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The Role of Morphological Spatial Indices in the Suitability of Urban Earthquake Management

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ABSTRACT

Effective earthquake response is one of the main challenges of urban crisis management in earthquake-prone countries. The quality of the task will be affected by the urban structure, especially in the heterogeneous arrangement of urban components. This paper aims to introduce the spatial indices of urban structures and assess their role in earthquake response. The main contribution is the formulation of spatial indices and implementation of a GIS-based multi-criteria decision-making method to derive the suitability levels of crisis management. Therefore, first, the effective spatial indices have been specified and formulated based on the expert knowledge and literature which have been considered as 'junction degree', 'street width', 'traffic network direction', 'height of buildings', and 'shelters in place'. Then suitability levels of areas to respond to earthquakes were determined using the fuzzy-best-worst method (F-BWM). The proposed approach has been implemented in Districts 3, 6, and 7 of Tehran, the capital of Iran. The achieved results showed that the most important factors are 'street width' and 'height of buildings', while the 'direction of the roads' is not as significant as the other criteria. Also, in the southern part of the study area, the suitability levels of earthquake response in less than the other regions especially rather than the northern part, which is mostly related to the structure of the roads and also the height of the buildings.

KEYWORDS

Earthquake,
Response,
F-BWM,
Morphological Spatial Indices,
Suitability

1. Introduction

Earthquakes are one of the most devastating and terrifying natural disasters which a human being can experience, and they can cause almost two-thirds of total annual world economic losses (Dell'Acqua et al. 2013; Nikoo et al., 2016; Alizadeh et al., 2018). While earthquakes remain unpredictable, their impact on the population can be significantly reduced by taking appropriate and timely actions following strong ground motions (Zhai et al., 2019; Guerin-Marthe et al., 2020; Meimandi Parizi et al., 2022).

The earthquake distribution map of Iran shows that most of the residential areas are located in seismic zones and facing earthquake problems. There have been three major earthquakes in Iran and each one of them has claimed between 30,000 to 50,000 precious human lives. The severity of these earthquakes has also been over 7 RM (Richter Magnitude) (Pourjafar and Taghvaee, 2005). Therefore, improving a response strategy is important to have effective earthquake management. As seen in Figure 1, preparing the suitability levels of earthquake management based on spatial indices of urban structure will affect on response phase in the crisis management cycle.

The suitability level of earthquake management especially in the response stage is related to the ease of

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movement in urban areas for search and rescue operations. In this regard, the morphology of the urban structure has a direct influence on facilitating earthquake management. Any obstacle which limited this activity should be recognized before earthquake indigence. Buildings are the most prone features to collapsing after an earthquake (Barrosa and Santa-Maríabc, 2019; Aigwia et al., 2020; Harirchian and Lahmer, 2020; Han et al., 2020; Alasiri et al., 2021; Meimandi Parizi et al., 2022). Also, having the appropriate shelters in place in the urban environment could facilitate the disaster response process. This paper aims to introduce the spatial indices of urban morphology and assess their role in the earthquake response process. The main contribution is the formulation of spatial indices and implementation of a GIS-based multi-criteria decision-making method to derive the suitability levels of crisis management. The proposed method is implemented in part of Tehran, the Capital of Iran.

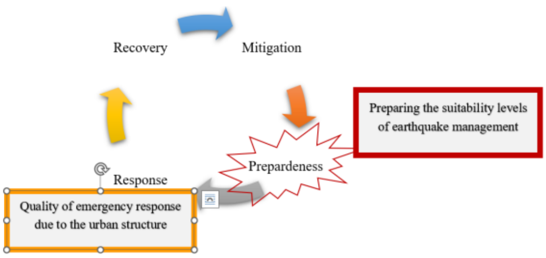

Figure 1. An illustration of the proposed idea in the earthquake management cycle

2. The Related Work

Many studies concentrated on assessing the morphology of urban structures on crisis management, specifically in earthquake response. Morphology means the relationship between the built space and the free space, between buildings, parcels, and streets (Bostenaru Dan and Armas, 2015). According to Lynch (1960) on the image of the city, the main structural elements of the cities are nodes, paths, districts, edges, and landmarks. Bostenaru Dan (2004a) detailed a retrofit decision based on the analysis of an urban quarter, following Lynch's principles. In Gociman (2006), elements of the urban morphology have been defined by architectural history, but also, green security nodes, a new type of strategic element that can be connected to the lost green spaces of the area. Bostenaru Dan and Dill (2014) stated the walkability in routes in Rapid Visual Screening for earthquake vulnerability (FEMA, 2015). The RISK UE project (Mouroux and Le Brun, 2006) also identified strategic elements according to the disaster cycle phase. A grid was superposed on a map, as is done in planned cities or computer games. This made it easier to choose a typology that is common among other studied areas.

D'Ovidio et al. (2016) investigated the main factors of the current urban structure and accessibility in the post-earthquake and analyzed the relationship between mobility and the spatial structure of the city. Bernardini et al. (2017) studied some important environmental and behavioral factors including the vulnerability of buildings, compact urban fabric, cascade effects, presence of people unfamiliar with the urban layout, and absence of information on efficient evacuation wayfinding strategies. These elements have been measured as really important in historical centers where evacuees suffer a mixture of unfavorable conditions to safely escape. Xia and Wang (2019) assessed the effects of earthquakes in urban areas from a network perspective to improve disaster mitigation. They demonstrated that the width of roads is one of the most important morphological elements of urban structure. Giulian et al. (2020) assessed the role of urban configuration and morphology of historic settlements in the definition of urban safety and resilience after the earthquake which concentrated on route characteristics. Kodag et al. (2022) proposed an urban resilience assessment framework due to different earthquake scenarios. They concluded that economically weaker regions are more vulnerable to earthquake disaster risk based on their locations and restricted access to the facilities.

According to these studies, the morphology of the urban infrastructure is obvious in disaster response, but the role of spatial indices in determining the suitability level of the earthquake response has been ignored in the literature.

3. Materials and Methods

This paper focused on the specification and formulation of spatial indices to prepare the suitability levels of the earthquake response process. In this section, after explaining the study area, the proposed method will be described.

3.1. Study Area

Tehran the capital of Iran is one of the most prone areas to earthquakes. The study area encompasses Districts 3, 16, and 7 of Tehran as depicted in Figure 2. These three areas were selected out of 22 districts in Tehran due to their longitudinal extension, which stretches along a north-south direction, to obtain an overview of the urban vulnerability of Tehran. Figure 3 shows some pictures from the study area.

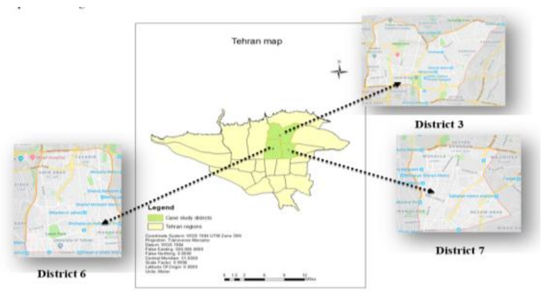

Figure 2. Map of Tehran districts, focusing on Districts 3, 6 and 7

Figure 3. Some kinds of the road in the study area

3.2 Proposed method

To achieve the aims of this paper, first, the effective spatial indices of urban morphology on the quality of earthquake response are specified and formulated. Then each spatial indices are weighted using the fuzzy best worst method (F-BWM) and the criteria maps are produced based on spatial analysis. Then the normalized criteria layers are combined using the weighted overlay. The procedure of the proposed method is displayed in Figure 4.

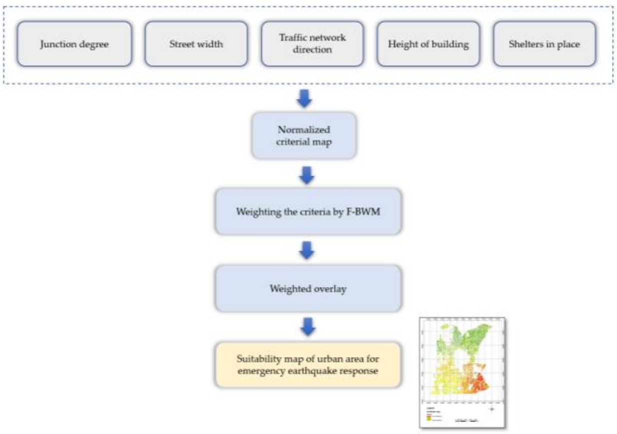

Figure 4. Flowchart of the proposed method

Step 1- Specification and formulation of morphological spatial indices

The morphological spatial indices are the main urban structural factors that contribute to evacuating the people and accomplishing the search and rescue operations. According to the experts' knowledge and literature, the main spatial indices are ‘junction degree’, ‘street width’, ‘traffic network direction’, ‘height of buildings’, and ‘shelters in place’ (Jankowski, 2008; Anbazhagan et al., 2012; Xu et al., 2016; Rastegar, 2017; Li et al., 2017; Yariyan et al., 2020; Wu et al., 2020; Satheesh et al., 2020)

Junction Degree

Nodes in a travel network are its intersections. For car drivers nodes may be street intersections, for pedestrians' nodes may be places, and for business travelers, nodes may be airports. The central structural characteristic of a node is its grade of connectivity, or, in terms of graph theory, its degree (Figure 5). The degree may be additionally weighted by the quality of the incoming and outgoing edges. Weights could be defined on a scale from 5 (highways) to 1 (footpaths), with state streets, overland streets, and town streets in between (Pourjafar and Taghvaee, 2005).

Figure 5. An example of junction degree in part of the study area (Scale: 1/2000)

Eq. 1 shows the designed formulation for the junction degree:

$$J_{D}=\sum_{i=1}^{n} W_i R_i \quad (1)$$

Where W_i is selected based on Table 1 and R_i is the number of streets that are related directly to a node. The weights are determined by experts (13 urban planners along with rescue and relief managers derived the final weights for nodes).

Table 1. Weights of streets in an urban environment (https://simplicable.com/new/streets)

Street types	Weights	Description
Alley	0.2	A narrow lane, path, or walkway, habitually designed for pedestrians, usually exists around buildings.
Avenue	0.4	A straight path or road with a line of trees or large shrubs running along each side.
Boulevard	0.6	A wide, multi-lane major way, habitually separated by a central median, and maybe with thoroughfares along each side designed as slow trip and parking lanes, also for bicycle and pedestrian usage.
Main street	0.8	Wide streets with several lanes are regularly nominated in this kind.
Highway	1	These types of roads are designed for high-capacity vehicular transportable with structures such as several lanes. The vehicles have usually high speeds on this road.

b) Street Width

Street width is a morphological factor that affects the movement of rescue and relief managers after the earthquake. Generally, with growing the width of streets, the suitability level of earthquake response will increase (Anbazhagan et al., 2012). Figure 6 shows a schematic view of the street width in the study area. The streets' width is varied between 4 to 24 meters in this area.

Figure 6. An example of street width in part of the study area (Scale: 1/2000)

c) Traffic Network Direction

The direction of the streets is important for traversing the roads. Usually, bi-directed streets are more feasible than one-directed streets. Figure 7 shows two streets with one/bi-directed. It has been shown that the width of the bi-directed streets is more than the one-directed.

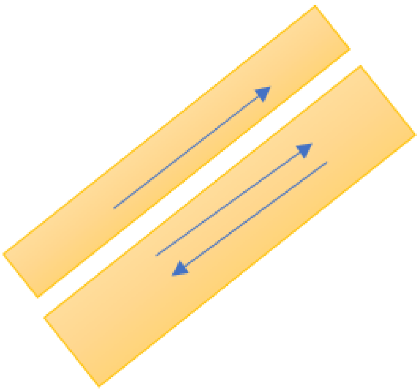

Figure 7. One-directed and bi-directed streets

d) Height of Buildings

Building height means the average maximum vertical height of a building or structure measured at a minimum of three equidistant points from the finished grade to the highest point on the building or structure along each building elevation (Jankowski, 2008). Generally, tall buildings with low resilience will decrease the suitability level of earthquake response. The height of buildings varied between 4 to 90 meters in the study area.

e) Shelters in Place

Safe areas or temporary shelters in place are the sites that are at low risk due to the earthquake disaster according to the effect of spatial and environmental criteria. These areas are candidates as emergency evacuation stations in earthquake response. Three types of land use are considered as shelters in place after an earthquake. Figure 8 shows an example of the shelter-in-place factor.

Green spaces: urban green spaces mean any open area that is public including plant life and preservation as parks. The area of these spaces is usually more than $500m^2$. Primary facilities such as drinking water and restroom have existed in these places.

Sport lands: sport lands are the outdoor spaces that have adjusted for playing different sports while their area is usually more than $1000m^2$. These places may be public or private, but primary facilities such as drinking water and restroom have existed in these places.

Bare Lands: bare land in the general sense is defined as land which is not used and exists abandoned in one place without construction. These are don't equipped with primary public facilities their extent is usually more than 50 m^2.

Figure 8. An example of shelters in place (green space) after the earthquake

Step 2: Spatial analysis and normalization

The criteria produced are based on spatial analysis using raster-to-vector. Values of all criteria will be normalized based on Eq. s (2) and (3):

$$\mathrm{vmax}_{ij} = \frac{X_{ij} - X_{imin}}{X_{jmax} - X_{jmin}} \quad (2)$$

$$\mathrm{vmin}_{ij} = \frac{X_{jmax} - X_{ij}}{X_{jmax} - X_{jmin}} \quad (3)$$

Where, vmax_{ij} is the normalized value of maximized criteria, vmin_{ij} is the normalized value of the minimized criterion, X_{ij} is the raw value for the location i and the indicator j, X_{imin} represents the minimum value for the indicator j, and X_{jmax} is the maximum value for the indicator j.

Step 3: Determining Factor Weights using F-BWM

To clarify the concept of F-BWM, first, a brief explanation of fuzzy set theory is introduced. The theory was stated by Zadeh (1965) to manage the uncertainty of the humanoid judgment, also the fuzzy set theory could transform the linguistic decision of human decisions into fuzzy functions (Celik et al., 2015; Gul et al., 2016). One of the common fuzzifier functions for converting linguistic variables to fuzzy numbers is triangular fuzzy functions which consist of minor, intermediate, and higher numbers of the fuzzy as $\tilde{A} = (l, m, n)$, in which m, n, and r (m ≤n ≤ r). The triangular fuzzy number membership function (see Figure 9) is formulated using Eq. 10 (Moslem et al., 2020):

$$\mu_{\tilde{A}} = \begin{cases} 0, & x < l \\ \frac{x-l}{m-l}, & l \le x \le m \\ \frac{u-x}{u-m}, & m \le x \le u \\ 0, & x \ge u \end{cases}$$

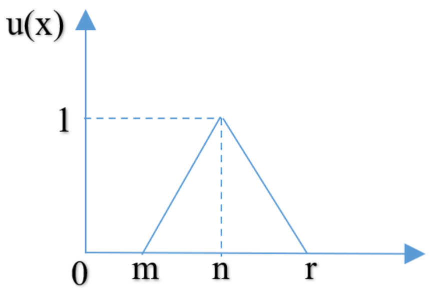

Figure 9. Triangular fuzzy number (Moslem et al., 2020)

The triangular fuzzy numbers and linguistic terms are also specified in Table 2 (Moslem et al., 2020).

Table 2. The linguistic terms and fuzzy numbers (Moslem et al., 2020).

Linguistic Term	Triangular Fuzzy Number
Equally Importance (EI)	(1,1,1)
Weekly Importance (WI)	(2/3, 1, 1.5)
Fairly Important (FI)	(1.5, 2, 2.5)
Very Important (VI)	(2.5, 3, 3.5)
Absolutely Important (AI)	(3.5, 4, 4.5)

$\tilde{A}_1 = (m_1, n_1, r_1)$ and $\tilde{A}_2 = (m_2, n_2, r_2)$ are any two triangular fuzzy numbers, and the two triangular fuzzy numbers are calculated using Eq. s (11-15) (Moslem et al., 2020):

The addition operator:

$$\tilde{A}_1 + \tilde{A}_2 = (m_1 + m_2, n_1 + n_2, r_1 + r_2) \quad (11)$$

The subtraction operator:

$$\tilde{A}_1 - \tilde{A}_2 = (m_1 - r_2, n_1 - n_2, r_1 - m_2) \quad (12)$$

The multiplication operator:

$$\tilde{A}_1 x \tilde{A}_2 = (m_1 x m_2, n_1 x n_2, r_1 x r_2) \quad (13)$$

The arithmetic operator:

$$kx\tilde{A}_1 = (kxm_1, kxn_1, kxr_1) \quad (k>0) \quad (14)$$

$$\frac{\tilde{A}_1}{k} = \left(\frac{m_1}{k}, \frac{n_1}{k}, \frac{r_1}{k}\right), \quad (k > 0) \quad (15)$$

$R(\tilde{A}_i)$ as the arranged mean integration index for the ranking of triangular fuzzy numbers is computed using Eq. 16 (Moslem et al., 2020):

$$R(\tilde{A}_i) = \frac{m_i + n_i + r_i}{6} \quad (16)$$

The complete stages of F-BWM for computing the fuzzy weights (Guo and Zhao, 2017) are described as well as follows (the notation is the same as BWM) (Moslem et al., 2020):

a) Criteria definition. n decision criteria are considered as $c_1, c_2, \ldots, c_n$.

b) Best and worst criteria determination. This stage is carried out by experts.

c_b is the best criterion and c_W is the worst criterion.

c) Fuzzy comparisons for the best criterion to the others. The pairwise comparison $\tilde{a}_{ij}$ is carried out. Formerly, the fuzzy judgments are transformed to triangular fuzzy numbers based on Table 3 descriptions. The fuzzy Best-to-Others comparisons are formulated as Eq. 17:

$$\tilde{A}_B = \{\tilde{a}_{b1}, \tilde{a}_{b2}, \ldots, \tilde{a}_{bn}\} \quad (17)$$

$\tilde{A}_B$ defines the fuzzy best-to-others vector; $\tilde{a}_{bj}$ defines the fuzzy comparison of the best criterion c_b due to j^{th} criterion, j = 1, 2, … , n. It is obvious that $\tilde{a}_{bb}$ = (1, 1, 1).

d) Fuzzy comparisons for the worst criterion to the others. Based on the principles of step (c), in this stage, the fuzzy others-to-worst vector is computed using Eq. 18:

$$\tilde{A}_W = \{\tilde{a}_{w1}, \tilde{a}_{w2}, \ldots, \tilde{a}_{wn}\} \quad (18)$$

in which $\tilde{A}_W$ represents the fuzzy others-to-worst vector; $\tilde{a}_{iw}$ represents the fuzzy comparison of the worst criterion c_w, i = 1, 2, …, n. It is obvious that $\tilde{a}_{ww}$ = (1, 1, 1).

e) The optimal fuzzy weights determination. The optimal fuzzy weight for each factor is computed for each fuzzy pair $\tilde{w}_b / \tilde{w}_j$ and $\tilde{w}_j / \tilde{w}_w$, where $\frac{\tilde{w}_b}{\tilde{w}_j} = \tilde{a}_{bj}$ and $\frac{\tilde{w}_j}{\tilde{w}_w} = \tilde{a}_{jw}$. The result is adjusted such that the maximum absolute gaps between $\left|\frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{a}_{Bj}\right|$ and $\left|\frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{a}_{jW}\right|$ for all j are minimized for all j. $\tilde{w}_b$, $\tilde{w}_j$ and $\tilde{w}_w$ in F-BWM are triangular fuzzy numbers. Sometimes, it is preferred to apply $\tilde{w}_j = (l_j^w, m_j^w, u_j^w)$ for optimal criteria assortment. The triangular fuzzy weight of the criterion $\tilde{w}_j = (m_j^w, n_j^w, r_j^w)$ is converted to a crisp value based on Eq. 19.

$$\min \max_j \left\{ \left|\frac{\tilde{w}_b}{\tilde{w}_j} - \tilde{a}_{bj}\right| - \left|\frac{\tilde{w}_j}{\tilde{w}_w} - \tilde{a}_{jw}\right| \right\} \quad (19),$$

$$\sum_{j=1}^{n} R\tilde{w}_j = 1, \quad m_j^w \le n_j^w \le r_j^w, \quad m_j^w \ge 0,$$

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

where
$\tilde{\omega}_B = (m_b^w, n_b^w, r_b^w), \tilde{\omega}_j = (m_j^w, n_j^w, r_j^w), \tilde{\omega}_W = (m_W^w, n_W^w, r_W^w), \tilde{a}_{Bj} = m_{bj'}^w, n_{bj'}^w, r_{bj'}^w)$
and $\tilde{a}_{bjw} = (m_{bj'}^w, n_{bj'}^w, r_{bj'}^w)$. Eq. 20 is converted to the nonlinearly constrained optimization problem:

$$\min \xi \quad (20), \quad \left|\frac{\tilde{\omega}_b}{\tilde{\omega}_j} - \tilde{a}_{bj}\right| \le \xi,$$

$$\left|\frac{\tilde{\omega}_j}{\tilde{\omega}_w} - \tilde{a}_{jw}\right| \le \xi,$$

$$\sum_{j=1}^{n} R\tilde{\omega}_j = 1, \quad m_j^w \le n_j^w \le r_j^w, \quad m_j^w \ge 0,$$

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

in which $\xi = (m^{\xi}, n^{\xi}, r^{\xi})$.

where $m^{\xi} \le n^{\xi} \le r^{\xi}$, it is assumed that $\xi^* = (k^*, k^*, k^*)$, $k^* \le m^{\xi}$, formerly Eq. 20 can be changed as:

$$\min \xi^* \quad (21),$$

$$\left|\frac{(m_b^w, n_b^w, r_b^w)}{(m_j^w, n_j^w, r_j^w)} - (m_{bj}, n_{bj}, r_{bj})\right| \le (k^*, k^*, k^*),$$

$$\left|\frac{(m_j^w, n_j^w, r_j^w)}{(m_W^w, n_W^w, r_W^w)} - (m_{jw}, n_{jw}, r_{jw})\right| \le (k^*, k^*, k^*),$$

$$\sum_{j=1}^{n} R(\tilde{\omega}_j) = 1, \quad m_j^w \le n_j^w \le r_j^w, m_j^w \ge 0,$$

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

f) CR calculation. The CR is calculated in the equal method as BWM.

g) Combination of criteria weights. As there are different members in each group, to compute the final weights for each POI in each group, Eq. 22 should be used (Malczewski & Rinner, 2015):

$$W_{it} = \sqrt[n]{w_{i1} w_{i2} \ldots w_{in}} \quad (22)$$

in which w_{in} is the weight of criterion i based on the opinion of expert n, and w_{it} is the weight of criterion i based on the preferences of the experts.

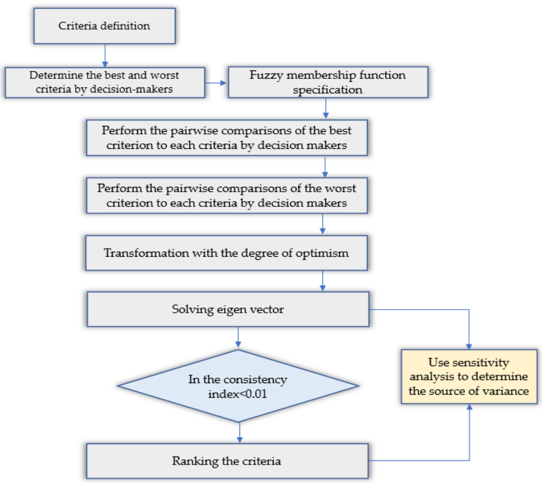

Figure 10. The procedure of F-BWM

Step 4: Weighted overlay

The weighted overlay is one of the common techniques in MCDA which is based on the weighted average concept (Malczewski, 2011). Then, by multiplying the relative weight by the value of that criterion, a final value is obtained for each alternative. In this method, the decision rule calculates the value of each alternative by Eq. (23). In the weighted overlay model, two components of the value of functions $V(a_{ik})$ and the weight of criteria (W_k) are used and calculated as well as follows (Malczewski, 2011):

$$V(A_i) = \sum_{k=1}^{n} W_k \, V(a_{ik}) \quad (23)$$

where $V(a_{ik})$ is the value of cell i according to criterion k, W_k is the weight of criterion k and $V(A_i)$ is the final value of output cell i.

4. Implementation and Results

The proposed algorithm is implemented in the study area to validate its effectiveness and performance. The preparation of geodatabase, also running weighted overlay has been conducted in ArcGIS 10.3. Moreover, fuzzy-BWM has been executed using Expert choice 11 software.

4.1. Data Preparation

Before running a weighted overlay, first, all layers should be prepared using spatial analysis and normalized according to the maximum and minimum criteria described in Eq.s 2 and 3. All the data are on a 1:2000 scale. The normalized criteria maps are illustrated in Figure 11.

4.2. Running F-BWM

To create the criteria maps and risk maps, weighting the criteria and sub-criteria should be carried out. The weighting procedure has been accomplished by fulfilling the questionnaires with 50 experts via interviewing. Table 3 shows the achieved weights of criteria with an acceptable inconsistency rate.

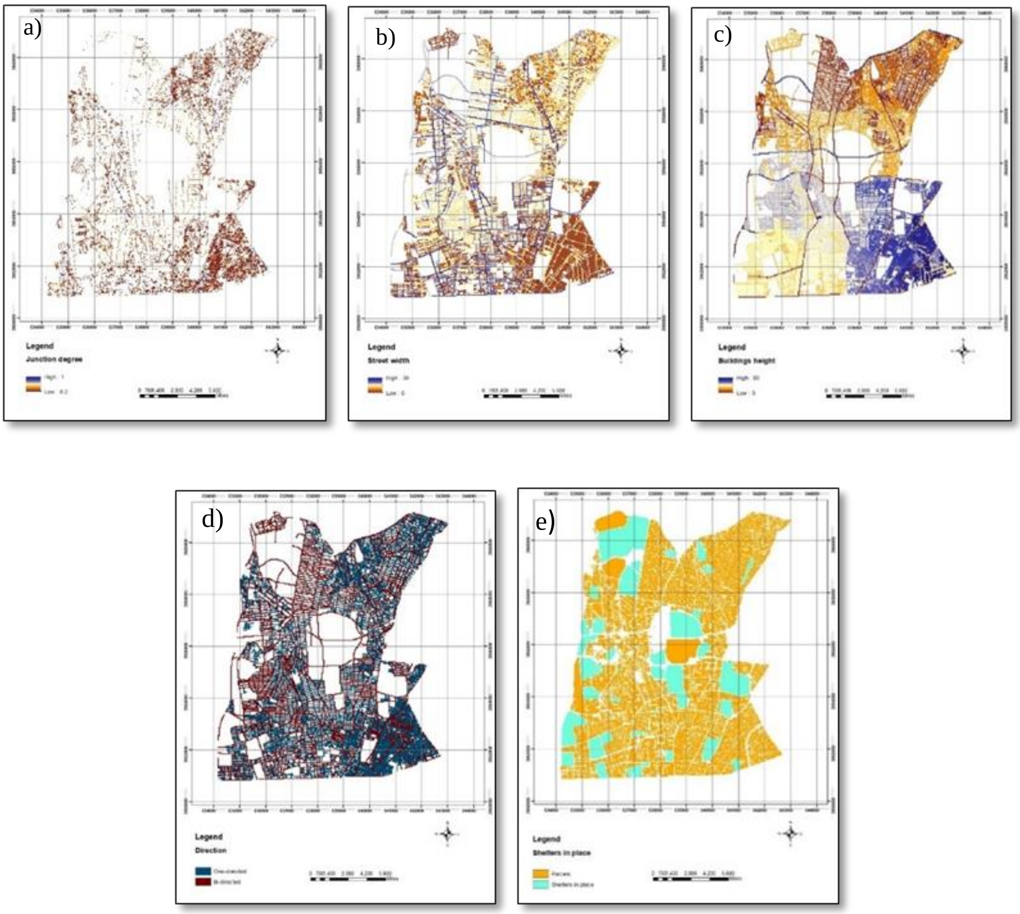

Figure 11. The normalized criteria maps: a) Junction degree, b) Street width, c) Building height, d) Direction, and e) Shelters in place

3.4. Running Weighted Overlay

The weighted overlay is used to integrate the criteria and produce a suitability map using Eq. (23) employing ArcGIS 10.5 via the ‘weighted overlay’ toolbox. Lastly, a suitability map of the morphological structure is achieved which is depicted in Figure 12. As seen, the north of districts 3, 6, and 7 are more suitable for rescue and relief operations and disaster response.

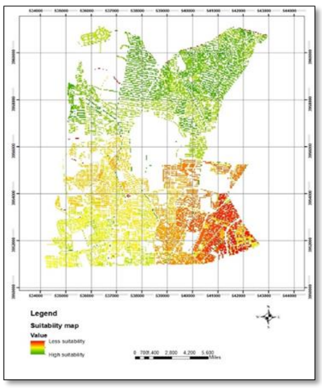

Figure 12. The suitability map of urban morphological structure

The achieved results showed that the most important factors are ‘street width’ and ‘height of buildings’, while the 'direction of the roads' is not as significant as the other criteria. Also, in the southern part of the study area, the suitability levels of earthquake response in less than the other regions especially rather than the northern part, which is mostly related to the structure of the roads and also the height of the buildings.

5. Conclusions

Operative earthquake response is one of the main tasks of urban disaster management in earthquake-prone countries. The efficiency of the process will be affected by the urban structure, especially in the heterogeneous arrangement of urban components. This paper purposes new spatial indices of urban morphologies which could be applied in earthquake response. The main contribution is the formulation of spatial indices and the employment of a GIS-based multi-criteria decision-making technique to derive the suitability levels of earthquake response. So, first, the involving spatial indices have been specified and formulated based on the expert knowledge and literature which have been considered as 'junction degree', 'street width', 'traffic network direction', 'height of buildings', and 'shelters in place'. Then suitability levels of areas to respond to earthquakes have been determined using the fuzzy-BWM. The proposed approach has been implemented in Districts 3, 6, and 7 of Tehran, the capital of Iran. The achieved results showed that the most important factors are 'street width' and 'height of buildings', while the 'direction of the roads' is not as significant as the other criteria. Also, in the southern part of the study area, the suitability levels of earthquake response in less than the other regions especially rather than the northern part, which is mostly related to the structure of the roads and also the height of the buildings.

As a continuous to this work, we intended to apply a fuzzy inference system to extract the effective rules in suitability levels of earthquake response. Also, the vulnerability maps of this area could be integrated into these spatial indices which could provide new strategies for disaster management.

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