GIS-Based Hierarchical Fuzzy MCDA Framework for Detecting Critical Urban Areas in Climate Scenarios

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Abstract. In this research we propose a GIS-based multicriteria framework that implements a hierarchical MCDA fuzzy model aimed at the detection of urban risk areas in climate hazard scenarios. The fuzzy-based multi-criteria approach adopted has the advantage of adapting to the hierarchical modeling of urban systems and of implementing the approximate reasoning adopted by decision makers. The criteria are defined in a hierarchical structure where the leaf nodes consist of fuzzy numbers; each node is assigned a weight, called coefficient of relative significance, which represents its relevance in the generation of the parent node in the upper level. The fuzzy set in the parent node is implemented through a fuzzy operator of intersection of the fuzzy sets of the child nodes.

The framework was tested on a study area including densely populated neighborhoods in the municipality of Naples (Italy), with the aim of determining which subzones of the study area were most at risk in scenarios of heat waves in the summer months. The results obtained are consistent with the results of the evaluations carried out by experts in the field.

Keywords: Fuzzy Hierarchical model · GIS-based MCDA · Climate risk scenarios

1 Introduction

Recently various Multi-criteria Decision Analysis (MCDA) techniques were combined in GIS-based platforms in urban planning [1, 2, 8, 9, 13], landscape assessment [5–7] and land use analysis [10–12]. In many urban planning and land use models criteria need to modelled following the approximate reasoning used by the expert; in that case, it is necessary to resort to the use of fuzzy sets to implement the multicriteria model. In [3] a fuzzy GIS-based MCDA model for land use analysis is proposed; the area of study is partitioned in land parcels and fuzzy sets are used to manage criteria. The major benefits of this model compared to a traditional MCDA GIS-based model are its usability and its adaptation to various problems. Its main criticality is the impossibility of implementing complex criteria, which require partitioning by levels up to the composition of subcriteria that refer to atomic characteristics of the urban area analyzed. To overcome this restriction, in [4].

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An extension of the model [3] is proposed in which a hierarchical structure of the criteria is constructed in which the leaf nodes represent the subcriteria referred to atomic urban characteristics. Each node in the hierarchy of criteria consists of a fuzzy set related to a criterion where the membership degree of an alternative to it represents how much how much the alternative meets the criterion. The user creates the fuzzy sets assigned to the leaf nodes; the fuzzy sets in the higher-level nodes are obtained starting from those in the child nodes.

In this research we test a GIS-based framework in which the fuzzy hierarchical model proposed in [4] is implemented in order to detect which sub-zones of the study urban area are more critical with respect to the population risk generated by heat wave scenarios. Following [4], each subzone of the study urban area constitutes an alternative. Four main criteria are taken into consideration, related to the density of residents, the presence of buildings in poor condition or old construction, the scarcity of urban green areas and the presence of waterproof open spaces. We have tested our framework on a study area consisting of the municipality of Naples, Italy; the subzones are made up of the individual districts into which the municipality is divided.

In the next section the hierarchical model [4] is briefly illustrated; the proposed framework is discussed in Sect. 2. Section 3 shows the results of the experimentation on the study urban area; final evaluation and future perspectives are described in Sect. 4.

2 Proposed Methodology

Figure 1 shows the flow chart which summarizes the structure of the proposed model.

Initially the area of study is partitioned in subzones taking into account the hierarchical model of criteria; then, the *Data extraction by subzone* component creates the *Subzones spatial dataset* extracting the characteristics of each subzone. The m subzones constitute the m alternatives for the hierarchical model.

In the next step the *Hierarchical Fuzzy subzone suitability assessment* (HFSSA) algorithm proposed in [4] is executed in order to assess the suitability of each subzone to the set of criteria.

Finally, the *Suitability thematic map* are created, where the spatial distribution of the suitability of the subzones to compliance with the criteria is shown. In addition, the Suitability thematic maps of the subzones to compliance each main criterion are performed.

In next subsection is detailed the HFSSA algorithm.

2.1 The Hierarchical Fuzzy Subzone Suitability Assessment Algorithm

Let the study area segmented in m subzones, representing the set $A = \{a_1, a_2,\ldots,a_m\}$ of alternatives. Aim of the HFSSA algorithm is to find the alternatives more suited to compliance with a set of n criteria $r_1, r_2,\ldots,r_n$, where the kth criterion r_k is expressed as a linguistic label of the fuzzy set:

$$R_k = \left\{\mu_{R_k}(a_1)/a_1, \ldots, \mu_{R_k}(a_i)/a_i, \ldots, \mu_{R_k}(a_m)/a_m\right\} \quad k = 1, 2, \ldots, n \tag{1}$$

with μ_{Rk}: A → [0,1] membership function.

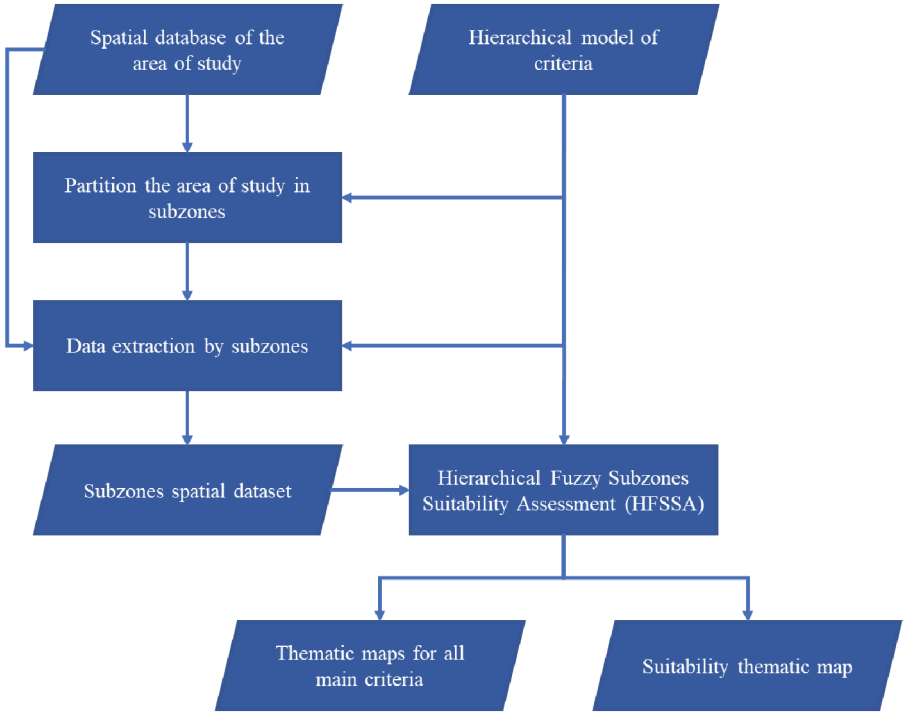


Fig. 1. Flow chart of the methodology

In [3] to the kth criterion is assigned a weight α_k called *Coefficient of Relative Significance* (for short, CRS), providing the relevance of the criterion in choosing the best alternative.

The coefficients of relative significance are assigned to each criterion by the decision maker, considering the constraint:

$$\frac{1}{n}\sum_{k=1}^{n}\alpha_k = 1 \tag{2}$$

The CRSs are obtained by using the Saaty's AHP pairwise comparison method in which is constructed the pairwise comparison nxn matrix B whose elements b_{kj}, k,j = 1,….,n, represent the relevance of the criterion r_k with respect to the criterion r_j. The diagonal elements b_{kk} are set to 1 and $b_{jk} = 1/b_{kj}$.

In Table 1 are shown the pairwise comparison matrix values.

The coefficients of relative significance α_1, α_2,… α_n are obtained resolving the characteristic equation: $\det(\mathbf{B}\text{-}\lambda\mathbf{I}) = 0$ where **I** is the identity matrix.

If w_k is the k-th component of the eigenvector **w**, the kth coefficient of relative significance is given by:

$$\alpha_k = n \cdot w_k \tag{3}$$

Table 1. Values of the Saaty's pairwise comparison matrix.

Relevance of r_k on r_j	b_{kj}	Relevance of r_k on r_j	b_{kj}
Equally important	1		
Equally or slightly more important	2	Equally or slightly less important	1/2
Slightly more important	3	Slightly less important	1/3
Slightly to much more important	4	Slightly to way less important	1/4
Much more important	5	Way less important	1/5
Much to far more important	6	Way to far less important	1/6
Far more important	7	Far less important	1/7
Far more important to extremely more important	8	Far less important to extremely less important	1/8
Extremely more important	9	Extremely less important	1/9

The best alternative is found creating the fuzzy set:

$$R = \bigcap_{k=1}^{n} R_k^{\alpha_k} \tag{4}$$

with membership function:

$$\mu_R(a_i) = \min_{k=1,..,n} \left(\mu_{R_k}^{\alpha_k}(a_i) \right) \tag{5}$$

The most suitable subzone is given by the alternative a^* that best meets all the criteria, i.e. such that is, that the membership degree μ_R (a^*) is maximum.

Moreover, a suitability thematic map of the subzones is constructed, by classifying them based on the membership values $\mu_R(a_i)$ i = 1,…,m.

In order to handle the criteria complexity, in [4] is proposed an extension of this method in which each criterion is decomposed in subcriteria, following a hierarchical structure.

Let $r_1^{(1)}$ $r_2^{(1)}$,…, $r_n^{(1)}$ be the n criteria, where the subscript in round brackets (1) denotes the level in the hierarchy.

The kth criterion $r_k^{(1)}$ is decomposed in n_k subcriteria $r_{k1}^{(2)}$ $r_{k2}^{(2)}$,…, $r_{knk}^{(2)}$.

The fuzzy set $R_k^{(1)}$ is constructed starting from the subsets assigned to the subcriteria $r_{k1}^{(2)}$ $r_{k2}^{(2)}$,…, $r_{knk}^{(2)}$. It is given by the formula:

$$R_k^{(1)} = \bigcap_{h=1}^{n_k} \left(R_{kh}^{(2)}\right)^{\alpha_h^{(2)}} \tag{6}$$

Applying the min t-norm operator, the membership degree of the ith alternative to R_k is given by

$$\mu_{R_k}(a_i) = \min_{h=1,..,n_k} \left\{ \mu_{R_h^{(2)}}^{\alpha_h^{(2)}}(a_i) \right\} \tag{7}$$

This process can be iterated partitioning the subcriteria in a set of subcriteria in next level.

If a node in the hierarchical structure is a leaf node, the fuzzy set of the corresponding subcriterion is assigned by the decision maker using triangular or trapezoidal fuzzy numbers. The fuzzy set is constructed on the domain of a specific numerical characteristic given by an index calculated from the spatial dataset of the area of study.

For example, let the area of study be a municipality partitioned in district and a subcriterion in a leaf node is given by the fuzzy set *High percent of elderly population*. This fuzzy set is constructed on a numerical domain given by the interval [0, 100] and the characteristics is obtained summing the data of the number of residents and the number of elderly people in the district and calculating the ratio between the number of elderly people and the number of residents, converting this results in percent.

The decision maker assigns the CRSs of the subcriteria in a level $l + 1$ in which is partitioned a criterion in the level l creating the corresponding Saaty's pairwise comparison matrix.

Starting from the subcriteria in the leaf nodes, it builds the fuzzy sets of the criteria in the upper level; after constructing the fuzzy sets of the criteria in level 1, the suitability of the ith subzone is given by

$$s(a_i) = \min_{h=1,..,n} \left\{ \mu_{R_h^{(1)}}^{\alpha_h^{(1)}}(a_i) \right\} \tag{8}$$

The most suitable subzone is given by the alternative a^* for which the suitability value is maximum.

In Algorithm 1 is schematized in pseudocode the HFSSA algorithm.

Algorithm 1. Hierarchical Fuzzy subzone suitability assessment (HFSSA)

```
Input:   Spatial dataset of the subzones
         Hierarchical model of criteria
         AHP comparison matrices among criteria
Output:  Spatial dataset updated with the suitability of
         each subzone to all main criteria and to the
         set of criteria
Set the m alternatives given by the m subzones
Set the n criteria r_1, r_2,…,r_k,…, r_n at the 0-level in the
hierarchy
Import the L-levels hierarchical model of the criteria
For l = L-1 to 1
   For each node R^(l)_k at the l^th level
    If R^(l)_k is a leaf node then
     Create as a fuzzy number the fuzzy set R^(l)_k in the
     domain of the corresponding characteristics
    Else
     Create the AHP pairwise comparison matrix of the
      fuzzy sets in the child nodes of R^(l)_k
     Compute the coefficients of relative
       significance of the child nodes of R^(l)_k
     Construct the fuzzy set R^(l)_k
    End if
   Next node
Next l
Construct the fuzzy set R given by (4) with membership
degree (5)
For i = 2 to m
   Compute the membership degree of the i^th alterna-
     tive to each main criterion μ_Rk(a_i) by (7)
   Compute the suitability s(a_i) by (8)
Next i
Return the updated spatial dataset
```

2.2 The Hierarchical Framework

We apply our model to evaluate which subzones of the study urban area are the most critical in the presence of heatwave scenarios.

The hierarchical structure of the criteria, composed by two levels, is shown in Fig. 2. In Fig. 2 are also shown the data need to calculate the characteristics of each subcriterion.

The hierarchical model is given by two levels; the expert creates the fuzzy sets related to the subcriteria in the second level. Each fuzzy set is constructed as a fuzzy number on

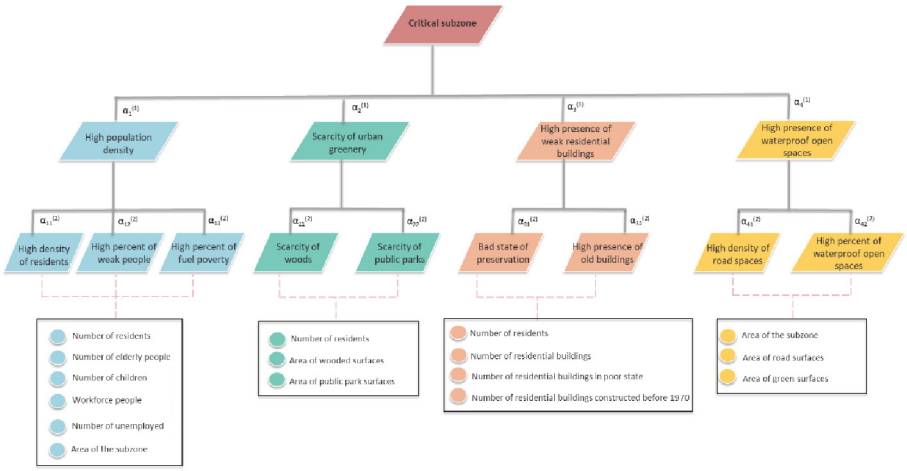


Fig. 2. Hierarchical structure of the criteria.

the domain of a characteristic. In the next paragraphs are detailed the four main criteria and their subcriteria; for each subcriterion is shown the corresponding fuzzy set.

High Population Density Criterion

The *High population density* criterion is partitioned in three subcriteria: *High density of residents*, *High percent of weak people* and *High percent of fuel poverty*.

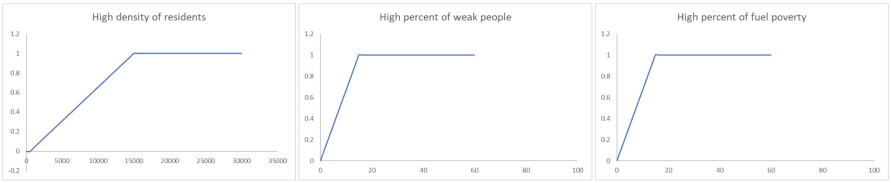
The *High density of residents* subcriterion evaluates the impact of the density of residents. The correspondent fuzzy set is constructed on the domain of a characteristic given by the density of inhabitants per square kilometer. The *High density of residents* fuzzy set is given by the L-function fuzzy number in Fig. 3a.

The *High percent of weak people* subcriterion evaluates the presence of high concentrations of weak people, where by weak people we mean the elderly and children, whose health is particularly exposed to risk. The correspondent fuzzy set is constructed on the domain [0, 100] of an index measuring the percent of weak residents with respect to the total number of residents. The number of weak residents is given by the number of elderly people over the age of 74 and children under the age of 5. The *High percent of weak people* fuzzy set is given by the L-function fuzzy number in Fig. 3b.

The *High percent of fuel poverty* subcriterion evaluates the presence of high concentrations of fuel poverty people, understood as a population with difficulty in accessing essential energy services due to their high costs. The correspondent fuzzy set is constructed on the domain [0, 100] of an index measuring the percentage of unemployed compared to workforce people, where the workforce people is given by the number of residents aged 15 and over in the total workforce. The *High percent of fuel poverty* fuzzy set is given by the L-function fuzzy number in Fig. 3c.

Scarcity of Urban Greenery Criterion

The *Scarcity of urban greenery* criterion is partitioned in two subcriteria: *Scarcity of woods* and *Scarcity of public parks*.

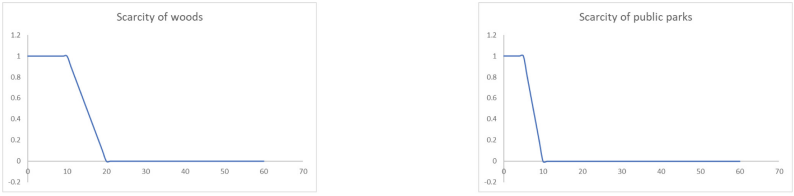


(3a) (3b) (3c)

Fig. 3. Fuzzy sets High density of residents (3a) High percent of weak people (3b) and High percent of fuel poverty (3c).

The *Scarcity of woods* subcriterion evaluates the scarcity of woods and cultivated green areas. The correspondent fuzzy set is constructed on the domain of a characteristic given by square meters of woods and cultivated areas per inhabitant. This fuzzy set is given by the R-function shown in Fig. 4a.

The *Scarcity of public parks* subcriterion evaluates the scarcity of urban green areas as parks, as public parks and gardens, flowerbeds, etc. The correspondent fuzzy set is constructed on the domain of a characteristic given by square meters of urban green areas per inhabitant. This fuzzy set is given by the R-function shown in Fig. 4b.



(4a) (4b)

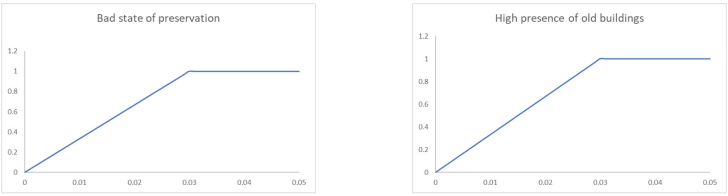
Fig. 4. Fuzzy sets *Scarcity of woods* (4a) and *Scarcity of public parks* (4b).

High Presence of Residential Buildings

The *High presence of residential buildings* criterion is partitioned in two subcriteria: *Bad state of preservation* and *High presence of old buildings.*

The *Bad state of preservation* sub-criterion evaluates the presence of buildings in bad state of conservation, without making any difference based on the construction period. The correspondent fuzzy set is constructed on the domain of a characteristic given by the percent of inhabitants living in bad state residential buildings. This fuzzy set is given by the R-function shown in Fig. 5a.

The *High presence of old buildings* sub-criterion evaluates the presence of buildings with ancient construction periods, regardless of their state of conservation. The correspondent fuzzy set is constructed on the domain of a characteristic given by the percent of inhabitants living in old residential buildings. This fuzzy set is given by the L-function shown in Fig. 5b.



(5a) (5b)

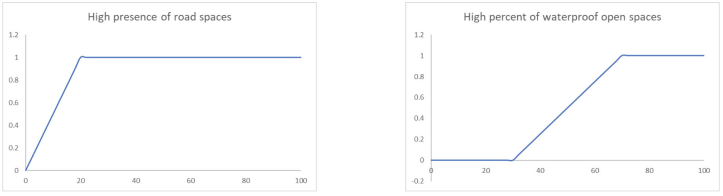
Fig. 5. Fuzzy sets Bad state of preservation (5a) and High presence of old buildings (5b).

High Presence of Waterproof Open Spaces

The *High presence of waterproof open spaces* criterion is partitioned in two subcriteria: *High density of road spaces* and *High percent of waterproof open spaces* (Fig. 6).

The *High density of road spaces* subcriterion evaluates the presence of road spaces in the subzone. The correspondent fuzzy set is constructed on the domain of a characteristic given by the percent of road areas with respect to the total area of the subzone. This fuzzy set is given by the L-function shown in Fig. 6a.

The *High percent of waterproof open spaces* subcriterion evaluates the percentage of waterproof open space surfaces with respect to the total open space surface in the subzone. The correspondent fuzzy set is constructed on the domain of a characteristic given by the percent of the ratio between the area covered by waterproof open spaces and the area covered by open spaces in the subzone. This fuzzy set is given by the L-function shown in Fig. 6b.



(6a) (6b)

Fig. 6. Fuzzy sets High density of road spaces (6a) and High percent of waterproof open spaces (6b).

We've implemented our model in a GIS platform, using the ESRI ArcGIS Desktop 10.8 Tool GIS suite. The algorithm was implemented by using Python libraries.

3 Test Results

We test our framework an area of study given by the districts of the municipality of Naples, Italy. The municipality of Naples is a densely populated city divided into 30 districts with different urban characteristics. The districts of the historic centre are characterized by the prevalence of historic and old buildings and by a scarcity of green areas. Outlying districts have undergone more recent urban development; moreover, in the

peripheral districts to the west of the city there is a greater presence of green wooded areas than in the districts of the eastern area.

The framework of the study urban area with the division into its districts is shown in the map in Fig. 7.



Fig. 7. The area of study: the municipality of Naples, Italy.

To test our framework, we have used the following data sources:

- Geo-Topographic data – scale 1: 5.000
- Census socio-demographic data – scale1: 10,000
- Partition of the municipality in districts – scale 1:2000.

All data were normalized in the planimetric coordinate system ETRS 1989 UTM Zone 33 Nord. Then, a set of spatial geoprocessing operator and spatial analysis functions are used in the GIS platform to summarize the data for district and to calculate the characteristics.

An expert urban planner was asked to assign values from Saaty's AHP pairwise comparison matrix for the criteria and corresponding subcriteria. In Table 2 are shown the four criteria and their subcriteria.

Table 3 shows the pairwise comparison matrix of the four criteria designed by the expert. It assigns a greater importance to the high population density than the scarce presence of green areas and the high presence of weak residential buildings and waterproof open spaces. The scarce presence of green areas is considered to be of greater importance than the high presence of weak residential buildings and waterproof open spaces. The high presence of weak residential buildings is considered to have a greater impact than the high presence of waterproof open spaces.

Table 4 shows the pairwise comparison matrices of subcriteria for the four criteria constructed by the expert.

Table 2. Criteria and their subcriteria in the hierarchical structure.

Criterion	Subcriterion
A High population density	
	A_1 High density of residents
	A_2 High percent of weak people
	A_3 High percent of fuel poverty
B Scarcity of urban greenery	
	B_1 Scarcity of woods
	B_2 Scarcity of public parks
C High presence of weak residential buildings	
	C_1 Bad state of preservation
	C_2 High presence of old buildings
D High presence of waterproof open spaces	
	D_1 High density of road spaces
	D_2 High percent of waterproof open spaces

Table 3. Pairwise comparison matrix of four criteria.

	A	B	C	D
A	1	3	4	5
B	1/3	1	2	3
C	1/4	1/2	1	2
D	1/5	1/3	1/2	1

Table 4. Pairwise comparison matrices of the subcriteria.

	A_1	A_2	A_3
A_1	1	1/5	1/4
A_2	5	1	2
A_3	4	1/2	1

	B1	B2
B_1	1	3
B_2	1/3	1

	C_1	C_2
C_1	1	4
C_2	1/4	1

	D1	D2
D1	1	1/2
D2	2	1

After constructed all pairwise comparison matrices, the hierarchical model is executed for each district. In Fig. 8 we show the thematic map obtained for the four criteria; to create each thematic map in those districts that belong to the fuzzy set connected to the criterion with a membership degree lower than or equal to 0.3 are labeled as “Low”; Medium Low those districts that belong to it with a membership degree between 0.3 and 0.6 and High those districts that belong to it with a membership degree greater than 0.6.

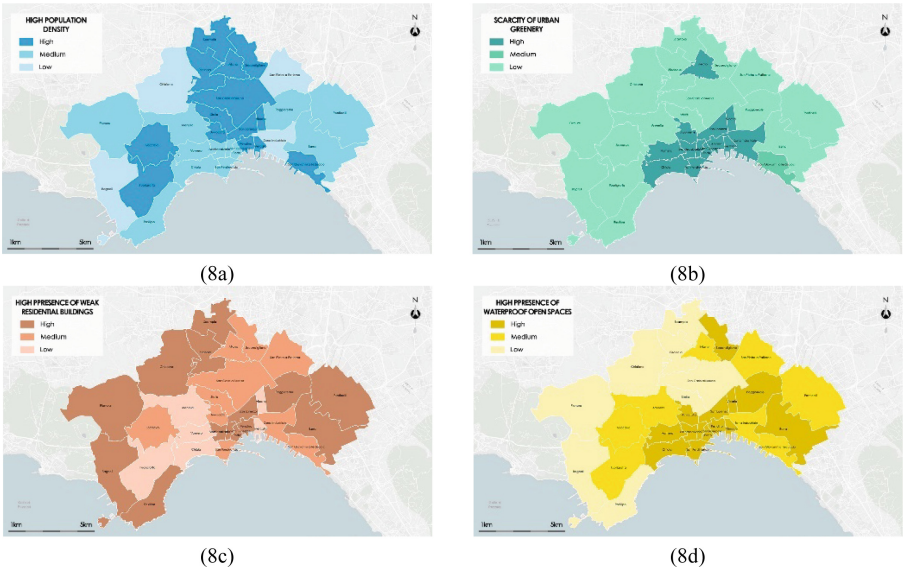


Fig. 8. Thematic maps of the four main criteria: High population density (8a), Scarcity of urban greenery (8b), High presence of weak residential buildings (8c), High presence of waterproof open spaces (8d).

Finally, we construct the suitability thematic map showing the critical subzone; the assessed suitability is partitioning into the three classes applied for the construction of the thematic maps of the main criteria. This map is shown in Fig. 9.

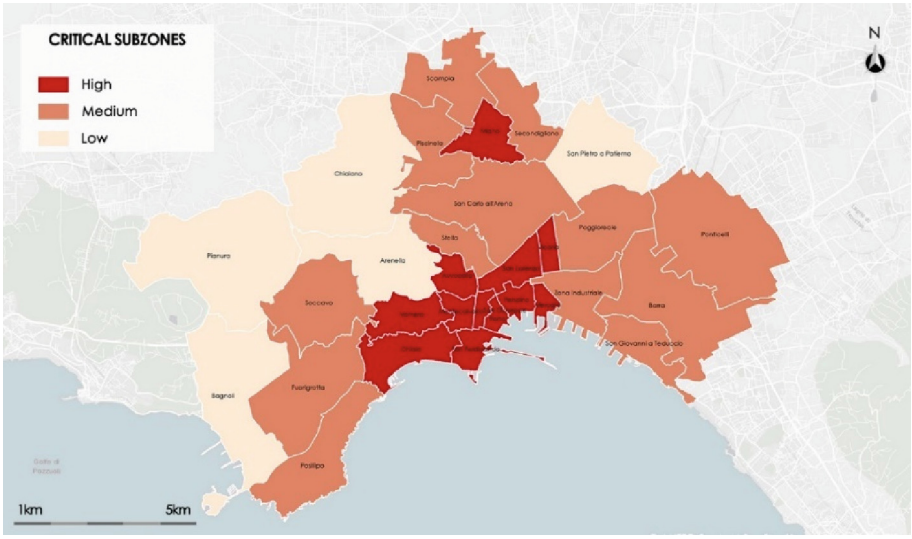


Fig. 9. Final suitability thematic map showing the critical subzones.

The suitability thematic map shows that the districts most at risk are, predominantly, the districts of the city center; they are the most populated, devoid of vegetation, with a high quantity of old or poorly-constructed residential buildings and mainly covered by waterproof open spaces. These results agree with the deductions made by the expert.

4 Conclusions

In this research we tested a GIS-based framework that implements the hierarchical MCDA fuzzy model [4] to detect which districts of the municipality of Naples are more critical with respect to the presence of heatwave scenarios.

The usefulness and adaptability of this approach to different issues are its key benefits over a traditional MCDA GIS-based model. It is feasible to get beyond the limitation of implementing complicated criteria, typical of other classic MCDA models, by building a hierarchical structure of criteria in which the sub-criteria correspond to atomic urban features. In this manner, the degree to which an alternative belongs to a fuzzy set relative to a criterion allows one to quantify the measure to which the alternative satisfies the requirement.

The critical subzone resulting thematic map highlights that the most critical subzones are those that cover the city center; this result is in line with the deductions of the expert.

The benefit introduced by the research consists of providing a MCDA tool with high usability and adaptability to model different urban problems involving complex criteria. IN fact, the criteria can be partitioned in a hierarchical fashion and the suitability of a subzone to meets the criteria is assessed starting using a fuzzy-based approach near to the approximate reasoning of the decision maker.

The limitation of the approach consists of not being able to obtain a more detailed analysis on a smaller scale since the data used are processed on a subzone scale. To carry out an analysis at a detailed scale, the input data summarized by subzone need to be substituted with data processed at a local scale.

In the future we intend to test our framework on different urban planning issues, increasing the complexity of the criteria and the number of levels of the hierarchical structure.

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