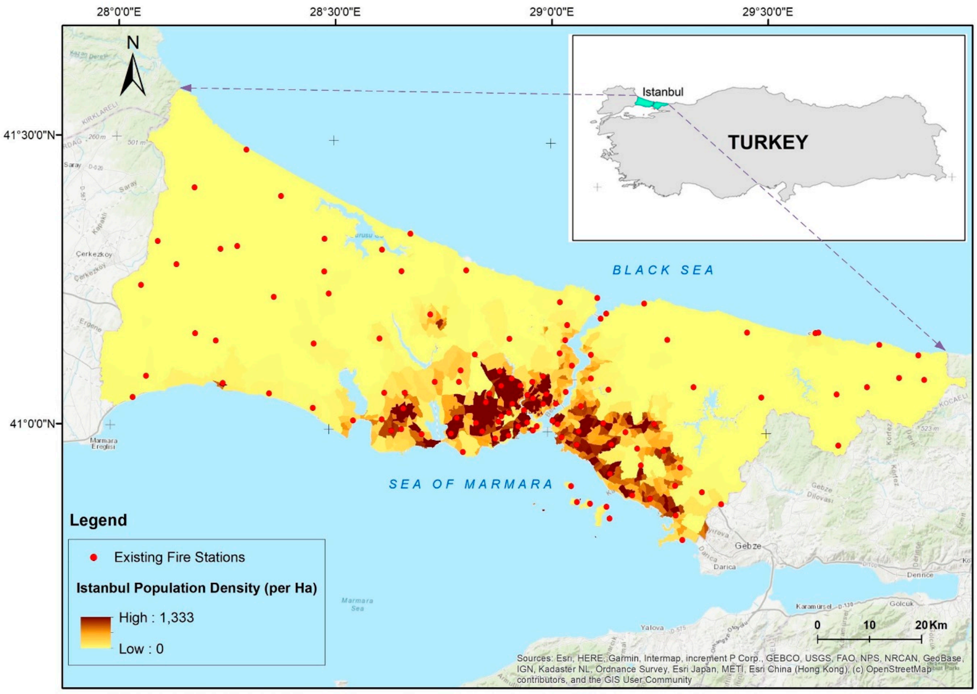


Figure 1. Istanbul province showing the existing fire stations and population density.

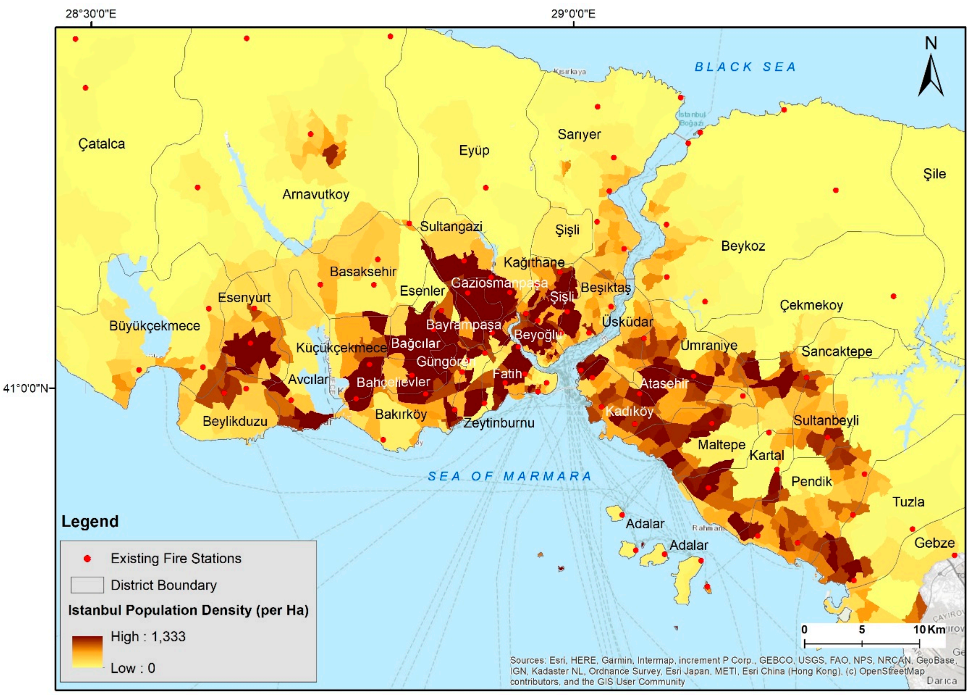


Figure 2. Detailed map showing the districts of the metropolitan area of Istanbul.

In recent years, the prevalence of urban fires and potential fire risk in Istanbul [3] has been exacerbated by rising urban populations and migration [1]; this has been a source of growing public safety concerns, having profound negative impacts on the social and economic circumstances of the inhabitants.

2.2. Data and Screening of Criteria

Spatial planning of the distribution of urban emergency service systems that include fire, medical, police and ambulance services requires careful design and layout considerations. Fire stations also function as emergency medical communication and district/regional control centers in cases of major scale disaster and emergencies such as earthquakes, floods, landslides, etc. Therefore, planning locations of these facilities involves the combined effort of experts and decision-makers, administration, emergency response personnel in consultation with other stakeholders such as local communities impacted by the decision outcome. The most influencing criteria for comprehensively planning new urban emergency facilities were selected in a thorough screening process based on recommendations from the literature and expert input [21,38,47,48]. Population density is one of the main factors to be considered and represents a high potential for fire risk, especially in areas with a very large concentration of people. These high population density (HPD) zones include commercial, trading, social facilities and clustered urban settlements and therefore increase the demand for fire protection services with a greater potential for loss resulting from the impacts on communities. Emergency services should be located near or within these areas to provide adequate fire protection. The proximity to main roads (PMR) criterion was considered to facilitate easy access to the fire stations Narrow roads such as streets are not easily accessible by fire engines and responding apparatus. Fire stations should, therefore, be located close to the main arterials and road networks but outside traffic-congested areas to achieve a better response time to emergency incidences [48]. Planning and construction of new emergency facilities in areas already serviced by the existing facilities must be avoided. In this regard, the distance from existing fire stations (DEF) criterion is taken into account to ensure optimal service coverage without any overlaps. Drive time, topology and road traffic conditions defined by speed limits on the main transportation route network are considered for analysis of the emergency service coverage within a response time of 5 min. The density of hazardous materials (DHM) criterion was incorporated in the study in recognition of the demand for emergency services in or near land use areas which have gas and oil stations, industrial and warehouse facilities containing hazardous materials such as compressed and liquid petroleum gases (LPG) [38]. These hazard-prone areas are often the sources of fires and explosions and therefore should take priority in planning new emergency facilities. Istanbul, being a historical, cultural and tourist center, still preserves the old building and housing architecture made of wood that easily catches fire and increases the spread of fire and related incidences. The wooden building density (WBD) criterion is determined as vital in planning new emergency facilities within these areas with a prevalence of high density of wooden buildings. Environmentally critical areas susceptible to seismic risk are not preferred for siting new fire stations, which consequently should be located as far away from these areas as possible [48]. For this reason, the distance to earthquake risk (DER) criterion is considered in our research because Istanbul is vulnerable to occurrences of earthquakes which cause massive infrastructural damage. Post-earthquake hazards, which induce post-ignition fires, often result in more extensive damage than the initial earthquake. On account of that, it is recommended that new emergency facilities should be built away from these liquefaction zones of high seismic risk as, for example, in an earthquake event, damage to street and motorways would inhibit emergency vehicles and fire engines from reaching the emergency sites.

A summary description of the criteria and their influence on new urban fire station siting is given in Table 1.

Table 1. Criteria selection for new urban fire facilities.

Determined Criteria	Description	Locational Influence on Planning New Fire Stations
high population density (HPD)	areas with high population are at high fire risk and therefore prioritized for planning new fire stations	+
proximity to main roads (PMR)	fire stations must be situated in areas with easy access to main transport routes to be able to reach fire incident areas faster	+
distance from existing fire stations (DEF)	new fire stations must be built away from service areas covered by already existing fire stations	-
density of hazardous materials (DHM)	areas with oil stations, facilities housing hazardous materials such as liquid petroleum gas (LPG) and compressed gases, etc., increase the spread and risk of fires, explosions; therefore, they should be prioritized for planning new fire stations	+
wooden building density (WBD)	areas with wooden buildings increase the risk of fire spread and impact, hence are candidate locations for new fire stations	+
distance to earthquake risk (DER)	new fire station facilities should be built away from high earthquake risk areas (as Istanbul is prone to earthquake occurrences) to reduce the risk of infrastructural damage as a result of earthquakes	-

The collection and preparation of data were very vital components as the successful implementation of this research hinged on the reliability and accuracy of these procedures. Most of the data were collected from the Istanbul Metropolitan Municipality (IMM) and represent the most up-to-date records of main road network layers, existing fire station locations, locations of facilities that have hazardous materials that included oil stations, natural and processed gases/oils, compressed gases, liquid petroleum gas (LPG) and other chemical substances. The population density was obtained from the Turkish Statistical Institute (TUIK) [2] and the earthquake hazard map for evaluating distances to areas of earthquake risk was acquired from the HAZTURK Project [49]. It is recommended that within concentrated urban environments, the minimum plot area for constructing fire and emergency medical service facilities should range approximately from between 1,000 and 1,500 m^2 up to 3,000 m^2 for small and medium-sized stations to accommodate the full fire and emergency service programs [38,48]. In this research, we suggested processing and analyzing the data in the form of criteria map layers to a sub-district level using ESRI ArcGIS 10.3 software at a spatial cell size resolution of 50 × 50 m^2, accounting for a plot area within the stated site requirement guidelines.

2.3. Research Methodology

The GIS-based AHP-Entropy methodology was initiated by defining the decision goal of assessing the suitability of locating new urban fire facilities in Istanbul. Within the context of this study, the research methodology was outlined as shown in Figure 3.

In this regard, screening of the influencing factors was done based on a review of literature, expert knowledge and experience. Within a group decision–making (GDM) approach, a panel of decision-makers (DMs) were selected that had the requisite knowledge and experience in disaster and emergency planning and related works, consisting of academic professionals, planners and fire brigade personnel. Using the Delphi technique, the DMs were interviewed, from which their criteria preferences were acquired by the pairwise comparison method of the AHP to derive the subjective criteria weights. After checking for consistency in the DM judgements, the Entropy method was used to compute the objective criteria weights. The results from both the AHP and Entropy methods were integrated to calculate the final criteria weights which were subsequently used as input in GIS via a weighted linear combination (WLC) method of the weighted sum analysis function and reclassified for final production of the raster suitability map of new urban fire facility sites. A spatial sensitivity analysis (SA) procedure was then performed for model validation.

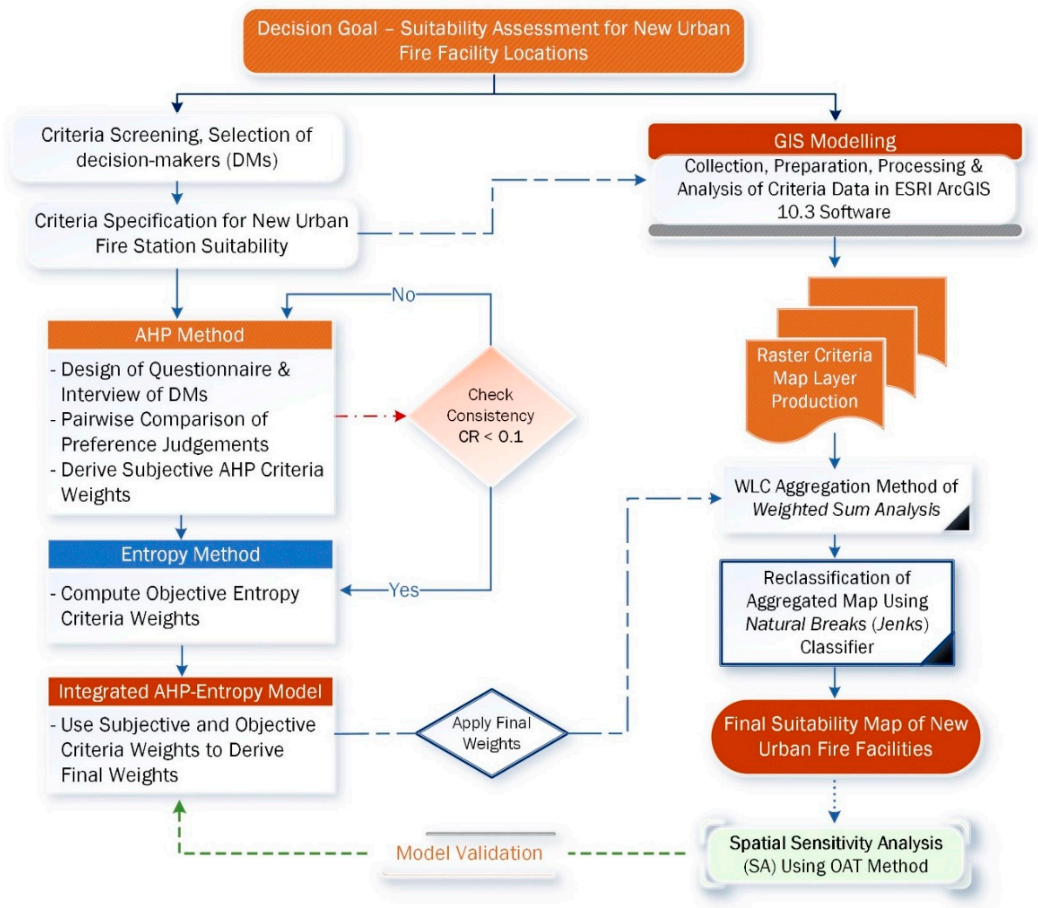


Figure 3. GIS-based AHP-Entropy model flow chart for new urban fire station suitability.

2.3.1. AHP

The analytical hierarchy process (AHP) [9] is a comprehensive multi-criteria decision analysis (MCDA) method that utilizes hierarchical structures to evaluate complex decision problems through a series of pairwise comparisons for weighting criteria. These pairwise comparisons are based on expert or decision-maker (DM) judgements that are used to synthesize priorities among criteria and alternatives to be evaluated. The decision-making process can be characterized in the main principles that include problem structuring, evaluation, computational analyses and synthesis of the priority model.

The approach for integrating GIS and AHP for the emergency facility decision problem in the present study follows the estimation of weights associated with criterion/attribute map layers which are subsequently combined with attribute map layers using a weighted linear combination (WLC) rule [50]. The key implementational steps are outlined as follows:

Step 1: Decomposing a complex unstructured problem into decision goals, criteria and alternatives.

Step 2: Developing the AHP hierarchy model to be used in the urban emergency facility selection suitability map.

Step 3: Design and construction of a judgement matrix using the pairwise comparison method representing experts' subjective preferences of criteria and alternatives. The outcome of the comparisons will be in the form of a positive pairwise comparison matrix $A = a_{ij}$, and reciprocal elements for all $a_{ji} = 1/a_{ij}$ as shown in Equation (1):

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

$$(i,\ j = 1,\ 2,\ \ldots,\ n)$$

Step 4: Assigning ranking values of relative importance to the subjective judgements based on a 9-point ratio scale proposed by Saaty [9] and calculation of the respective weights of each criterion.

Step 5: Checking the consistency of the pairwise comparison assessments using a consistency ratio (CR). Consistency ensures coherence in the DMs' judgements in specifying their respective criteria preferences. If the CR < 0.1, the level of consistency is acceptable and comparison judgements are reliable.

Step 6: Synthesis of ratings (criteria) and alternatives to compute the overall priority variables for each decision alternative using a weighted sum of criteria weights.

2.3.2. Shannon Entropy Weight Method (EWM)

Entropy is a concept based on information theory first introduced by Shannon [51] and it is widely used across engineering, economics, physics, finance, spectral analysis, information and physical sciences, language modelling and social disciplines. It is a measure of the uncertainty or degree of disorder in a system or information contained in the original data (attribute values of alternatives) formulated using probability theory. In solving most MCDA problems, determination of criteria weights is essential to indicate the level of importance of each criterion relative to other criteria affecting decision alternatives and outcomes. Entropy weights can determine the amount of useful information provided by the index, based on differences between the attribute values without relying on subjective information from experts or DMs. Compared with subjective-based weighting methods, the key advantage of the Entropy method is that it eliminates human interference in the weighting process, thereby objectively determining the criteria weights [52,53]. These weights evaluated by the Entropy method are called objective weights which implies that the higher the entropy, the smaller the value difference among evaluated objects, resulting in a smaller relative weight, and vice versa. This indicates a lower information content as some information may be lost or unreadable [54,55].

In recent years, some examples of the entropy weight method (EWM) applied in GIS-based MCDA include waste landfill site selection [45], landslide susceptibility mapping [56–58], flood risk assessments [27,59] and migration modelling [60].

The objective weights can be calculated using the Shannon entropy method by the following procedures [8,18,61]:

Step 1: Formation of a decision matrix **R** which shows the performance of m feasible alternatives with respect to n evaluation attributes (criteria).

$$R = X = (X_{ij})_{mn} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{2}$$

$$(i = 1,\ 2,\ \ldots,\ m;\ j = 1,\ 2,\ \ldots,\ n)$$

Step 2: Normalization of each criterion of the decision matrix to have comparable and dimensionless performance measures (indices). Denoting p_{ij} as the standardized value of the non-negative index, X_{ij}, which is the performance measure of the jth attribute in the ith alternative, calculated by:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \tag{3}$$

$$(i = 1,\ 2,\ \ldots,\ m;\ j = 1,\ 2,\ \ldots,\ n)$$

Step 3: Computation of the entropy value (E_j) for each criterion by the equation:

$$E_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}, \tag{4}$$

$$(i = 1,\ 2,\ \ldots,\ m;\ j = 1, 2,\ \ldots,\ n)$$

where $k = 1/\ln(m)$ is a constant that ensures $0 \leq E_j \leq 1$. The larger the value of E_j, the greater the degree of differentiation of index i is, and the more information that can be derived. Therefore, a higher weight should be assigned to the index.

Step 4: After normalizing $\left(1 - E_j\right)$, determination of the entropy weights w_j of the jth attribute (each criterion), is given by:

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{n}\left(1 - E_j\right)}, \tag{5}$$

$$j = 1,\ 2,\ \ldots,\ n$$

where $0 \leq w_j \leq 1$ and $\sum_{j=1}^{n} w_j = 1$, following the entropy properties.

The value of $\left(1 - E_j\right)$ is known as the degree of diversification D_j of the jth index. It describes the divergence degree of the inherent information of each criterion. The larger the value of D_j, the larger the variation in the jth index.

The entropy weight specifies the importance of the criterion in the decision-making process where a smaller entropy value indicates a larger entropy-based weight having more information that can be derived from the particular criterion [62].

2.3.3. Integrated AHP-Entropy

Although derived entropy weights are effective and depict useful information, they rely heavily on the objective data that ignore the wealth of the knowledge and experience of the experts in decision-making which may not be in tandem with the reality and comprehensibility of the problem situation. Considering the entropy weights only, irrespective of the expert's opinion would be insufficient and may not always accurately reflect the importance of the index in practice, resulting in biased decision-making [22,63–65]. It is, therefore, necessary to combine the subjectivity of the AHP and the objectivity of the entropy weight method (EWM) to ensure that weights are comprehensively determined for increased reliability and effectiveness. Integrating the two approaches aims to build on the knowledge and experience of expert judgements and objective variability of the evaluation data.

An overall combined weight value is calculated from the AHP and Entropy weighting procedure using the general form of the Shannon entropy weight w_j^* given by the following equation:

$$w_j^* = \frac{S_j\, w_j}{\sum_{j=1}^{n} S_j\, w_j}, \tag{6}$$

$$j = 1,\ 2,\ \ldots,\ n$$

where S_j is the subjective weight calculated from the AHP, and w_j is the objective weight derived from the Entropy method.

2.3.4. GIS Analyses

The geographic information system (GIS) is a computer system designed with an array of tools and the functionality to capture, store, manipulate, manage, analyze and visualize spatial data. Additionally, when combined with MCDA analytical methods, GIS provides powerful capabilities to handle the limitations of GIS when dealing with multiple complex criteria and objectives, essentially evolving into a decision support system (DSS) [20,66–69]. The integration of GIS and MCDA, hence known as GIS-MCDA, and its applications have been a subject of growing research interest [60,70–73].

In our study, the objective is to suggest areas suitable for locating urban emergency facilities within Istanbul and this goal is operationalized by selecting six influencing criteria/attributes. These criteria are identified as factors which increase or decrease the suitability of discrete alternatives or as constraints to limit alternatives [66,74]. Representation of the feasible alternatives is in the form of a raster suitability map, consisting of a large number of raster cells in our selected study region.

After the criteria are selected and derived, the following main processes and analyses are implemented in a GIS, using ESRI ArcGIS 10.3 software:

- Standardization and extraction of data: Most of the input data representing each criterion map layer were initially in vector format. After a series of processing and data management operations that included spatial join, field calculator, a process of rasterization was performed to convert the polygon-based data to raster data. The criteria map layers were processed and resampled to a selected cell resolution of 50 × 50 m^2 based on plot area recommendations stated in Section 2.2 and other procedures as a prerequisite for further GIS modelling and analyses.
- Buffer analysis: A multiple-ring buffer analysis was performed on the main road map layer to generate incremental buffer distance maps with a value range from 0 to 300 m, at 60 m intervals. The buffer distance classifications used for the road network was as adopted by Erden and Coskun [21] and from similar work by Chaudhary et al. [32]. This analysis determined the suitability index for locating new emergency facilities which should be positioned close to the main road network for easy access of the fire brigades.
- Network analysis: The network analysis tool was used to find the service areas of the existing fire station facilities accessible on the main road network. This analysis showed the efficiencies and gaps of the current fire station coverage for defined travel time (emergency response time of 5 min) using the main roads at impedance values ranging from 1 to 5 min. The service areas were evaluated using the attribute information at intersections of each road line segment layer that included the three road type classifications (local, main and highways), respective speed limits (in km/hr) and road segment lengths (in km). The travel time for each road segment was then evaluated in the attribute table of the main road layer data using the attribute information of the three road types and their corresponding speed limits—local (30 km/hr), main (60 km/hr) and highways (90 km/hr). A topology of the road layer was created using a new network dataset generated from the road layer. This network dataset simulated the real road network of Istanbul.

The criteria were analyzed by using actual travel distances, vehicle speeds, time delays caused by roadway conditions such as congestion, connectivity of road network, and taking one-way or unusable roadways into account. The network dataset was subsequently used as input for the new service area analysis in the Network Analyst function. Service area polygons using the ring overlap type were generated using the current 121 fire station facilities at travel time impedance value settings (away from the facility locations) ranging from 1 to 5 min. These service areas modelled the fire station coverage scenario at an emergency response travel time of 5 min.

- Overlay analysis: Using a compensatory decision rule method of weighted linear combination (WLC) [75,76], all criteria map layers are aggregated into a single raster suitability map of urban fire station locations. Utilizing the weighted sum overlay tool, the final suitability map, S is generated by multiplying each criterion by its respective AHP-Entropy weight assignment followed by the summation of the results:

$$S = \sum w_i x_i \tag{7}$$

given w_i as the weight of criterion i where $w_i \in [0, 1]$ and x_i is the standardized score of criterion i, $x_i \in [0, 1, 2, 3, 4, 5, 6]$.

- Sensitivity Analysis

In any decision-making process, and particularly for the multi-criteria decision-making (MCDM) methodology, it is necessary to undertake a sensitivity analysis (SA) due to uncertainties in the input data, processing, selection of criteria and respective thresholds as well as influencing exogenous factors which the decision-maker (DM) cannot control, e.g., government policy, weather [55,77]. Therefore, SA is performed after problem-solving, to ascertain if a solution is retained when there are variations in this uncertain data, hence significantly contributing to accurate decision-making [55,78].

SA examines the correlation between the inputs and outputs of a modelling application [77]. As defined by Saltelli et al. [79], it is "the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and how the model depends upon the information fed into it". SA is paramount in validating and calibrating numerical models and checking the robustness of the final decision solution against known, decremental or incremental input parameter changes in values [55,77,80,81]. In this respect, SA is mostly used to determine how variations in criteria weight alter the ranking because criteria weights frequently contribute to uncertainty and contention [55,77]. This is likely because the scale and nature of the criteria are unknown or because the DMs have no understanding of their criteria preferences, or because, notably, in group decision-making (GDM) there is often a possibility of acquiring more than one set of results because the series of weights are derived as opposed to only a set of weights [77]. A solution is therefore considered stable when the ranking is retained for different alterations in the criteria weights [55].

Spatial SA approaches have been utilized in several GIS-based MCDA studies to enable geographic visualization and analysis of weight sensitivity as recommended by several researchers [77,82–89]. In this paper, the SA method of one-at-a-time (OAT) [90,91] is used to estimate criteria weight sensitivity by changing one input factor at a time whilst keeping all other factors fixed to analyze the resultant effects on model outputs, visually in a GIS.

If the weight of the *i*th attribute (criterion) is changed from ${w_i}^\circ$ to w_i, then the weight of the other criteria, w_j, would change as given by [92]:

$$w_j = \left(\frac{1 - w_i}{1 - {w_i}^\circ} \right) * {w_j}^\circ \tag{8}$$

where w_j is the new weight value of the other attribute (criterion) to be changed; ${w_i}^\circ$ and ${w_j}^\circ$ are the initial weight values of the criteria before being subjected to SA.

The different stages involved in the research methodology were briefly described. After defining the decision goal of assessing the suitability for planning new emergency facility locations in Istanbul, the data and criteria screening, decision-maker (DM) formulation and interview procedures were initiated as elaborated in Sections 2.2 and 2.3. The DMs' preferences of the six selected criteria were used to evaluate the subjective weights via the pairwise comparison approach in the AHP method (Section 2.3.1). Using the Entropy method described in Section 2.3.2, the objective weights were subsequently derived. To ensure that the weights of the criteria were comprehensively determined, the AHP and Entropy methods were integrated to compute an overall combined weight value in a process given in Section 2.3.3. The overall weight value was then implemented in GIS for modelling and analysis under Section 2.3.4 after the preparation, pre-processing and analysis of criteria data in the form of raster criteria map layers. The main procedures in the GIS analyses included standardization and data extraction, buffer, network and overlay analysis. By a weighted linear combination (WLC) method, the weights from the combined AHP-Entropy process were applied onto the six aggregated criteria map layers using the weighted sum overlay analysis to generate the final suitability map for planning new urban emergency facilities. In the spatial sensitivity analysis (SA) process outlined at the end of Section 2.3.4, the final decision solution and AHP-Entropy model were validated and checked for robustness.

The next section presents the research results of the implementation of the research methodology from the DM evaluation of criteria weights using AHP, Entropy and integrated AHP-Entropy techniques. The GIS modelling, after processing, analysis and reclassification of each of the six aggregated raster criteria map layers, resulted in the production of a final urban fire facility suitability map. Map simulations of the spatial sensitivity analysis (SA) are presented for the criteria with the strongest influence to test the model validity and range of sensitivity by using the one-at-a-time (OAT) method.

3. Results

3.1. Evaluation of Criteria Weights

Nineteen decision-makers (DMs), including academic professionals and experts and fire brigade practitioners with over 10 years' experience in emergency planning, were invited to fill in a questionnaire using the Delphi technique, designed to capture their criteria preferences and judgements. The DMs' preference judgements reflected which criteria they perceived to be the most important in selecting suitable locations for urban fire station facilities. The results of the level of importance among the six criteria were analyzed and evaluated as weight coefficients using the AHP, Entropy and combined AHP-Entropy methods.

3.1.1. Subjective Weights from the AHP

Using the AHP method, the pairwise comparison matrix for all the nineteen DMs was aggregated by geometric mean to provide the group judgements as shown in Table 2.

Table 2. Preference matrix for DM's group judgements.

Criteria	HPD	PMR	DEF	DHM	WBD	DER
HPD	1	1.98	3.15	0.64	2.15	3.27
PMR	0.5	1	1.86	0.34	1.55	2.09
DEF	0.32	0.54	1	0.30	0.68	1.23
DHM	1.56	2.91	3.28	1	2.99	3.86
WBD	0.47	0.65	1.47	0.33	1	1.49
DER	0.31	0.48	0.81	0.26	0.67	1

The values of the E_{max} (6.037), CI (0.00739) and CR (0.00596) from the group judgment computations were used to evaluate the final AHP weights (W) and corresponding rankings of the six criteria as given in Table 3.

Table 3. AHP weights and rankings.

Criteria	W (%)	Rank
HPD	*24.8*	*2*
PMR	*14.4*	*3*
DEF	*8.5*	*5*
DHM	*33.7*	*1*
WBD	*11.1*	*4*
DER	*7.5*	*6*

To check the reliability of the evaluations, the consistency ratio (CR) was calculated to be 0.00596 which was less than 0.1 (indicating reliable and consistent judgements).

3.1.2. Objective Weights from Entropy

The collected responses from the DMs were also analyzed to compute the objective weights using the Shannon Entropy weight method (EWM) following the steps outlined in Section 2.3.2. The entropy (E_j), degree of diversification $\left(D_j\right)$ and objective criteria weights $\left(W_j\right)$ for the assessment of suitable locations for urban fire station facilities are presented in Table 4.

Table 4. Entropy, degree of diversification, entropy weights and rankings.

Criteria	E_j	D_j	W_j (%)	Rank
HPD	*0.8933*	*0.1067*	*20.1*	*2*
PMR	*0.8702*	*0.1298*	*24.4*	*1*
DEF	*0.9294*	*0.0706*	*13.3*	*5*
DHM	*0.9259*	*0.0741*	*13.9*	*4*
WBD	*0.9159*	*0.0841*	*15.8*	*3*
DER	*0.9340*	*0.0660*	*12.4*	*6*

3.1.3. Subjective-Objective Weights from the AHP-Entropy model

In this study, both advantages of the AHP and Entropy methods were considered, and it was therefore proposed to integrate the AHP and Entropy methods for weighting the criteria for the decision problem [93]. The combined AHP-Entropy weight (W_j^*) was calculated using Equation (6) from Section 2.3.3 and the results are as shown in Table 5.

Table 5. AHP, Entropy and integrated AHP-Entropy weights of criteria and the final ranking.

Criteria	*AHP (%)*	*Entropy (%)*	W_j^* (%)	Final Rank
HPD	*24.8*	*20.1*	*29.3*	*1*
PMR	*14.4*	*24.4*	*20.7*	*3*
DEF	*8.5*	*13.3*	*6.6*	*5*
DHM	*33.7*	*13.9*	*27.6*	*2*
WBD	*11.1*	*15.8*	*10.3*	*4*
DER	*7.5*	*12.4*	*5.5*	*6*

More realistic weights were computed using this approach and were used for subsequent GIS modelling and analysis to generate a final suitability map for the assessment of suitable locations for urban fire station facilities.

3.2. GIS Modelling

3.2.1. Processing, Analysis and Criteria Map Layer Production

Based on the six determinant factors identified for suitably locating urban fire station facilities in Istanbul, these were used as input in a GIS for processing and analysis to produce raster criteria map layers. All the six criteria in the form of criteria map layers were processed and analysed to raster map resolution of cell size, 50×50 m^2. The raster cell value range for each criterion map, ranging from the lowest to the highest suitability, were as shown in Table 6.

Table 6. Suitability class value ranges for each criterion from the lowest to the highest.

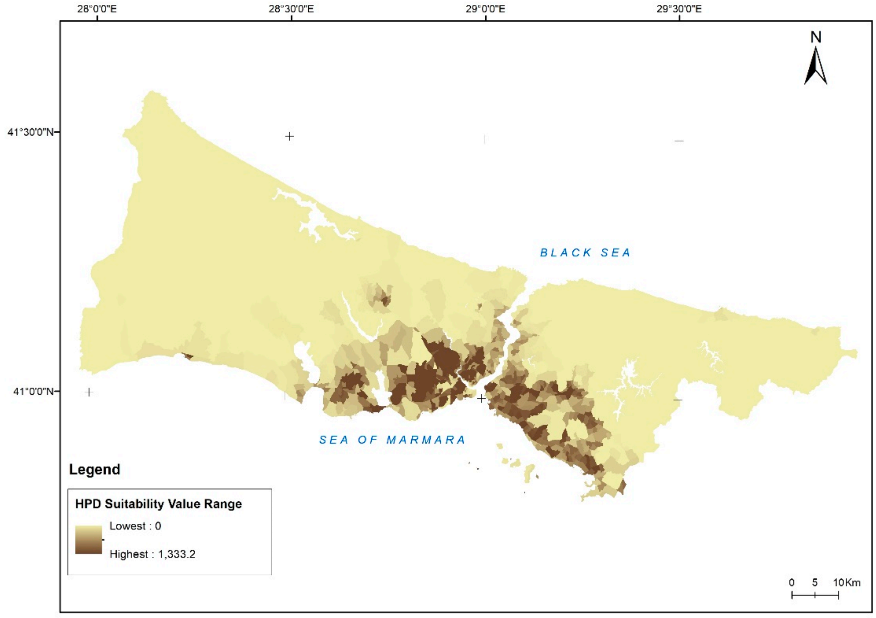
Criteria	Suitability Class Value Ranges	
	Lowest Suitability	Highest Suitability
HPD (no. of people per hectare)	0	1333.2
PMR (meters)	300	0
DEF (service areas in minutes)	1	5
DHM (number of, per sub-district)	0	153
WBD (ratio in, total no. of buildings)	0	1781.8
DER (PGA [1] values in g)	2.39	0.26

[1] PGA = peak ground acceleration value of the Istanbul earthquake hazard map, in units of acceleration due to gravity (g).

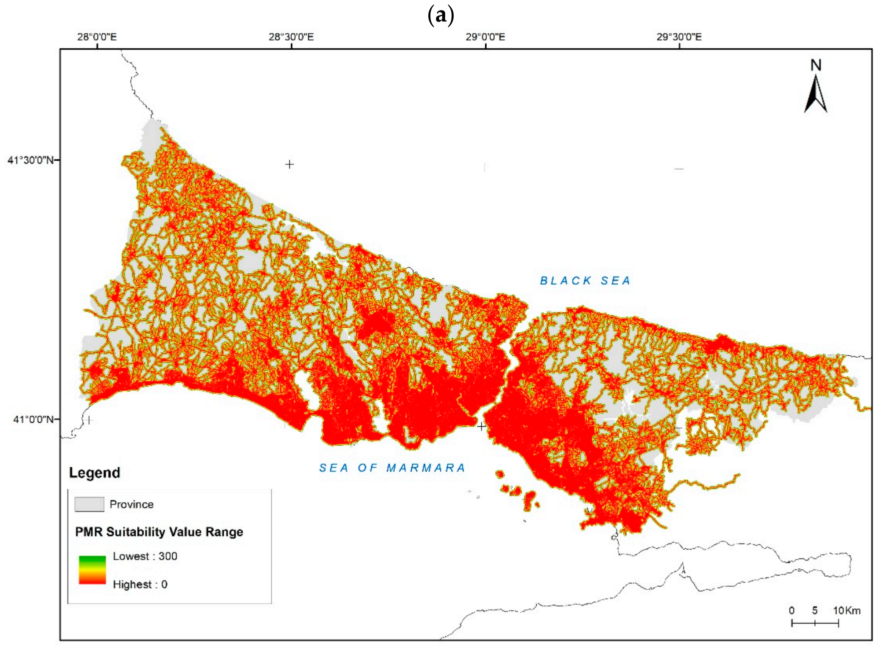
Each of the criterion map layers depicted by the suitability class value ranges shown in Table 6, and whose processing procedures are briefly described, were as illustrated in Figure 4. The determination of which areas were suitable was dependent on the desired reclassification scheme (the natural breaks classifier) result of the range of data values for the final suitability raster map to be generated in Section 3.2.1.

1. High population density (HPD): The HPD criterion map layer was initially processed from population data per sub-district area of Istanbul and calculated in hectares (ha) (Figure 4a). Generally, our definition of a high density of population is determined by the data value ranges of our specified reclassification.
2. Proximity to the main road (PMR): The PMR criterion map layer was processed from a multiple ring buffer analysis which was defined from the main roads of Istanbul over a value range of up to 300m in incremental distances of 60 m (Figure 4b). The main road data were specified by attribute information for the three road segment types, namely local, main and highways, with the corresponding average speed limits (based on traffic flow and road width data) of 30, 60 and 90 km/h. The buffer distance map generated at varying Euclidean distances characterized the level of accessibility of the fire engines from the emergency station to emergency sites to achieve a better response time. Areas at distances beyond 300 m from the main roads were considered to be less suitable, while those close to the road were ideal for locating fire station facilities. The inter-connections of the road network, as well as the width (for easier passage), provided alternative access points to a fire station site.
3. Distance from the existing fire stations (DEF): Using the network analysis function as described in Section 2.3.4, the DEF criterion map layer was processed in a service area determination of 121 existing fire stations and topology of road layers at travel impedances ranging from 1 to 5 min (Figure 4c).
4. Density of hazardous material facilities (DHM): For the DHM criterion layer, processing was done based on the number of latest records of facilities' locations with hazardous materials and other flammable chemical substances that included liquid petroleum gas (LPG), oil stations and compressed gases and oils; determined per sub-district area of Istanbul (Figure 4d).
5. Wooden building density (WBD): The WBD criterion map layer was processed by computing the ratio of the number of wooden buildings to the total number of wooden buildings in each sub-district. The density of wooden buildings is the representative ratio values per sub-district of Istanbul (Figure 4e).
6. Distance from earthquake risk (DER): The DER criterion map layer was derived from the earthquake hazard map of Istanbul, with peak ground acceleration (PGA) values indicated in units of gravity, which showed areas exposed to earthquake risk (Figure 4f). For Istanbul, areas of higher seismic risk are located closer to the southern part because of the proximity to the fault line which runs along the Sea of Marmara. These areas represent the highest PGA values, indicating the highest earthquake risk as shown in darker green color. For this reason, it is not preferable to

locate fire station facilities in these zones which are considered to be of low suitability. The further away from these regions, the lesser the exposure to earthquake risk and in turn, the higher the suitability, the interval value scale of which is dependent on the chosen reclassification result of the data values.

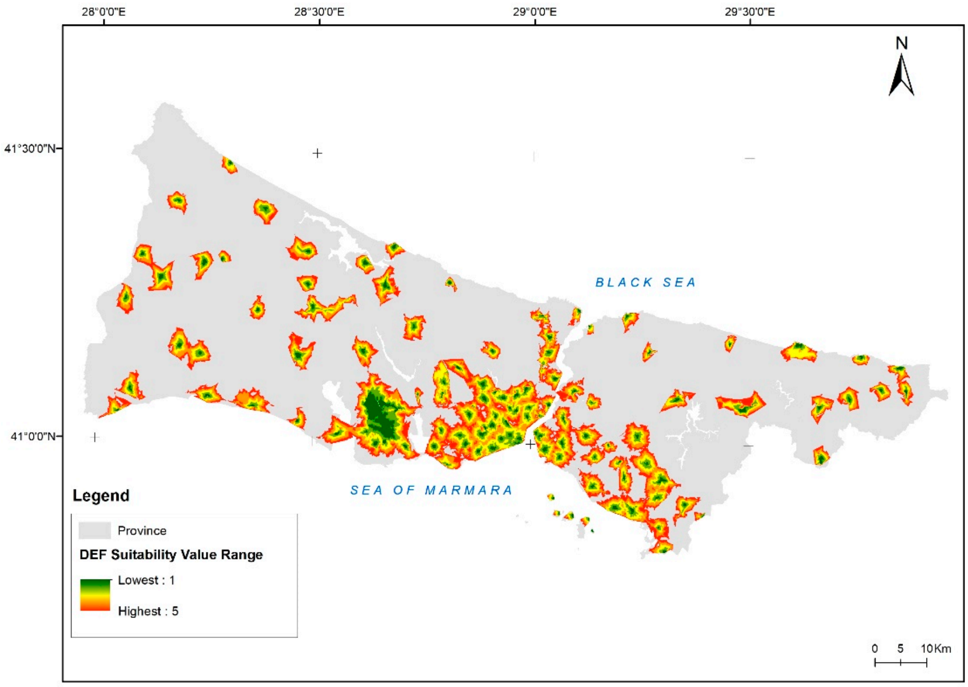


(**a**)

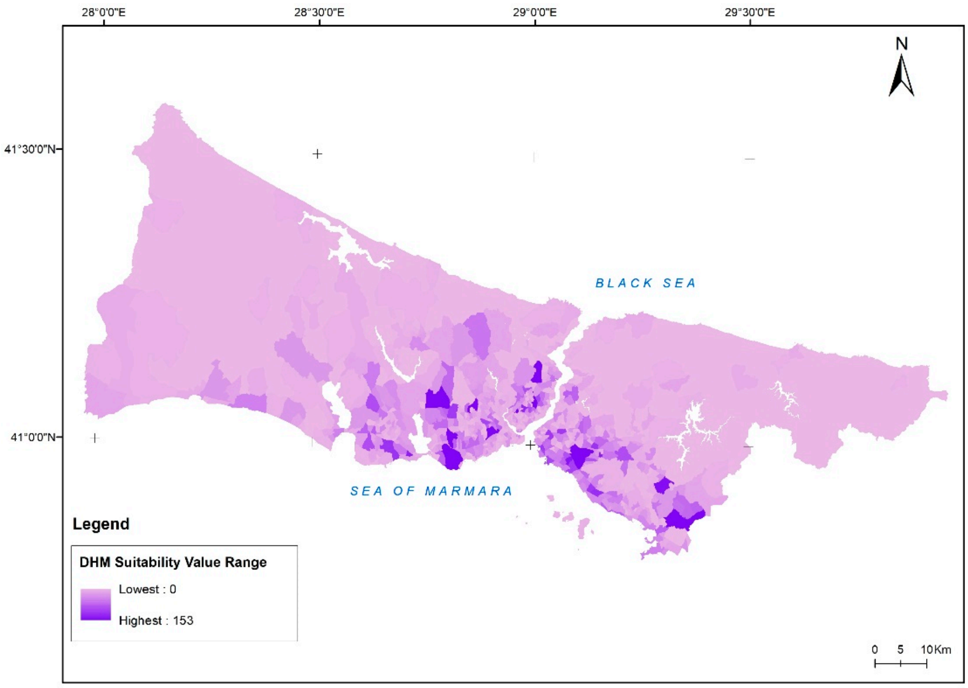


(**b**)

Figure 4. *Cont.*

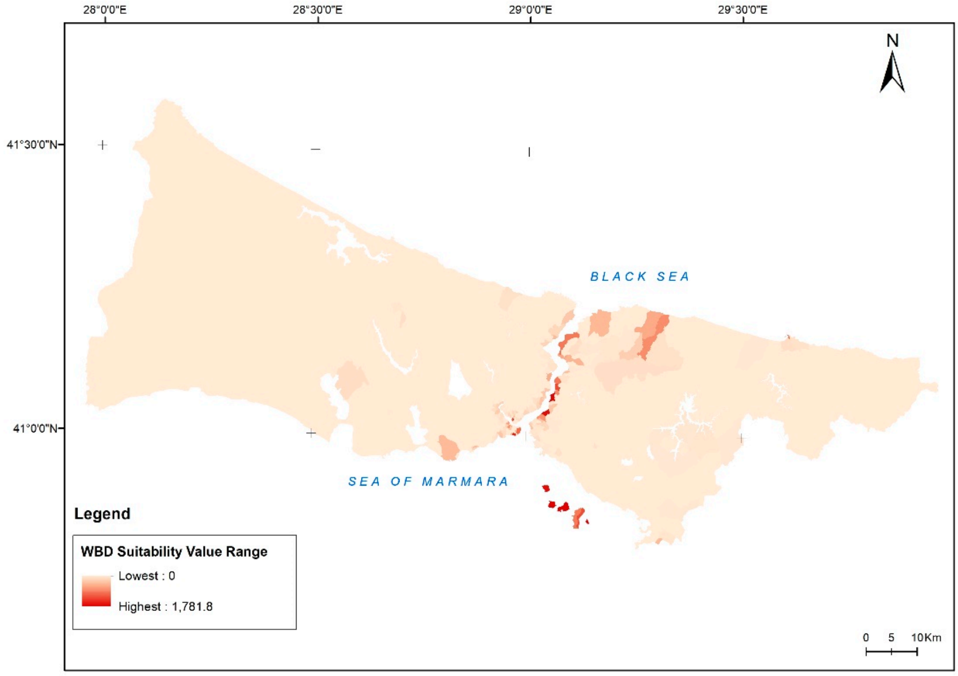


(c)

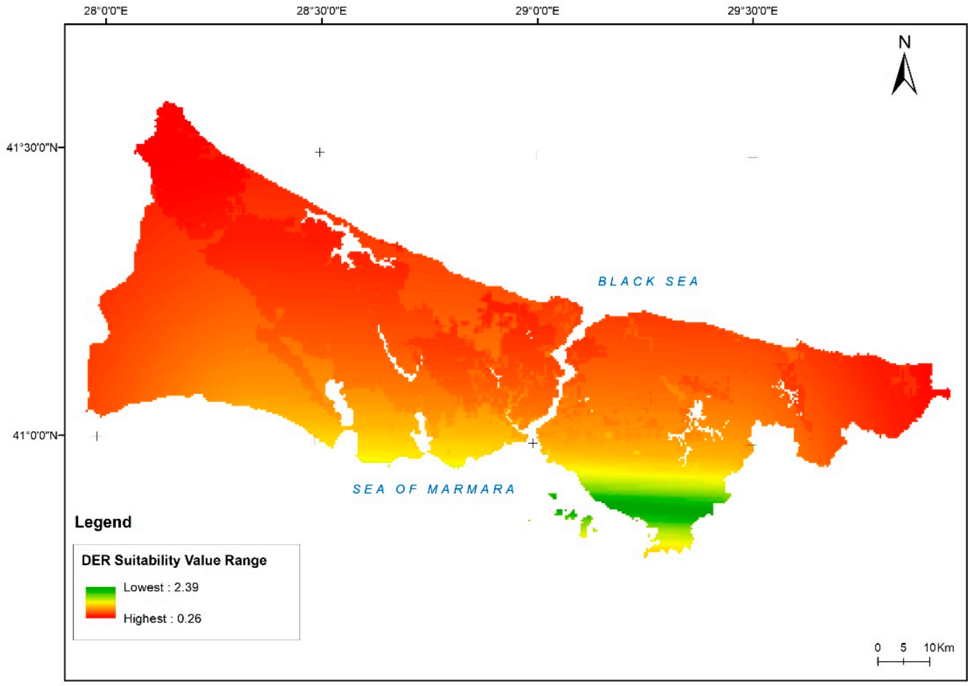


(d)

Figure 4. *Cont.*



(e)



(f)

Figure 4. (**a**) The processed high population density (HPD) criterion map layer related to the suitable locations for urban fire station facilities. (**b**) The processed proximity to the main road (PMR) criterion map layer related to the suitable locations for urban fire station facilities. (**c**) The processed distance from the existing fire stations (DEF) criterion map layer related to the suitable locations for urban fire station facilities. (**d**) The processed (density of hazardous material facilities) DHM criterion map layer related to the suitable locations for urban fire station facilities. (**e**) The processed wooden building density (WBD) criterion map layer related to the suitable locations for urban fire station facilities. (**f**) The processed distance from earthquake risk (DER) criterion map layer related to the suitable locations for urban fire station facilities.

3.2.2. Urban Fire Facility Suitability Assessment

The thematic raster data layers representing the six criteria, from Figure 4, were aggregated in ESRI ArcGIS 10.3 using a method of weighted linear combination (WLC) via Equation (8). The final weights from the integrated AHP-Entropy model were applied to each of the criterion maps using the weighted sum (overlay analysis) and then reclassified using the natural breaks (jenks) classification into five categories ranging from 1 to 5. The class value of 5 (in red color) depicts the most suitable areas, whereas class value 1 (in blue color) represented the least suitable areas for locating new urban fire station facilities as displayed in the final composite suitability map for Istanbul in Figure 5.

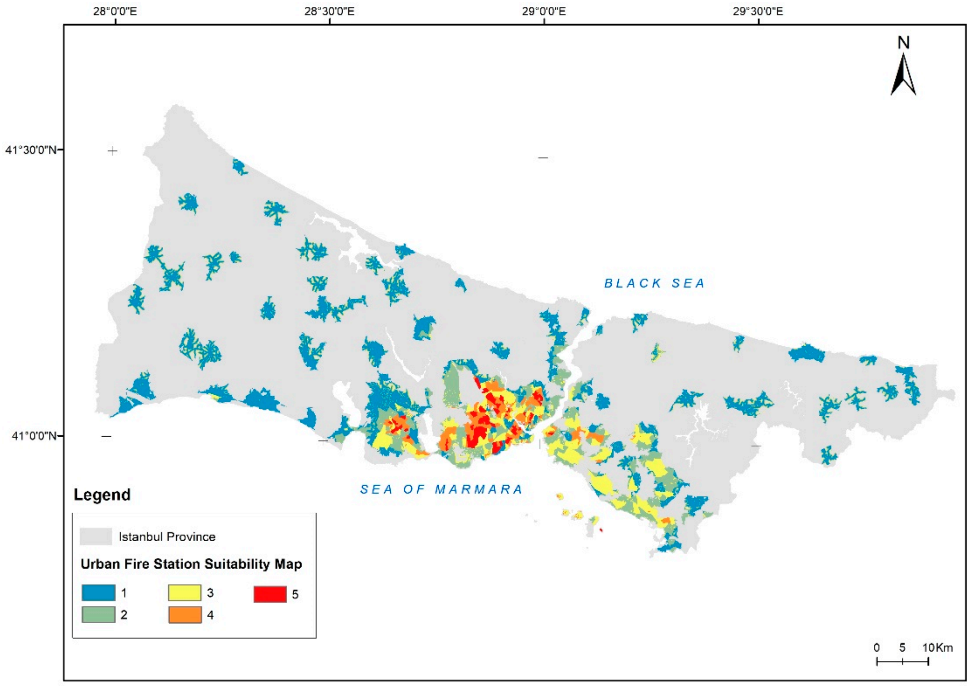


Figure 5. Final urban fire station suitability map of Istanbul Province.

A quantitative assessment of the land area covered by each of the resulting suitability classes is given in Table 7.

Table 7. Land area coverage of suitability.

Suitability Map Class	*Area in km^2*	*% Suitability*
Class 1 (lowest)	*490.143*	*42.7*
Class 2 (low)	*334.865*	*29.2*
Class 3 (moderate)	*206.648*	*18.0*
Class 4 (high)	*77.725*	*6.8*
Class 5 (very high)	*38.308*	*3.3*

The results of the land area coverage in the suitability analysis account for 322.68 km^2 from the representative class values labelled 3 to 5 as moderate, high and very high, mostly covering the metropolitan areas of Istanbul.

3.2.3. Spatial Simulation of Sensitivity Analysis Results

The spatial dimension of the sensitivity analysis (SA) of the integrated AHP-Entropy model results was evaluated in terms of the criteria weight using the one-at-a-time (OAT) method given by Equation (8). This study considered varying the criteria weights with the strongest influence, identification of the sensitivity of the respective criteria to known weight changes relative to the stability of the rankings and visualizing the spatial changes of the evaluation results.

From the final AHP-Entropy model results, the HPD and DHM criteria had the strongest influence on the urban fire facility location decision problem, yielding weight values of 29.3% and 27.6%, respectively. Therefore, the sensitivity analysis was performed by adjusting the weight values of the HPD and DHM criteria to five new incremental weight bands of 20%, ranging from 0% to 80%.

The resulting distribution of the adjusted weights and rankings for the rest of the criteria were tabulated in Tables 8 and 9.

Table 8. Sensitivity analysis of the HPD criterion (the grey value) adjusted to new weight values ranging from 0% to 80%.

Criteria	*Initial*		*0%*		*20%*		*40%*		*60%*		*80%*	
	Weight (W)	*Rank (R)*	*W*	*R*	*W*	*R*	*W*	*R*	*W*	*R*	*W*	*R*
HPD	***0.293***	*1*	***0.000***	*6*	***0.200***	*3*	***0.400***	*1*	***0.600***	*1*	***0.800***	*1*
PMR	*0.207*	*3*	*0.293*	*2*	*0.235*	*2*	*0.176*	*3*	*0.117*	*3*	*0.059*	*3*
DEF	*0.066*	*5*	*0.094*	*4*	*0.075*	*5*	*0.056*	*5*	*0.038*	*5*	*0.019*	*5*
DHM	*0.276*	*2*	*0.390*	*1*	*0.312*	*1*	*0.234*	*2*	*0.156*	*2*	*0.078*	*2*
WBD	*0.103*	*4*	*0.146*	*3*	*0.117*	*4*	*0.088*	*4*	*0.058*	*4*	*0.029*	*4*
DER	*0.055*	*6*	*0.077*	*5*	*0.062*	*6*	*0.046*	*6*	*0.031*	*6*	*0.015*	*6*
Total	*1.000*		*1.000*		*1.000*		*1.000*		*1.000*		*1.000*	

Table 9. Sensitivity analysis of the density of hazardous material facilities (DHM) criterion (the grey value) adjusted adjusted to new weight values ranging from 0% to 80%.

Criteria	*Initial*		*0%*		*20%*		*40%*		*60%*		*80%*	
	Weight (W)	*Rank (R)*	*W*	*R*	*W*	*R*	*W*	*R*	*W*	*R*	*W*	*R*
HPD	*0.293*	*1*	*0.404*	*1*	*0.323*	*1*	*0.243*	*2*	*0.162*	*2*	*0.081*	*2*
PMR	*0.207*	*3*	*0.286*	*2*	*0.229*	*2*	*0.172*	*3*	*0.114*	*3*	*0.057*	*3*
DEF	*0.066*	*5*	*0.092*	*4*	*0.073*	*5*	*0.055*	*5*	*0.037*	*5*	*0.018*	*5*
DHM	***0.276***	*2*	***0.000***	*6*	***0.200***	*3*	***0.400***	*1*	***0.600***	*1*	***0.800***	*1*
WBD	*0.103*	*4*	*0.143*	*3*	*0.114*	*4*	*0.086*	*4*	*0.057*	*4*	*0.029*	*4*
DER	*0.055*	*6*	*0.075*	*5*	*0.060*	*6*	*0.045*	*6*	*0.030*	*6*	*0.015*	*6*
Total	*1.000*		*1.000*		*1.000*		*1.000*		*1.000*		*1.000*	

Assessment of the SA results of the HPD and DHM criteria was simulated using ESRI ArcGIS software in the form of re-processed composite suitability maps that incorporated the new distribution of the criteria weight values by utilizing the weighted sum analysis function. By use of the reclassify function in the Spatial Analyst tool of ArcGIS, each cell of the aggregated maps was reclassified into five suitability class values using the natural breaks (jenks) classifier. The simulated SA outputs were geographically visualized at cut-off weight values of 0%, 20%, 40%, 60% and 80% for each of the HPD and DHM criteria as presented in Figures 6 and 7, covering the metropolitan region of Istanbul for better visual appreciation.

The model output sensitivity was tested by visually assessing the spatial variability in the generated maps at the defined input weights.

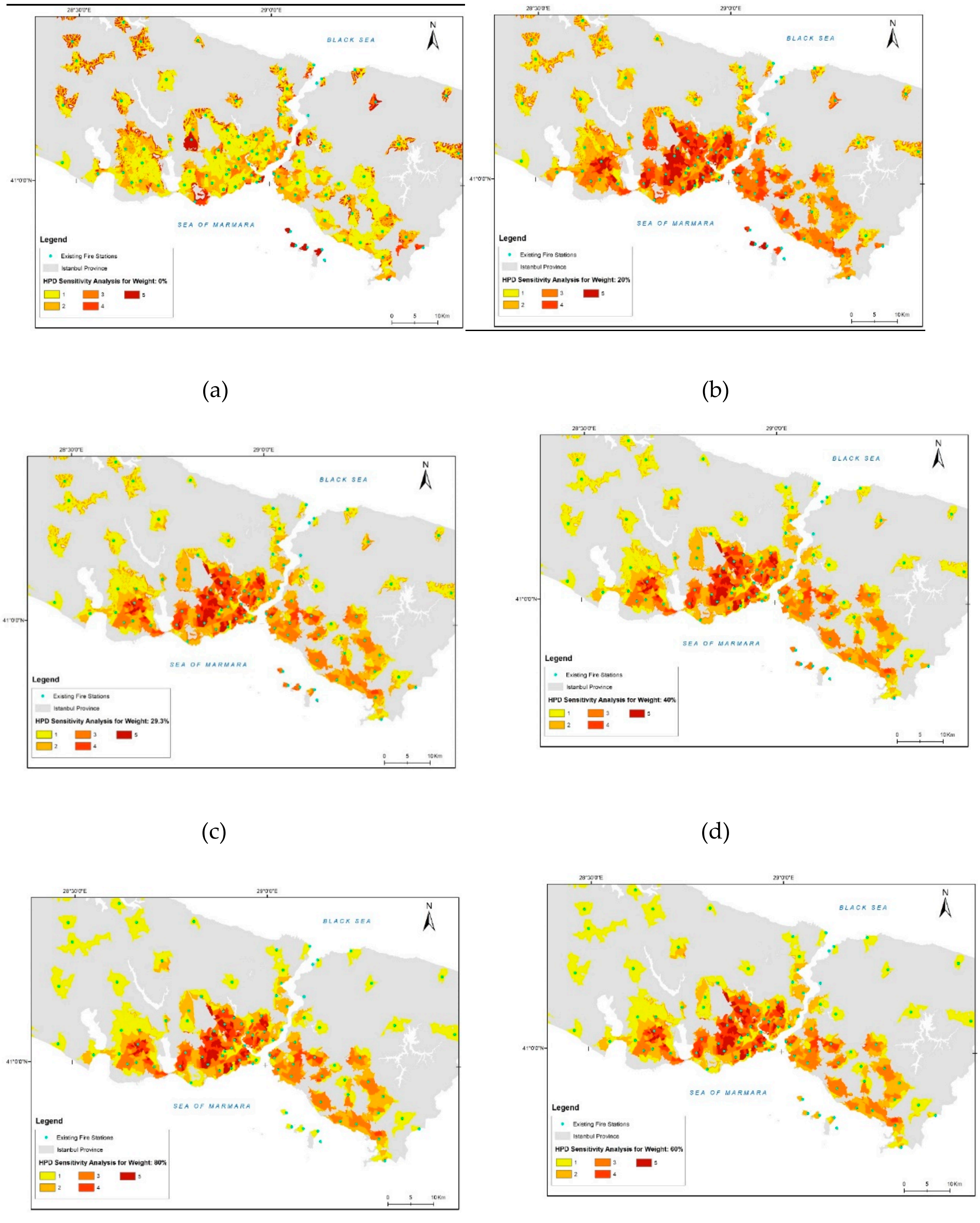
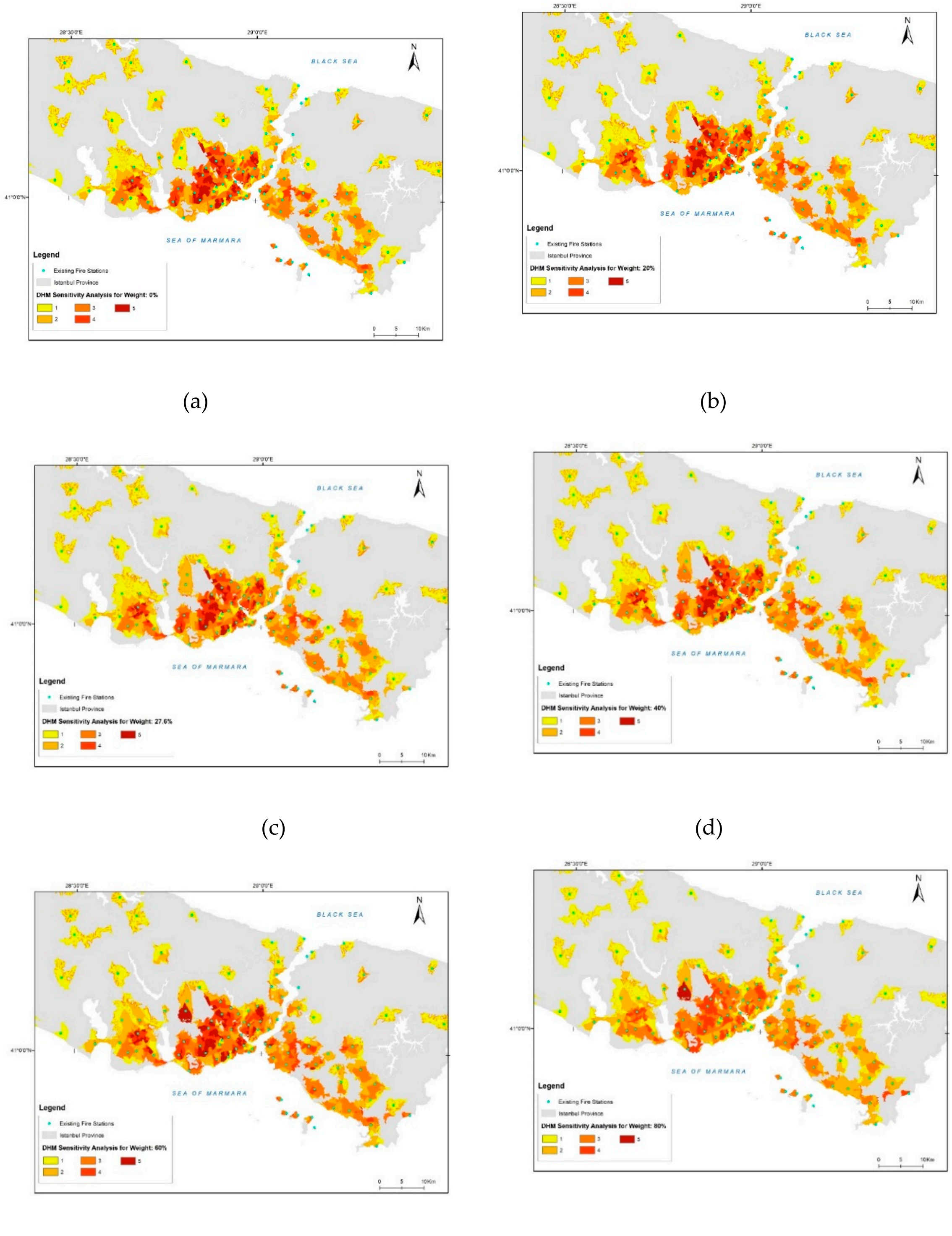


Figure 6. (**a–f**) The simulated sensitivity analysis (SA) outputs were geographically visualized at cut-off weight values of 0%, 20%, 29.3%, 40%, 60% and 80% for the HPD criterion.



(a) (b)

(c) (d)

(e) (f)

Figure 7. (**a–f**) The simulated SA outputs were geographically visualized at cut-off weight values of 0%, 20%, 27.6%, 40%, 60% and 80% for the DHM criterion.

4. Discussion

For achieving a more intuitive, realistic and comprehensive model result, drawing from the advantages of both weighting techniques as applied in several studies [94–98], an integration of the AHP and Entropy techniques was used in this study. Based on a similar study by Erden and Coskun [21] that used the AHP, this work broadens the contribution to the research by combining the use of AHP and Entropy in both subjectively and objectively evaluating the weights of the criteria deemed relevant for recommending sites for new urban emergency facilities. Furthermore, the inclusion of fire brigade practitioners in our study, which had not been previously considered, increases the reliability of this research result, reflecting valuable insights into the practioners' point of view in decision-making as part of a collaborative process. Additionally, use of the spatial sensitivity analysis (SA) based on the one-at-a-time (OAT) method in the current research examines the criteria weight sensitivity to variations, thereby increasing the comparability and robustness of the model results which are visualized spatially.

The computed criteria weight and ranking results from the AHP-Entropy method (Table 5) show that the high population density (HPD) and the density of hazardous materials (DHM) factors, with the weights of 29.3% and 27.6%, respectively, have the strongest influences on the urban fire facility location problem. On the other hand, the distance to earthquake risk (DER) and the distance to existing fire stations (DEF), with corresponding weights of 5.5% and 6.6%, were perceived by the DMs to have the least and the weakest influence in the decision-making outcome. In contrast with the previous work by Erden and Coskun [21], the criteria deemed to have the highest influence were DHM and HPD with weights of 40% and 16%, respectively. Our research coincides with the previous work in terms of the two criteria perceived to have the highest influence on the decision outcome. However, the differences in the weight evaluation results could be largely attributed to the divergent views and perceptions of the DM groups. Only a group of academics and academia-related professionals were used in the criteria preference and weight evaluations by the AHP method in the previous study [21] while our work comprised a heterogeneous mix of DMs that included fire brigade personnel and practitioners and frontline staff. In the previous study, the criteria perceived to have the least influence were DER and DEF, corresponding with our research findings. Additionally, the variations in the weight coefficients are a result of the differences in methodologies used to obtain the final result, whereas our current work integrates them with the Entropy approach. This offers an improvement in overcoming the limitations of the AHP by introducing objectivity to avoid human interference in the indicator weight evaluations, whilst at the same time building on expert knowledge and practical experience to increase the reliability and effectiveness of the decision outcome.

The representative criteria were modelled in GIS, via a multi-criteria analysis in the form of processed criterion map layers, and visualized (Figure 4). Using the derived AHP-Entropy weights, a weighted linear combination (WLC) approach of a weighted sum analysis function was applied to aggregate each of the criterion map layers and subsequently reclassified into five class values to produce a final suitability map for new urban fire facilities in Istanbul as shown in Figure 5. A visual interpretation of the results indicates areas of high potential urban fire risk that are of immediate priority for the construction of new urban fire and emergency facilities. Class values ranging from 3 to 5, depicted in yellow, orange and red corresponding to moderate, high and very high suitability, can be prioritized accordingly (also dependent on site-acquisition access and ground siting conditions). These areas of potentially high urban fire risk represent almost a third of the area under consideration, accounting for about 28.1%, as evaluated in Table 7. It can be inferred that most of the areas most suitable for planning new fire station facilities are located on the European side of Istanbul which also conforms to the areas that have a very high population density and a high density of hazardous material facilities as a result of high industrial and trading activity. These findings are congruent with the results in the previous work [21] that recommended new sites in the metropolitan region of Istanbul. Notable among these suitable zones for new emergency facilities are the district areas of Esenyurt, Avcılar, Beylikdüzü, Bahçelievler, Güngören, Küçükçekmece, Bayrampaşa, Esenler, Fatih, Beyoğlu, Şişli, Kaığthane, Beşiktaş, Sarıyer, Gaziosmapaşa, Sultangazi, Bakırköy, Bağcılar, Sultangazi, Bahçelievler and Zeytinburnu. Similarly, on the Asian side, especially with expansive urban infrastructural and industrial activity, district areas to be prioritized for provision of sufficient fire protection services are Üsküdar, Kadikoy, Ümraniye, Ataşehir, Maltepe, Sancaktepe, Kartal, Tuzla, Pendik and Adalar.

The high suitability index on the map coincides with areas of potentially high urban fire risk, convergent with the results obtained in [21] which are largely consistent with the dominance of the HPD and DHM criteria represented with the highest weight coefficients. From the DM perspective, these criteria are the most significant in planning fire emergency infrastructure. In this context, the dominance of the HPD and DHM factors and their influence on the spatial domain were examined using simulations of the sensitivity analysis (SA) based on the one-at-a-time (OAT) technique, the results of which were given in Tables 8 and 9. The spatial changes were analyzed and visualized as aggregated urban fire suitability maps for each of the HPD and DHM criterion at their respective assigned weight values of 0%, 20%, 40%, 60% and 80%, as illustrated in Figures 6 and 7. The corresponding distribution of the rest of the criteria weights was re-calculated, as tabulated in Tables 8 and 9. For the HPD criterion, decremental and incremental changes to the initial (original) weight value by about 10% and 10–15%, respectively, do not yield significantly observable changes on the resulting suitability maps. This implies that at weights within the variation band of between 20% to about 40–45%, the model is not subjective to changes, while it is sensitive to changes in weights outside this band. Therefore, it can be said that the model weight sensitivity of the HPD criterion is within the range of 20% to about 40–45%. The stability of the rank preference order when the HPD criterion weight is increased beyond the new weight value of 40% also correlates to the model sensitivity (Table 8). Decreasing and increasing the initial DHM criterion weight value by about 20% does not result in significant visual changes on the suitability map, indicating that the model is sensitive to weight variations within the band of between about 10% and 40–45%. To this effect, the preference order of the criteria rankings when the weight of the DHM criterion is increased from the new weight value of 40% are consistent and in conformity with the sensitivity of the model (Table 9). The SA results also indicate that the other criteria have a notable spatial influence on the suitability assessment decision outcome since the HPD and DHM criteria are only dominant within the specified model sensitivity ranges of weights.

The research outcome provides a base map that is useful for assessing the long-term impact of current and future demands of fire and emergency services. However, there is a need to match the provision of better fire protection services in parallel with the demands of the complex urban dynamic system. From this perspective, some limitations exist in some aspects of this research. Key among these is data availability. Additional variables should be considered, such as land use and cover for assessing the availability of open spaces for new site developments, and acquisition of historical records of fire incident data for urban fire risk estimation, as recommended by Uddin and Warnitchai [40]. Validation of our research results would be conducted by cross-checking areas of urban fire risk with actual fire incident data for risk and spread modelling. Future research is directed towards the inclusion of these selection factors in addition to the use of buildings inspection records for predicting fire risk and improving the capacity of fire emergency facility planning. In collaboration with the Istanbul Metropolitan Municipality (IMM) fire department and policymakers, a data-driven approach will be developed to assist in optimizing fire and emergency service facility planning using machine learning, geo-coding, and geo-information visualization techniques. Other variables related to the size and type of the fire brigade facilities, such as firefighting equipment, number of staff and vehicle capacity, should be considered in optimizing our facility planning efforts in view of budget constraints and cost-saving strategies. In this case, it may not be necessary to construct a new fire station in areas where the options to expand existing infrastructure and improve firefighting capacity would be established as cost-effective alternatives for adequately meeting the increasing demand for fire protection services.

A comprehensive assessment of fire risk to include regions outside urban areas is suggested to account for impacts of forest fires in the fire station and emergency facility planning not accounted for in the scope of the current study.

5. Conclusions

This study establishes a framework utilizing a GIS-based unified AHP-Entropy model for assessing the suitability of locating new urban emergency facilities within a five-minute travel distance within

Istanbul, Turkey to be used by planners and decision-makers (DMs) engaged in emergency management services. Nineteen DMs and experts, including fire brigade personnel, were involved in a group decision-making (GDM) process via the AHP method. By the pairwise comparison approach of the AHP technique, the DMs' preferences of the relative importance of the six determinant criteria were captured through evaluation of questionnaires administered using the Delphi technique. Based on these assessments, the subjective weights of the criteria were derived. However, due to human interference in the weights of the criteria and other uncertainties which have a negative influence on the decision outcome, the Shannon entropy weight method (EWM) was used to enhance the objectivity of the evaluations. To achieve a more comprehensive and reliable result, the weights from the AHP and Entropy methods were integrated and subsequently used as input in GIS via the weighted linear combination (WLC) approach to produce a reclassified final suitability map of new urban emergency facility locations. From the suitability indices, 39.3 km^2 (3.3%), 77.7 km^2 (6.8%) and 206.6 km^2 (18.0%) of the coverage area were classified as having very high, high and moderate suitability, respectively. This result confirms the visual map interpretation and assessment which indicate that almost a third of the study region, about 28.1%, is at risk of urban fires and should be prioritized for urgent planning and construction of new urban fire stations to provide sufficient fire protection services.

The accuracy and robustness of our proposed AHP-Entropy model were validated by performing a sensitivity analysis (SA) using the one-at-a-time (OAT) method whose results for the criteria with the strongest influence, HPD and DHM, were geographically visualized. The model sensitivity for the HPD criterion was evaluated to be between variations in weight values of 20% to 40–45% while that for the DHM criterion was determined to be between 10% and 40–45%. This outcome correlated with the stability of the criterion rankings, showing the consistency, robustness and reliability of the model.

Our proposed method combining GIS and AHP-Entropy can be replicated globally in wider application areas of group decision-making related to emergency planning and aversion of risk and other disasters as it is easy to use, reliable and effective. The research findings will be shared with the planning authorities of Istanbul for coordination and collaboration, in line with regulatory and planning strategies for the provision of adequate fire protection and emergency services. Future research in this regard is directed towards the acquisition of fire incidence and other relevant data for real-time modelling of urban fire risk, applying machine learning and artificial intelligence techniques.

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