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Fire Risk Assessment in Dense Urban Areas Using Information Fusion Techniques

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Abstract: A comprehensive fire risk assessment is very important in dense urban areas as it provides an estimation of people at risk and property. Fire policy and mitigation strategies in developing countries are constrained by inadequate information, which is mainly due to a lack of capacity and resources for data collection, analysis, and modeling. In this research, we calculated the fire risk considering two aspects, urban infrastructure and the characteristics of a high-rise building for a dense urban area in Zanjan city. Since the resources for this purpose were rather limited, a variety of information was gathered and information fusion techniques were conducted by employing spatial analyses to produce fire risk maps. For this purpose, the spatial information produced using unmanned aerial vehicles (UAVs) and then attribute data (about 150 characteristics of each high-rise building) were gathered for each building. Finally, considering high-risk urban infrastructures, like the position of oil and gas pipes and electricity lines and the fire safety analysis of high-rise buildings, the vulnerability map for the area was prepared. The fire risk of each building was assessed and its risk level was identified. Results can help decision-makers, urban planners, emergency managers, and community organizations to plan for providing facilities and minimizing fire hazards and solve some related problems to reduce the fire risk. Moreover, the results of sensitivity analysis (SA) indicate that the social training factor is the most effective causative factor in the fire risk.

Keywords: fire risk assessment; information fusion; GIS; high-rise buildings

1. Introduction

Fires cause over 300,000 deaths annually and are the fourth-largest cause of accidental injury globally (after road accidents, falls, and drowning) [1]. Burn injury risk is strongly associated with urban areas with crowded regions, which are growing rapidly in an urbanizing world [2]. Fires in high-rise buildings and residential complexes are one of the major urban disasters due to the high population density and high economic value of buildings and their items [3]. The high concentration of people and property make firefighting and evacuation operations very difficult in case of a fire event [4]. The economic value of the building itself, the construction inside it, and the property of the occupants of the building underline the importance of the issue of fire crisis management [5].

The phases of the classical disaster model to help emergency managers, also known as the ‘life cycle’ of comprehensive emergency management, are four-fold: (1) Mitigation; (2) preparedness; (3) response; and (4) recovery. The cycle of disaster framework is concerned with minimizing human losses in disasters by identifying the right activities and developing timely and appropriate levels of human and financial resources [6,7]. Mitigation measures are taken to reduce vulnerability in a specific region at some unknown time in the future. Indeed, this phase is not aimed at addressing concerns relating to an ongoing disaster but rather focus on catastrophic events that are out of immediate sight [8,9]. This might involve changes in local building codes to fortify buildings; revised zoning, and land use management; strengthening of public infrastructure; and other efforts to make the community more resilient to a catastrophic event [10,11]. Meanwhile, risk assessment is an essential component in disaster risk management and the planning process. The purpose of a risk assessment is to define the nature of the risk and identify the vulnerabilities of communities and potential exposure to given hazard events. Risk evaluation helps in the prioritization of risk management measures, giving due consideration to the probability and impact of potential events, cost effectiveness of preventative measures, and resource availability [12].

During the last decade, disaster management has been widely implemented using spatial data sourcing, related technologies in the whole process of collection, access, and disaster information. Currently, there are unique challenges that cannot be met without incorporating *spatial* and *attribute* data together as an emerging technology for sourcing and managing disaster information [13,14]. Given that disasters are fundamentally spatial in nature, geospatial information science (GIS) plays a critical role in disaster management [15,16]. GIS-based risk and vulnerability assessment methods could be adapted to urban fire risk assessment and could be upgraded by advances in crowdsourcing using geospatial data creation and collection [17]. Vulnerability maps can assist urban planners, emergency managers, and community organizations who are working in resource-constrained settings to identify and assess relevant fire risk factors. However, in order to achieve this, information from many different sources is needed for modeling the risk of fire [1]. Thus, information fusion techniques as a tool can assist decision-makers in making policy and mitigation strategies.

Meanwhile, according to Pohl and Genderen (2017), information fusion has many aspects from simple pansharpening through various stages of complexity to feature-based fusion, then decision-based fusion, to data fusion, 3-D fusion, and information fusion, and to advanced sensor fusion. One of the issues in information fusion is fusing remote sensing images with data from a GIS and other spatial data sets [18]. This present study aims at employing both high-rise building characteristics along with urban structural factors to assess fire vulnerability. For this purpose, UAV images will be integrated and analyzed with different information from various sources using information fusion methods in GIS to produce fire risk maps. This tool will also help decision-makers to design a framework for mitigating fire disaster management.

2. Literature Review

Srivanit (2011) developed a GIS-based approach for fire risk assessment in order to identify sites for disaster mitigation planning and management in the Chiang Mai Municipality (CMM). Fire risk assessment in this study has two main factors: The vulnerability and capacity for mitigating the areas with a fire history. Selecting risk factors was mainly based on four stakeholder groups: Urban planners, fire wardens, local residents, and local government officials [19]. The extracted information was integrated into a geodatabase and then spatial analysis was performed to generate the fire risk, ranging from high to low according to its sensitivity to fire or fire-inducing capability. The product was a map of the varying levels of fire risk across the city [19].

Goncalves and Correia (2016) proposed a method to assess and acknowledge the fire risk in urban areas. Their case study area was Porto, an old city in Portugal. The aim of their research was to produce a map of detailed risk and intervention plans that allow for a better response and mitigation of the effects of urban fires. The CHICHORRO method, a new approach to urban fire risk assessment, was used in this study. The proposed method for the evaluation of the risk of fire for a given building served two purposes: 1) Risk analysis for the current situation and 2) post-rehabilitation risk analysis employing spatial and attribute information. The results included the map of fire risk in the area along with the response of the method to specific scenarios [20].

Tomar et al. (2018) aimed to analyze the spatial pattern of fire incidents in the South-West Division of the Delhi Fire Service using geospatial technologies for effective management with available resources. The fire hazard zonation maps were prepared based on available data of fire incidents, land use, fire stations, population density, and number of deaths and injuries that occurred during fire incidents. The fire risk map showed that about 70.01% of the study area falls in the zones with low fire risk potential, 26.39% with moderate risk, and 3.59% with high risk. Moreover, researchers reported that the cause of the fire and fire risk differ significantly under different fire stations of this South-West division. Low rise (below 15 m in height) dwelling units/apartment houses and residential occupancy were found to be involved in the highest number of fire incidents with the maximum number of deaths and injuries [21].

Li et al. (2018) analyzed the factors affecting fire occurrence in high-rise buildings in order to set up an assessment index system. The main factors used for this purpose are fire safety hardware facilities, fire safety evacuation ability, building fire prevention capability, and building fire safety management status. The gray risk degree method, analytical hierarchy process (AHP), and the fuzzy evaluation method were used to establish the mathematical model. This study modeled five high-rise buildings, namely Shaanxi Information Building, Zhongguancun Science and Technology Building, Yanjiao Cultural Building, Jinan Commercial Building, and Tide White House. The results showed the fire safety level of selected high-rise buildings separately [22].

A new urban fire risk assessment methodology was developed by Ferreira et al. (2014) and applied to the old city center of Seixal. This simplified methodology was based on a pre-established method designated as ARICA. Over 500 buildings were assessed using this methodology, and the results were spatially analyzed using an integrated GIS. To do so, in the first phase, the Seixal case study allowed identification and collection of the main fire risk vulnerability sources. Next, in a second phase, these data were used as input for the development and application of the new methodology to assess urban fire risk. The results of this work provide a platform for risk mitigation at an urban scale, allowing city councils or regional authorities to plan interventions on the basis of a spatial view and emergency planning in case of an urban fire [23].

As described by Yu et al. (2018), unmanned aerial vehicle (UAV)-based imaging systems have many advantages compared to other information sources. These vehicles are especially useful for disaster monitoring, such as their high flexibility because they can fly when there is a fire, are quick to launch and low cost, and provide large-scale imagery for detailed urban infrastructure analysis [24].

Recently, substantial research has been devoted to the analysis of UAV data, e.g., understanding and modeling the urban environment with visual information from multiple sensors. A special issue of the international journal *Geospatial Information Science* (Xia et al., 2018) shows how UAVs can develop new ideas, methodologies, and applications of UAVs for data analysis and remote sensing [25]. The special issue includes seven papers that cover topics mainly on the navigation, image analysis, and surveying/mapping applications of UAVs. In the present study, we used UAV technology for our urban fire hazard research.

Some characteristics of the mentioned studies vary for different objectives; however, the key target of these works is urban fire risk assessment models or methods. Some of them employed only the fire safety characters of buildings. They neglected the location of such buildings and the spatial dimension of these buildings in urban areas and problems, which may occur due to urban equipment and the location of high-rise buildings. For example, [22] and [23] used methods for fire risk assessment considering only the fire safety characteristic of limited buildings and some others focused on the urban infrastructure situation and the fire history (e.g., [21]). Meanwhile, some researchers used an intermediate methodology, like CHICHORRO by Goncalves and Correia (2016). This model incorporates both the characteristics of buildings and the urban infrastructures but not completely and rather ignored some spatial aspects of buildings in urban plans [20]. The main objective of the present research was to employ both high-rise building characteristics and their location in urban areas that may cause fire risk to assess vulnerability maps.

To the best of the authors' knowledge, information fusion is not only necessary to analyze the complex issues involved in fire risk assessment but can also be of vital importance in assisting the emergency services, especially when placed in a GIS/spatial analysis context.

3. Materials and Methods

The overall methodology of this research (Figure 1) consisted of need assessment, data gathering, weighting process, and information fusion based on GIS modeling. In this section, each stage is described in detail.

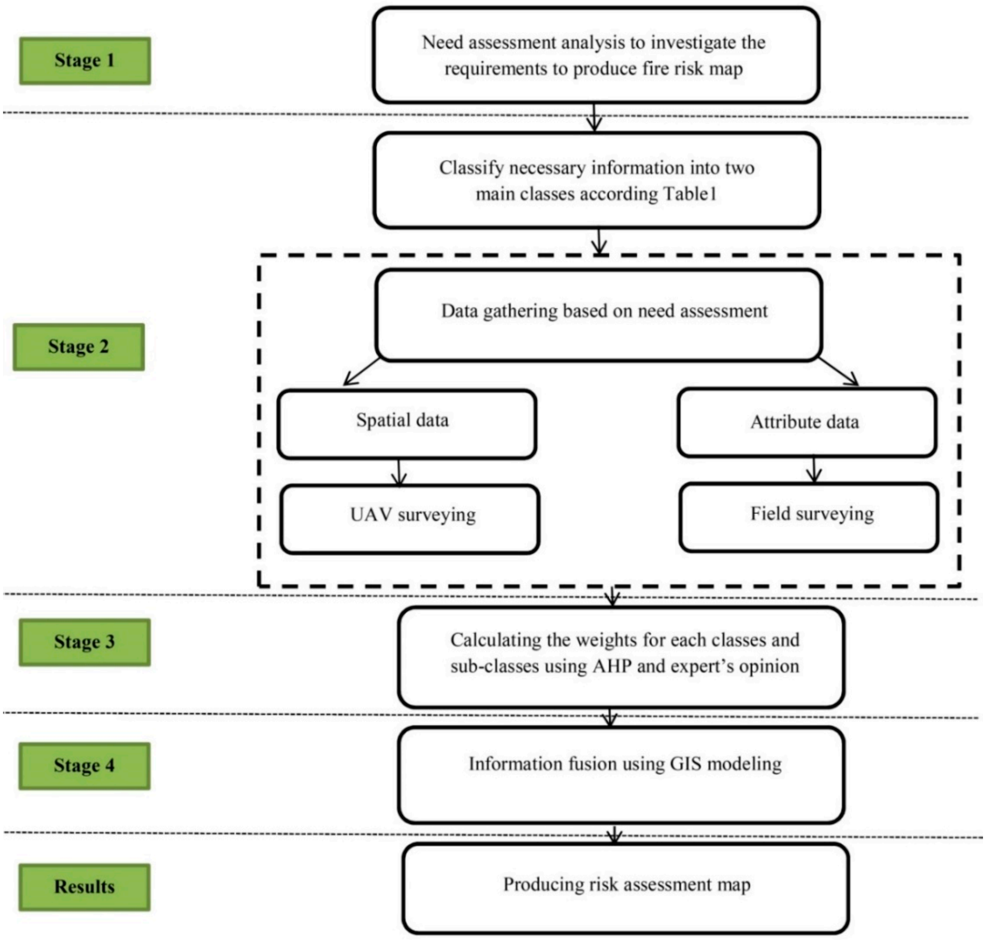

Figure 1. The main stages of the methodology to produce the fire risk map in this research.

3.1. Case Study Area

The city of Zanjan is located in the eastern part of Zanjan province, at an average altitude of 1663 m above sea level. The area of the city is 2469 hectares, representing 17% of the province's total area. The natural growth of the population; the regional role of Zanjan; the development of the industry; the construction of some industries, such as lead and zinc smelting factories; and the expansion of administrative, educational, and cultural services have made the city a desirable immigration spot, which has affected its physical development. Owing to the development of the city, some high-density towns were constructed recently to compensate for the residential needs in Zanjan city. Poonak town, with an area of 200 hectares, is one of these cases. The population density of Zanjan city is 90 persons per hectare but this amount is about 270 persons for Poonak town, which shows a noticeable population density in the area. The majority of settlements in this area are low-income families. About 60% of buildings in the area are high-rise buildings (more than 10 floors) according to the definition of the Ministry of Roads and Urban Development. The construction of the town began in 2003 but has not been completed yet. Figure 2 represents the geographical location of the study area.

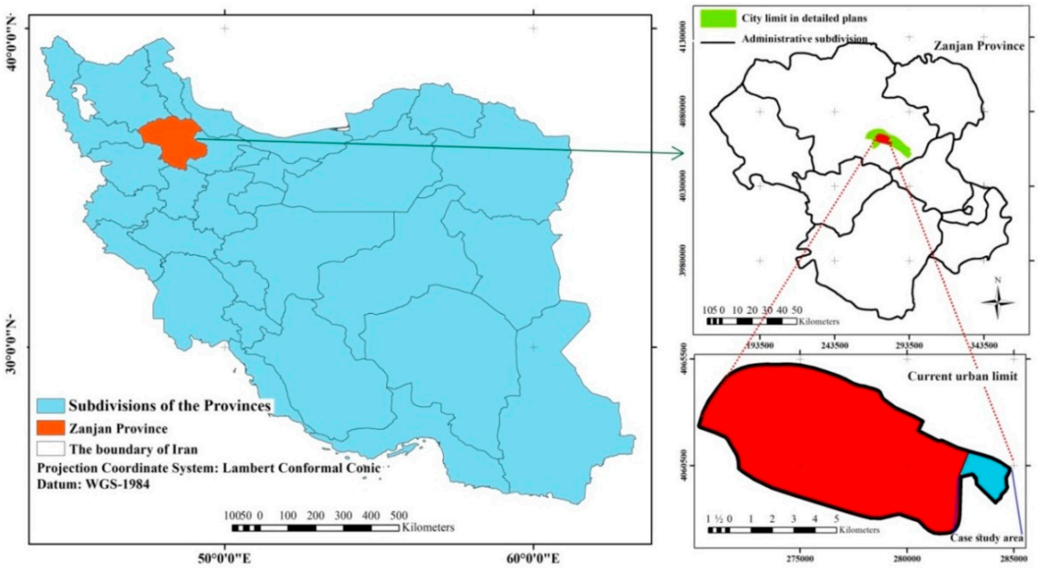

Figure 2. The geographical location of the study area.

3.2. Need Assessment

To achieve the fire vulnerability map of the study area after a need assessment process, the necessary information was classified into two categories: 1) Characteristics of high-rise buildings and their safety, and 2) urban infrastructure and their effect on the fire risk. Each class contains a variety of information gathered and integrated from different sources using spatial analysis. These variables were selected using literature reviews [2,5,12,16,17,21] and structures in Iranian buildings and housing research centers (BHRC), including building fire protection rules and passive defense rules in buildings [26,27]. Moreover, several hours of interviews were conducted to employ the experiences of the firefighting forces in this research.

Table 1 shows the necessary information to reach the fire risk assessment map based on the need assessment analysis in this research.

Table 1. Necessary information to an investigation of fire risk in the study area.

Main Classes	Sub-classes	Type of data (Spatial/Attribute)
Urban infrastructures affecting the fire risk	The position of CNG and gas stations The position of gas transmission pipes The position of gas substations The position of high voltage power transmission The position of electric power substations The position of flammable stores The position of industrial land-use Distance to the electrical poles The position of firefighting stations The position of fire hydrants	Spatial
High-rise building characters related to fire risk	Entry and exit access Fire alarm system Fire extinguishing system Technical specifications of the building Social training and periodic visits	Attribute

3.3. Data Gathering

To prepare the required information, spatial and attribute data were collected and processed to produce the needed information. In order to generate the spatial data of the study area, aerial surveying was performed using a unmanned aerial vehicle (UAV) in the area. UAV surveying was employed because the area includes high-rise buildings and surveying them with other methods involves more time and cost. Subsequently, the attribute data were surveyed in situ. The following sections will describe the implementation steps of data generation.

3.3.1. Spatial Data

The following steps were followed to perform the aerial surveying phases using a drone over the study area.

- Designing the benchmarks network: To geo-reference the images, it is necessary to identify some points on the ground and to determine their precise positions. These points were selected with respect to the precision of the required map, good coverage in the area, the suitable gap between points, and their availability. There were 36 target points in the area; the distribution of them is presented in Figure 3.
- Positioning by global navigation satellite system (GNSS): In this step, the positions of the designated points in the previous steps were determined using a dual-frequency GNSS kit.
- Surveying by drone: To perform drone-based surveying, a DJI S1000 drone equipped with a Canon M3 camera was utilized. The main steps done for the purpose of surveying by the drone are as follows:
- Designing the flight path: In this step, the flight paths were designed with respect to the specifications of the camera, the altitude, and the dimensions of the pixels on the ground, determined by the standards of the National Cartographic Center (NCC). Also, to enhance the precision, a 90% forward overlap and a 45% lateral overlap were adopted. Since the 2D map of the case study area is needed, the flight process was designed accordingly.
- Image Processing: At this stage, the ortho-photo-mosaics of the images were generated and the projective geometry of the images was converted to the parallel geometry. In this way, the elevation displacement effect on the images was eliminated.

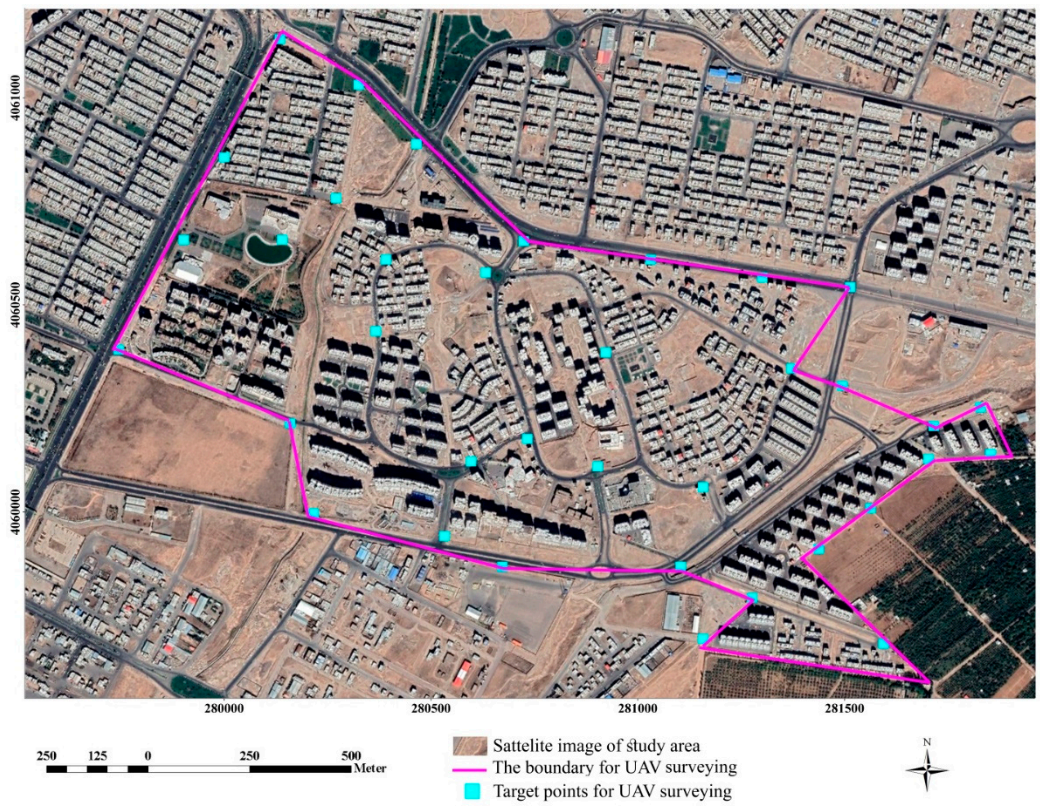

Figure 3. The distribution of target points for unmanned aerial vehicle (UAV) surveying in the study area (the blue points show the targets and the pink polygon shows the area for UAV surveying).

- Cartography: At this stage, the required features extracted during the needs' assessment process were mapped by visual interpretation and manually using the produced orthophoto. Moreover, for other important features that could not be extracted visually (e.g., gas pipelines), related maps were gathered from the municipality and associated organizations or gathered by field surveying.

3.3.2. Attribute Data Gathering

In this stage, according to the main classes in Table 1, the required hierarchies were extracted using the opinions of fire experts and available standards, such as the BHRC standard. To gather these data, multiple research methodologies, such as structured household questionnaires, key informant interviews, focus group discussions, and direct observations, were employed [28].

Table 2. The hierarchies and subclasses of entry and exit access factor in fire risk assessment.

Hierarchy 1	Hierarchy 2	Hierarchy 3	Hierarchy 4
Exit and entry access (A_1)	The access of complex site (A_11)	Entry of complex ($A_{11}1$)	Number of entries to the complex ($A_{111}1$)
			Distance from the high-rise-building to the passageway ($A_{111}2$)
			Access to the complex from neighborhoods ($A_{111}3$)
			Possibility of operation by lightweight fire truck ($A_{111}4$)
			Possibility of operation by heavy fire truck ($A_{111}5$)
			Possibility of operation by ladder ($A_{111}6$)
		Consistency of adjacent passageway to the complex ($A_{11}2$)	The height of building ($A_{112}1$)
			Enough space for lightweight fire truck deployment? ($A_{112}2$)
			Enough space for heavy fire truck deployment? ($A_{112}3$)
			Enough space for ladder deployment? ($A_{112}4$)
		Firetruck deployment ($A_{11}3$)	Disturbance of the trees in the operation? ($A_{113}1$)
			Disturbance of the curbs in the operation? ($A_{113}2$)
			Disturbance of the gas pipelines in the operation? ($A_{113}3$)
			Disturbance of the electric power transmission line in the operation? ($A_{113}4$)
			Disturbance of the land-use change in the operation? ($A_{113}5$)
			An inconveniency for the vehicle due to the slope of the terrain ($A_{113}6$)
			A possible inconvenience for the vehicle caused by the resistance of the ceiling ($A_{113}7$)
		Fire hydrants at the complex ($A_{11}4$)	The existence ($A_{114}1$)
			The activeness ($A_{114}2$)
			Minimum acceptable discharge ($A_{114}3$)
			Distance from the building ($A_{114}4$)
	Building access (A_12)	Exit and entry to building ($A_{12}5$)	Number of entry doors to building ($A_{125}1$)
			Automatic door ($A_{125}2$)
			The width of the entry door ($A_{125}3$)
			The width of Staircase ($A_{125}4$)
			The possibility of evacuation staircase to ground floor ($A_{125}5$)
			The possibility of evacuation to parking ($A_{125}6$)
			Exit barriers ($A_{125}7$)
			Fire elevator ($A_{125}8$)
			The possibility of evacuation from the ground floor to out considering the differences in elevation ($A_{125}9$)
			The possibility of evacuation from the balcony ($A_{125}10$)

For each building, about 150 attribute items (Table 2) in 4 hierarchies were gathered. Due to the high volume of attribute items at this stage, details of other factors in Table 1 were neglected.

3.3.3. Weighting Factors Using the AHP Method

Today, AHP is used as one of the most efficient multi-criteria evaluation methods in various studies [29,30,31,32]. In the AHP process, the elements are compared pairwise. The following steps were followed to obtain the relevant weights for fire risk causative factors [33].

- Paired comparison of the alternatives using the designed questionnaires according to AHP's common questionnaires.
- Creating a comparison matrix: A pairwise comparison matrix (A) is shown in Equation (1), where aij in the A matrix is the preference of criterion i over criterion j:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \quad i,j = 1,2, \ldots, n. \tag{1}$$

In Equation 1, *A* is the pairwise comparison matrix and a_{ij}s show the elements of the comparison matrix, and *n* indicates the number of criteria. In AHP, experts usually specify the importance of criterion *i* over *j* ranging from 1 to 9 [29] according to Table 3. Here, the fire risk causative factors in each hierarchy should be determined and their importance over each other should be prioritized by experts' knowledge. For the ease of calculation and specifying weights to each hierarchy separately, pairwise comparison tables were also designed separately for each hierarchy in Table 2.

Table 3. The comparison scale in analytical hierarchy process (AHP) [29].

Intensity of importance	Definition	Explanation
1	Equal importance of *i* and *j*	Two activities contribute equally to the objective.
3	Weak importance of *i* over *j*	Experience and judgment slightly favor one activity over another.
5	Strong importance of *i* over *j*	Experience and judgment strongly favor one activity over another.
7	Demonstrated importance of *i* over *j*	An activity is strongly favored and its dominance is demonstrated in practice.
9	Absolute importance of *i* over *j*	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values of the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If activity *I* has one of the above nonzero numbers assigned to it compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	

- Calculating the vector of weights, w = [w1,w2,w3,...,wn], based on Saaty's eigenvector method: For more details about AHP, the readers can refer to [33].
- Examining the consistency of judgment and finalizing the weight values.

3.3.4. Fire Risk Calculation Using Information Fusion

To calculate the fire risk, two separate approaches were used for urban infrastructure and building characteristics perspectives, and, finally, the results were combined. The following sections describe the fire risk calculations from these two aspects in more detail.

3.3.4.1. Fire Risk Calculation Considering Urban Infrastructure

There are several assumptions to calculate the risk caused by urban infrastructure. First, any feature can also be at risk of features that are themselves at a high risk of fire. Second, the risk decreases with increasing distance from high-risk features.

Figure 4 illustrates the first assumption. In this figure, the purpose is to calculate the risk for parcels 1 and 2. Regarding the distance of the parcels from high-risk features, parcel 1 has a shorter distance from the high-risk feature 1 and a greater distance from the high-risk feature 2. Therefore, this parcel is, in addition to the risk of the building itself, exposed to features 1 and 2. The dangerousness of feature 1 is greater than that of feature 2 due to its shorter distance to this parcel. This is in contrast with the case of parcel 2.

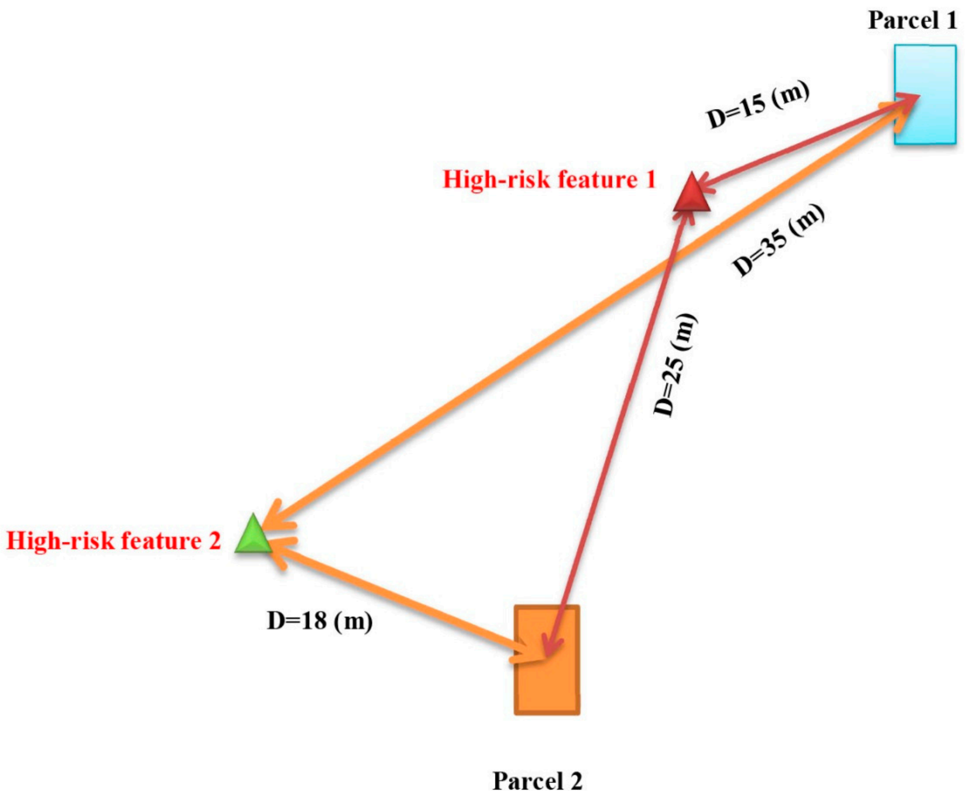

Figure 4. The method of fire risk calculation resultant of urban infrastructure risk.

For the second assumption, a function is defined to reduce the risk by increasing the distance from the high-risk features. In this way, the risk is lower at a greater distance and is highest at the neighborhood of the high-risk features. This is shown using a function in Figure 5.

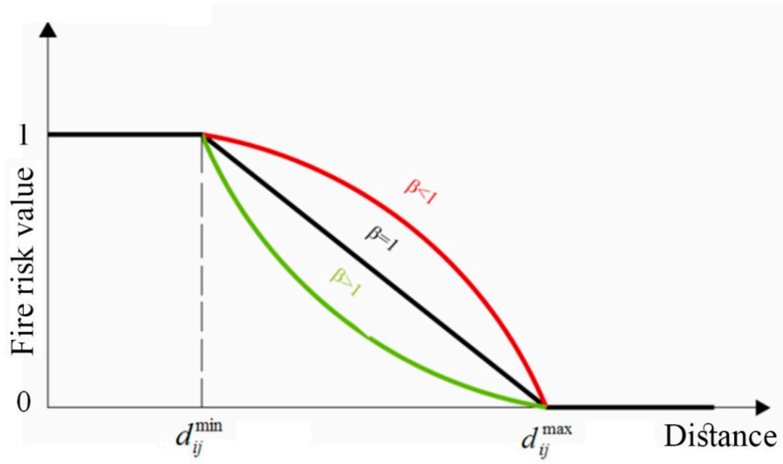

Figure 5. Defining a function to calculate the risk of high-risk urban infrastructures; d_{ij}^{max} shows the maximum effect distance, d_{ij}^{min} is the minimum impact distance; and β indicates how distance impacts the risk.

Figure 5 illustrates how the distance function is defined in the risk assessment of high-risk urban infrastructure. In other words, this function shows how distance impacts the risk. The risk of fire reaches its maximum value in the lowest distances from dangerous features that occur in the neighboring dangerous features. Then, the risk declines considering the value of β to its minimum, which occurs in the effect radius of dangerous features. In Figure 5, d_{ij}^{max} is the maximum impact distance and d_{ij}^{min} is the minimum distance. In addition, β denotes how distance impacts the risk and is considered here as equal to 1 for the sake of simplicity. To introduce the general form of this function, Equation (2) is defined:

$$\alpha(d_{ij})= \begin{cases} 1 & d_{ij} \le d_{ij}^{min} \\ \left(\frac{d_{ij}^{max}-d_{ij}}{d_{ij}^{max}-d_{ij}^{min}}\right)^{\beta} & d_{ij}^{min} \le d_{ij} \le d_{ij}^{max}. \\ 0 & d_{ij} \ge d_{ij}^{min} \end{cases} \quad (2)$$

Finally, to calculate the final risk, Equation (3) is used:

$$R_{pn} = \sum_{i=1}^{n} W_n \alpha_n, \quad (3)$$

where R_{pn} is the risk value of the n^{th} parcel, W_n is the weight of effective factors in the risk of the n^{th} parcel, and α_n is the mentioned function in Equation (2).

3.3.4.2. Fire Risk Calculation with Respect to the Characteristics of High-Rise Buildings

To calculate the fire risk in high-rise buildings, based on the descriptive information obtained, a set of if-then rules (decision rules) were used. The preferential information modeled by if-then rules seems to be close to the natural reasoning of decision-makers [34]. Production rules can be used alone to tackle the decision problem in this research. The rules base serves as a filter that preprocesses information and consequently reduces the amount of information to be processed. The base of rules must be developed with the help of experts and current standards in the fire safety field. Problems encountered during the development of the base of these rules are similar to those of other studies conducted in this area [34,35]:

a) A high number of rules are necessary when tackling this problem;
b) There are many possible values for the criteria in different standards; and
c) Difficulty of ensuring the consistency and completeness of the rules.

To overcome these problems, more general rules were considered and when modeling rule premises, interval values were used instead of simple values where possible. Below is the structure of rules used in this case for the exit and entry factors according to Table 2:

- If the number of entry doors to building ($A_{125}1$) is greater than 2 and the area of complex site (*Area*) is smaller than 2500 then the related risk of fire according to this factor $FR\ (A_{125}1)$ is equal to 0. Equation(4) shows this rule.

  If $(A_{125}1)>2$ and $Area<2500$, then $FR\ (A_{125}1) = 0\%$ (4)
- If automatic door ($A_{125}2$) exists, then the related risk of fire according to this factor is equal to 0, otherwise, the fire risk is 100%.
- If the width of the entry door ($A_{125}3$) is greater than the standard amount, according to Iranian standards of "building fire protection" ($a_{125}3$), the fire risk related to this factor ($FR\ (A_{125}3)$) is 0, otherwise the fire risk is 100%. Equation(5) illustrates this rule.

  If $A_{125}3>a_{125}3$, then $FR\ (A_{125}3) = 0\%$; otherwise, $FR\ (A_{125}3) = 100\%$ (5)

  where $a_{125}3$ is extracted considering the population of high-rise buildings from the Iranian standards of "building fire protection".
- If the width of staircase ($A_{125}4$) is gearter than the standard value considering Iranian standards of "building fire protection" ($a_{125}4$), then the fire risk related to this factor ($FR\ (A_{125}4)$) is 0, otherwise the fire risk is 100%. Equation(6) explains this rule.

  If $(A_{125}4)> a_{125}4$, then $FR\ (A_{125}4) = 0\%$, otherwise, $FR\ (A_{125}4) = 100\%$ (6)

  where $a_{125}4$ is extracted considering the population of high-rise buildings from the Iranian standards of "building fire protection".
- If it is possible to evacuate the staircase to the ground floor, then the related fire risk (FR) ($A_{125}5$)) is equal to 0; otherwise, the fire risk is 100%. This rule is shown in Equation (7):

  If $(A_{125}5) = 1$ then $FR\ (A_{125}5) = 0\%$; otherwise, $FR\ (A_{125}5) = 100\%$. (4)

  where $A_{125}5$ is a binary value, which is equal to *1* in the case of possibility for evacuation the staircase to ground floor and $FR\ (A_{125}5)$ is the related fire risk.

Other if-then rules are defined similarly for the rest of the factors. Finally, the overall *FR* is calculated for exit and entry to a building (A_{125}) as Equation (8):

$$FR_{12}5 = \sum (w_{125}i * FR_{125}i) \quad (5)$$

where $w_{125}i$ is the weight of the i^{th} factor of A_{125} ($A_{125}1$ to $A_{125}10$ in Table 2) and $FR_{125}i$ is the related fire risk calculated using if-then rules.

3.3.5. Software Design for Information Fusion

To facilitate the calculation of risk by users at different levels of knowledge, a C# script-based GIS tool was developed and compiled into a single interface. In this way, the users can modify risk calculation settings, such as weights, combine different data types, and view the results.

3.3.6. Sensitivity Analysis (SA)

SA was performed to evaluate and assess the effect of risk factors on the entire calculated fire risk model. One of the common approaches for SA is the one-at-a-time (OAT) method, which changes input factors one by one to investigate what effect this has on the outputs [36]. To increase the comparability of the results, all other criteria should be considered constant. In this method, a series of runs were executed to evaluate the effect of the alerted weights. Changing the weight of criterion *i* at a definite *PC* level, Equation (9) is defined as follows:

$$W_{PC}^{i} = W^{i} + W^{i} * PC \quad (6)$$

where W^i_{PC} denotes the alerted weight of the i^{th} criterion based on the percent change (PC) level and W_i shows the main weight achieved by the AHP method for the same criterion.

Since the sum of all criteria weights at any *PC* level should always be equal to 1 when weight is alerted, the other criteria are adjusted proportionally to satisfy this constraint. So, the weights of the other criteria can be computed as Equation 10:

$$W_{PC}^{j} = (1 - W_{PC}^{i}) * W^{j} / (1 - W^{i}) \quad (7)$$

where W^j_{PC} is the new weight of the j^{th} criterion after changing the i^{th} criterion in the *PC* level [37]. In this research, we considered the PC level as ±20 using 10 steps.

4. Results and Discussion

In this section, the results of all executive stages are presented and the obtained results are discussed.

Figure 6 shows an example of the output of the cartography steps conducted on the ortho-photo of the study area.

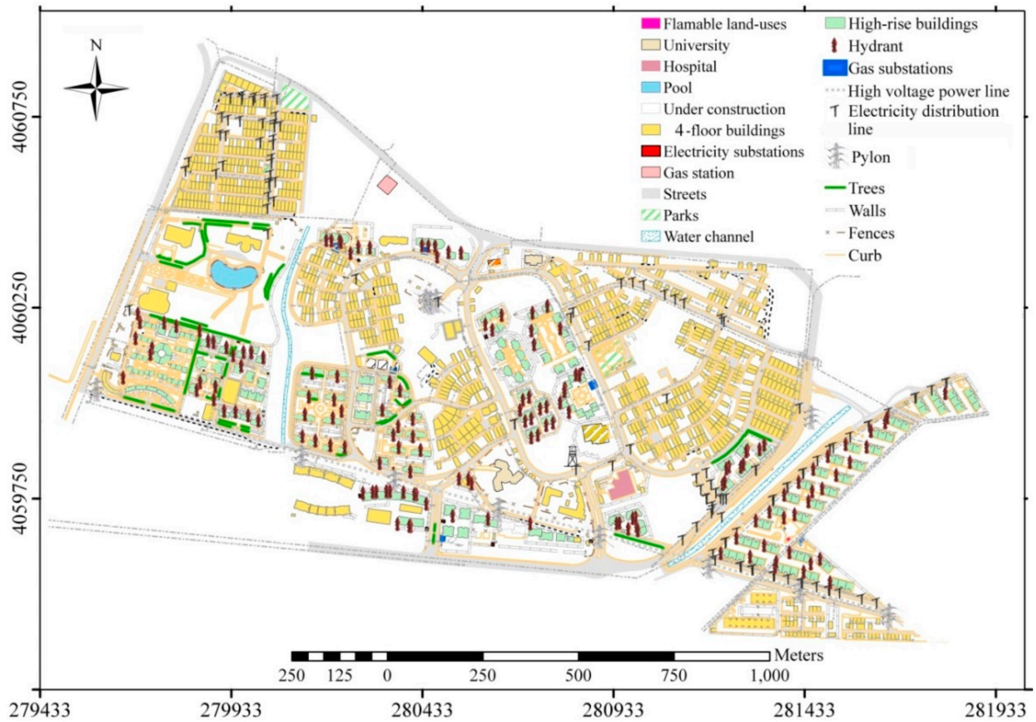

Figure 6. The map of the case study area after cartography steps.

Table 4 shows the calculated weights for the criteria related to building characteristics in hierarchy 1. The extracted weights and inconsistency coefficient relating to entry and exit access (*A1*) in hierarchies 2 and 3 are also shown in Tables 5 and 6, respectively. Due to the high volume of materials, other tables for the main criteria were excluded.

Table 4. Resultant weights from the AHP method for the main criteria (hierarchy 1) and related inconsistency coefficient.

Criteria	Weight
Social training and periodic visits	0.361
Fire extinguishing system	0.296
Fire alarm system	0.168
Entry and exit access	0.108
Technical specifications of the building	0.068
inconsistency coefficient	0.05

Table 5. Resultant weights from the AHP method for hierarchy 2 in the entry and exit main criteria and related inconsistency coefficient.

Entry and exit hierarchy	Weight
Building access	0.667
The access to the complex site	0.333
inconsistency coefficient	0

Table 6. Resultant weights from the AHP method for hierarchy 3 in the entry and exit and related inconsistency coefficient.

The access to the complex site	Weight
Firetruck deployment	0.380
Consistency of adjacent passageway to the complex	0.237
Fire hydrants at the complex	0.217
Entry of complex	0.167
inconsistency coefficient	0.08

Moreover, resultant weights related to urban infrastructure elements are represented in Table 7.

Table 7. Resultant weights from the AHP method for the urban infrastructure elements and related inconsistency coefficient.

The urban infrastructure elements	Weight
The position of CNG and gas stations	0.151
The position of gas transmission pipes	0.141
The position of gas substations	0.072
The position of high voltage power transmission	0.118
The position of electric power substations	0.090
The position of flammable stores	0.120
The position of industrial land-use	0.091
Distance to an electrical pole	0.028
The position of firefighting stations	0.130
The position of fire hydrants	0.058

As explained in the designed software section, the user is able to calculate the risk of different high-rise buildings at different levels, as listed in Table 2, using the implemented information fusion methodology. For example, Figure 7 shows a fire risk map from the aspect of high-rise building characteristics and its sub-classes in hierarchy 1. The overall risk map from this aspect is also shown in Figure 7f.

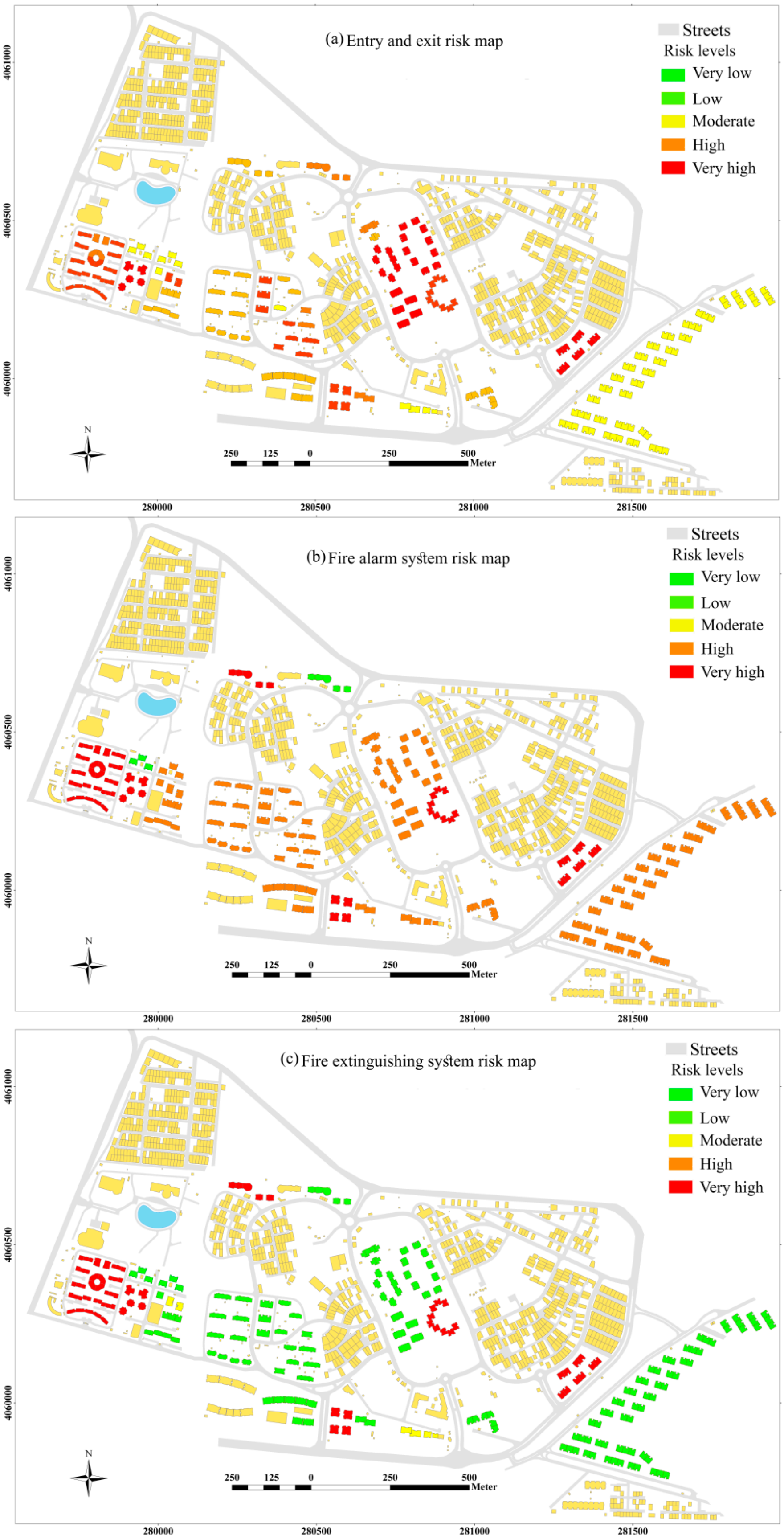
(a) Entry and exit risk map
Streets
Risk levels
Very low
Low
Moderate
High
Very high
N
250 125 0 250 500 Meter
4061000
4060500
4060000
280000
280500
281000
281500
(b) Fire alarm system risk map
Streets
Risk levels
Very low
Low
Moderate
High
Very high
N
250 125 0 250 500 Meter
4061000
4060500
4060000
280000
280500
281000
281500
(c) Fire extinguishing system risk map
Streets
Risk levels
Very low
Low
Moderate
High
Very high
N
250 125 0 250 500 Meter
4061000
4060500
4060000
280000
280500
281000
281500

Figure 7. The fire risk maps related to the main hierarchy of the building characteristics along with its overall risk; Figures 7**a** to 7**e** represent the fire risk maps of the main classes of the building in a characteristic map and Figure 7**f** shows the overall risk map of this issue.

As can be seen in the generated risk maps in Figure 7, the most high-rise buildings have a high risk in terms of training and periodic visits, and their deficiency is quite noticeable in the area. As most people in the area have low income, the vulnerability of this population is also very high. Certainly, this type of training is necessary for pre-event, during the event, and post-event stages. Training maneuvers also significantly contribute to risk control.

Alarm and fire extinguishing systems installed in buildings, despite the high costs involved, are either not active or not implemented properly. As shown in Figure 7, a low number of buildings are at risk in terms of alarm systems, but most residential buildings have incomplete and problematic fire extinguishing systems.

From an exit and entry point of view, many densely populated buildings have major problems. Incorrect landscaping in many buildings, despite adequate space, has created barriers that can be solved with proper management. This is evident even in the UAV images (Figure 8). For example, Figure 8a presents an instance of a building that has a high risk due to inappropriate green space for the entry and exit of firefighters and firefighting equipment. Also, Figure 8b shows another example of problems in the entry and exit related to incorrect parking areas. Therefore, the results of this study can help managers and decision-makers to identify problems and make decisions about them.

Figure 8a.

Figure 8b.

Figure 8. Two examples of entry and exit problems in a high-rise building in UAV images: (**a**) The problems related to inappropriate landscaping, and (**b**) problems related to the incorrect allocation of parking areas.

Figure 9. Fire risk map considering the risk of urban infrastructure.

Figure 9 displays the risk map of urban infrastructures in the study area. As shown in this figure, there is no building with very high risk. Moreover, the risk level considering urban infrastructures is considerably low in comparison with the risk related to building characteristics. However, there are some parts with high risk that are affected by high-voltage power lines, the low-width streets, and the lack of firefighting instruments (like fire hydrant) in the building complexes.

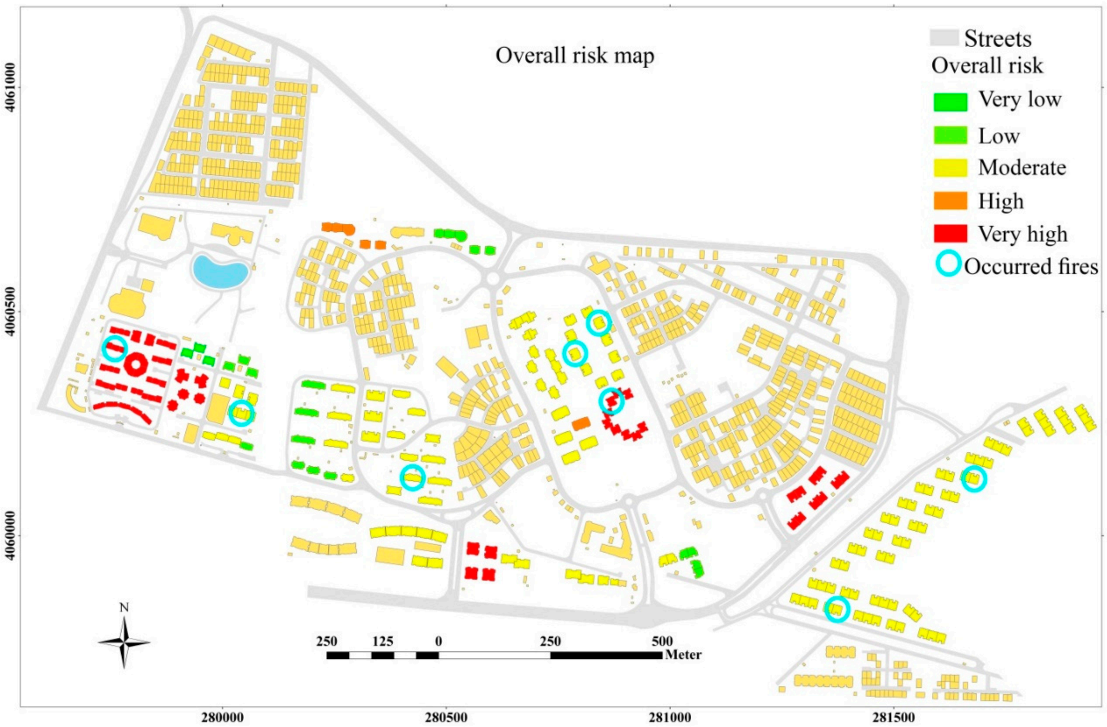

Figure 10. The overall risk map in the case study area considering building characteristics and urban infrastructures. Blue cirles show the location of occurred fires in the case study area.

Figure 10 also illustrates the overall risk map in the case study area considering two aspects of the calculated risk in this research: Building characteristics and urban infrastructures. As shown in the overall fire risk map, the majority of high-rise buildings have moderate-risk and high-risk levels. To investigate more, the location of serious fires that occurred in the case study area are mapped in Figure 10. Considering the location of the occurred fires in Figure 10, it can be concluded that most of the fires occurred in moderate-risk and high-risk areas, which shows that the model can compute the risk properly.

Figure 11 presents the results of the SA in the model. Since the number of factors related to all hierarchies in high-rise buildings' characters is high (150 factors), we just used SA for the main hierarchy of this category, which is mentioned in Table1. As realized in Figure 11, the minimum sensitivity of the model is related to the "fire alarm system" and the most influencing factor is "social training and periodic visits", respectively. As revealed in Figure 7(e), the risk level considering the social training factor in the majority of the case study area is very high; also, the weight of this factor is relatively larger than the other factors. Therefore, these reasons make the model highly sensitive to this factor.

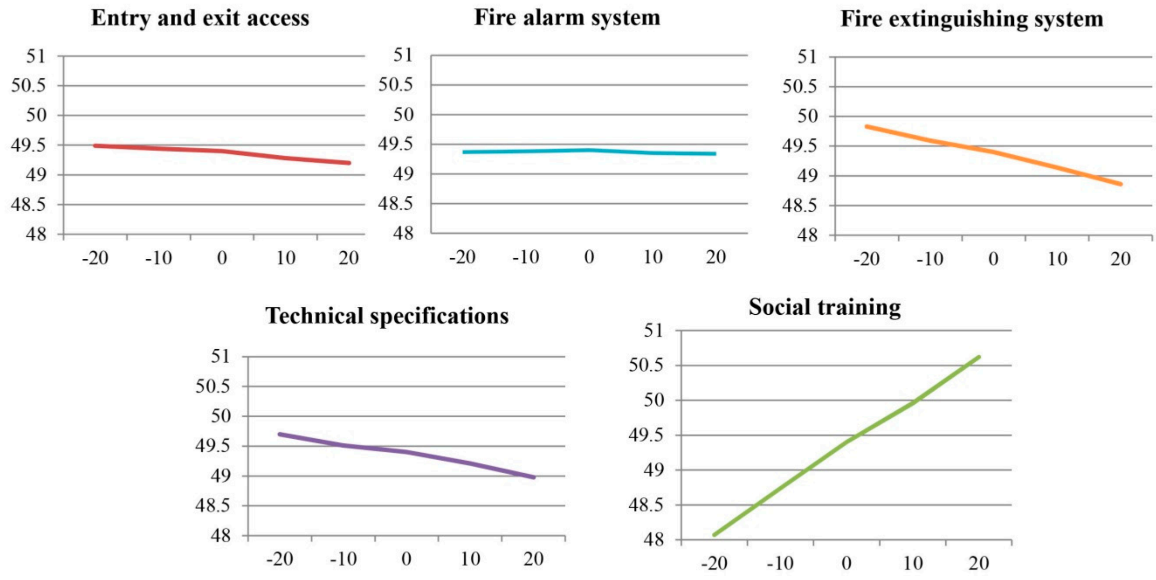

Figure 11. (**a**).

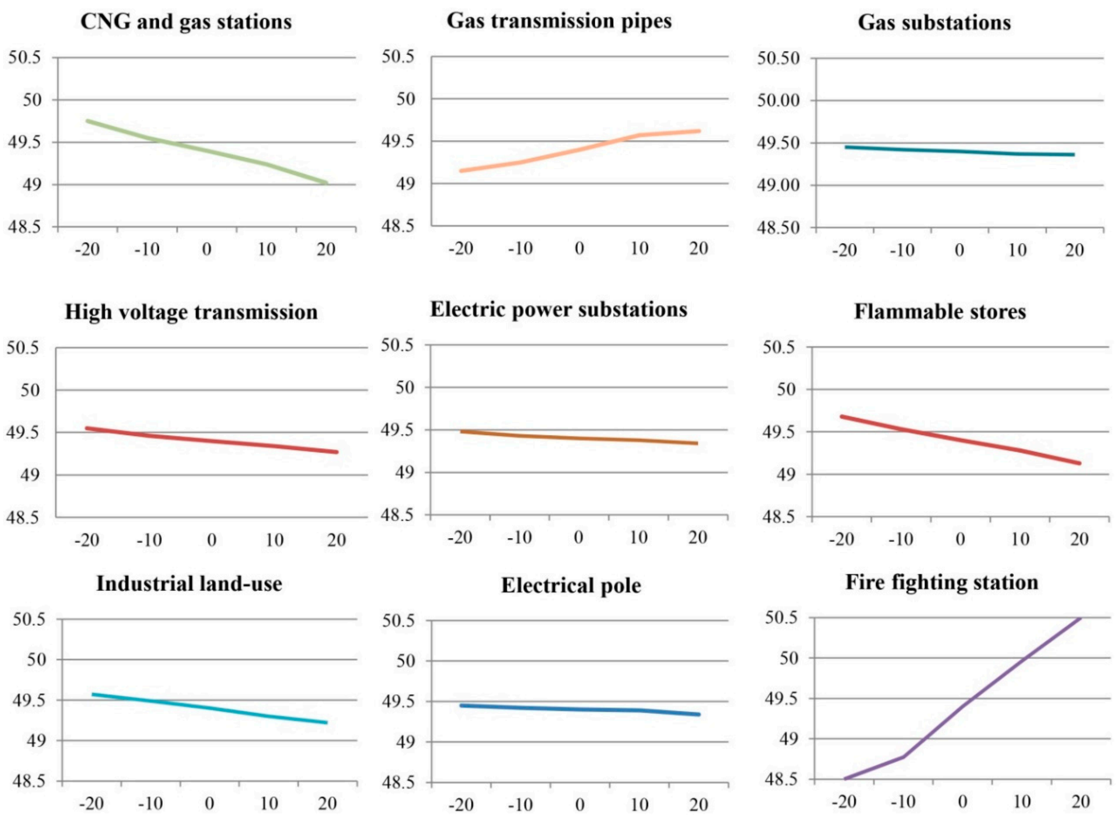

Figure 11. (b).

Figure 11. The results of the sensitivity analysis (SA) on the main factors of fire risk: (**a**) SA results on the high-rise building characters and (**b**) SA results on the factors of urban infrastructure.

5. Conclusion

The rapidly increasing adoption of information fusion technologies for he analysis of geospatial information appears to be promising. GIS and geospatial analyses provide very powerful tools to aggregate and fuse information from different sources to assess disaster risks in urban and regional scales.

In this research, using different types of spatial and attribute data from different sources, fire risk was evaluated in a very dense urban area with high-rise-buildings in Zanjan city, Iran. The main processes consisted of gathering spatial and attribute data and fusing this information using geospatial analyses. Also, a robust conceptual and analytical framework relating to fire risk vulnerability assessment was employed to address this issue. This was essential for the effective planning of data collection and for the interpretation of the results. Finally, by using fire risk maps integrated with a geospatial database, decision-makers can decide and plan more efficiently to solve problems and deficiencies in urban infrastructures and high-rise-buildings. The SA indicates that the model has the most sensitivity to the "social training and periodic visit" factor.

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