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A GIS-based Fuzzy Multi-Criteria Analysis Approach to Industrial Site Selection

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Abstract. The paper proposes a methodology for fuzzy multi-criteria analysis of decisions in a raster-based geographical information system (GIS) to determine the optimal locations for territorial objects. Recommendations about the stages of choosing alternatives for spatial and non-spatial constraints are given. It is shown that the fuzzyfication of criteria, that is, the conversion of their attribute values into a fuzzy set, based on expert evaluation of a fuzzy membership function, allows screening alternatives by determining thresholds of alpha-cut of fuzzy sets for each criterion, followed by combining criteria attributes using aggregation operators: minimum, maximum, weighted sum, OWA operator Jager. Adding to the procedure of multicriteria analysis of the additional stage of filtration of alternatives gives the opportunity to reduce the number of alternatives, and in the future and the processing time of the criteria layers by aggregator operators. The proposed algorithm for screening alternatives can be performed in a GIS environment using Fuzzy Membership, Overlay and raster calculators tools.

Key words: geographic information systems; multiple-criteria decision analysis; fuzzy set theory; alpha-cut; site selection.

INTRODUCTION

Spatial problems, in particular the problem of industrial site selection, according to their nature, are always multi-criteria [1] and require taking into consideration of the number of economic, ecological, social and other factors, which allow to assess the suitability of the territory.

To solve the facility location problem, various combinatorial methods, methods using network models, numerical methods, simulation modeling, etc. are often used [2, 3]. The presence of spatial factors determines the use of methods based on GIS technologies. GIS capabilities for generating alternatives and choosing the best solution are usually based on surface analysis, proximity analysis, and overlay analysis.

The disadvantages of most of the aforementioned methods are the requirement for crisp information, but in practice the problems of industrial site selection are poorly structured [4], that is, those requiring the use of unformalized (fuzzy) knowledge based on expert experience. Therefore, algorithms for solving the industrial location problem using fuzzy information on the basis of GIS technologies represent practical and theoretical interest. A promising approach that allows the most adequate description of this process is the mathematical apparatus of the theory of fuzzy sets [5].

THE PROPOSED FUZZY MULTI-CRITERIA ANALYSIS APPROACH IN GIS

For the last several decades, GIS has been used in conjunction with other systems and methods, such as Decision Support Systems (DSS) and Multicriteria Decision Analysis (MCDA) [6, 7]. The combination of GIS and MCDA tools gives a synergistic effect and helps to increase the efficiency and quality of spatial analysis when selecting the optimal location of objects. At an elementary level, the combination of GIS-MCDA can be considered as a process that converts and combines geographic data and assessment judgments, that is, the benefits of the decision maker (DM) to obtain information for decision-making.

Let us consider a formal description of the procedure for multi-criteria decision analysis in a geographic context. Selection of suitable places is carried out by spatial analysis using GIS, based on criteria that take into account various factors of influence: nature protection requirements, features of terrain, landscape morphology, socio-economic factors, etc. To do this, perform the procedure of decomposing a set of objects that belong to the investigated territory and affect the decision making, after which a map K is received, which is a set of thematic layers of criteria K_i [8]:

$$K = \{K_i\}, \quad i = \overline{1,n}. \tag{1}$$

Schematically, the process of decomposition of the set of objects O on thematic layers of criteria is shown in Fig. 1.

For spatial modeling in order to select a suitable spatial object location, we will use a raster data model. Therefore, all the received thematic layers of objects should be presented as a set of cells (pixels) in a raster model of GIS, which has the form of a two-dimensional discrete rectangular grid with $m_x \times m_y$ cells, where $\Delta x = \Delta y = \Delta r$ – cell sizes.

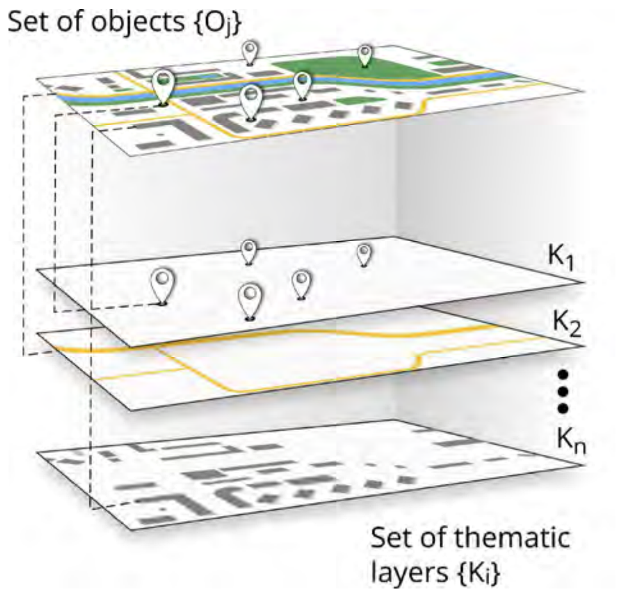

Fig. 1. Scheme of decomposition of objects in thematic layers

Each cell is an alternative, which is described by its spatial data (geographic coordinates) and attributive data (criteria values). We will write the set of alternatives A, which are evaluated according to the criteria C_j:

$$A = \{a_{ij} \mid i = \overline{1,m}, \quad j = \overline{1,n}\}, \tag{2}$$

It is important to choose such a procedure for rasterize vector layer criteria, which will get a set of cells whose attributes bear the content information about the value of the function of the effect of the objects of the layer. For example, attributes can be derived from vector maps that contain point objects of observation points by the value of some factor using different methods of interpolation. Often, to obtain spatial relationships between objects, different distance metrics are used: Euclidean, Manhattan, Chebyshev metrics, etc.

DM's preferences to evaluation the criterion are determined by assigning the weight of the criteria w_j, where j = 1, 2,..., n. We will assume that the DM's preferences are spatially homogeneous, that is, each criterion C_k is assigned one weight w_k. Thus, the matrix of decision-making will have the form shown in Table 1.

To select suitable sites locations of objects, it is advisable to apply a procedure consisting of two phases: macroanalysis (site screening) and microanalysis (site evaluation) [9]. The two-step selection approach suggests that for those alternatives that were tested in the first stage for compliance with minimum requirements, in the second stage a more detailed analysis by the MCDA methods is carried out. Preliminary screening of alternatives can be made taking into account restrictions: for attribute values (non-spatial constraints) or for location (spatial constraints). Constraints may be represented by raster layers in which attributes of cells with ineligible alternatives have a value of 0, and with acceptable alternatives – value 1. Using the constraint layer as a conjunctive filter, one can determine the set of possible alternatives.

Table 1. Matrix of decision making

Alternatives	Spatial coordinates		Criteria/attributes C_j			
A_i	X_i	Y_i	C_1	C_2	…	C_n
A_1	x_1	y_1	a_{11}	a_{12}	…	a_{1n}
A_2	x_2	y_2	a_{21}	a_{22}	…	a_{2n}
A_3	x_3	y_3	a_{31}	a_{32}	…	a_{3n}
…	…	…	…	…	…	…
A_m	x_m	y_m	a_{m1}	a_{m2}	…	a_{mn}
Weight, w_j			w_1	w_2	…	w_n

The general diagram of the GIS-MCDA site selection process is shown in Fig. 1.

Criterion layers generally has different ranges or scale values of attributes, so they require the transformation to comparable units. In addition, the criteria can be not only quantitative but also qualitative. Procedures for transforming raw data to comparable units are called scaling methods or standardization. The standardization procedure allows you to scale the attributes in the scale [0, 1].The approach to scaling attributes based on fuzzy logic methods is based on the transformation of the values of the j-th layer attributes in the degree of membership to the fuzzy set $B_j \subseteq A$:

$$B_j = \{(a, \mu_b{}^j(a)) \mid a \in A\}, \ \mu_b{}^j(a): a \to [0,1], \tag{3}$$

where a is an attribute value, A is an attributes values set.

Membership function $\mu_b(a)$ specifies the degree of membership of the attribute a to the fuzzy set B_j. The bigger the value $\mu_b(a)$, to a greater extent the attribute corresponds to the properties of the fuzzy set. As a rule, membership function is built with the participation of an expert or a group of experts.

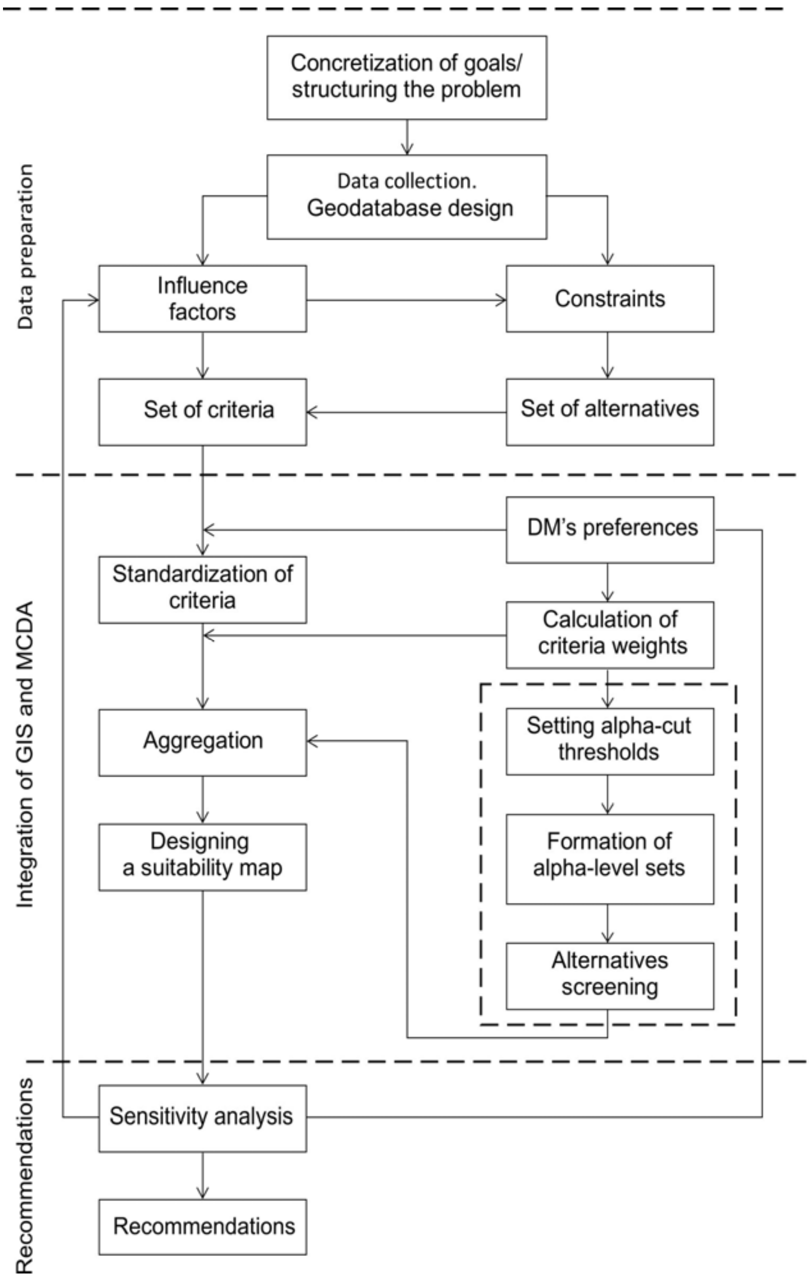

Fig. 2. Diagram of the proposed MCDA site selection process in GIS

After standardizing attributes of criteria, DM can perform an additional filtering (screening) alternatives, applying non-spatial constraints to attribute values. The following method is proposed for this purpose. Expert evaluations of alternatives according to the criteria are presented as fuzzy sets expressed by membership functions:

$$\tilde{C}_j = \{\mu_j(a_i)/a_i\}, \quad \mu_j(a_i) \in [0,1], \quad j = \overline{1,n}. \qquad (4)$$

Next, we will perform a ranking of criteria C_j by importance and number them in the order of decreasing the weight of the criteria w_j. To calculate the criteria weight, the analytic hierarchy process (AHP) [10]. In [11], his modified fuzzy version FAHP was proposed.

Let us set a threshold $\alpha_j \in (0,1]$ and α-cut of the membership function $\mu_j(a)$ of the following type:

$$A_j = \{a \mid a \in A_{j-1}, \mu_j(a) \geq \alpha_j\}, \; A_0 \equiv A, \; j \leq n. \qquad (5)$$

An α-cut threshold for fuzzy set A defines a minimum truth membership level for a fuzzy set. All membership values below the α-cut are considered equivalent to zero. Fig. 3 shows the example of the α-cut threshold applied to fuzzy set.

The calculation is repeated until the last iteration of the set An contain only alternatives that are considered by experts. DM can change the set An by varying the weights of the criteria w_j or thresholds α_j.

If the criteria are equivalent by importance, then for each criterion C_j, separate sets of α-levels A_j are calculated at given thresholds α_j, and then the set is built of the following type:

$$A^* = \bigcap_{j=1}^{n} A_j. \qquad (6)$$

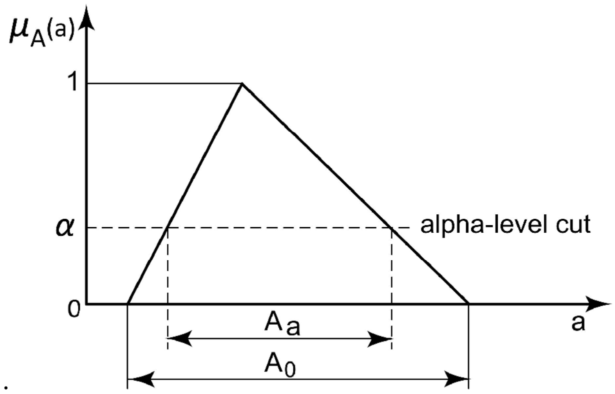

Fig. 3. Alpha-cut threshold applied to fuzzy set

For the set of alternatives A*, a convolution of the criteria is performed. To do this, the GIS environment usually uses various aggregation operators: minimum, maximum, average, weighed sum, OWA operator [12].

One of the simplest compensative aggregation operators implemented in the GIS is the weighted sum [13]:

$$\mu(a_i^*) = \sum_{j=1}^{n} w_j \mu_j(a_i). \quad (7)$$

An example of using the proposed algorithm for screening alternatives for the three layers of criteria $C=\{C_1,C_2,C_3\}$ is presented in Fig. 4.

RESULTS OF THE EXPERIMENTAL STUDY

To illustrate the proposed algorithm for screening alternatives for fuzzy sets of α-level, we use the data of the multicriterial decision-making model on the location of solid waste (SW) landfills site in the south of the Odessa region proposed by the authors in [5]. The model takes into account construction norms, physical, environmental and socio-economic factors for the location of solid waste landfill site. One of the sites found is located in Izmail Raion in southeast from Suvorovo village (45.5692N, 29.0088E).

Let us consider the implementation of the algorithm for the three criteria of the model: C_1 – Distance from road and rail (w_1=0.5); C_2 – Distance from the city limits (w_2=0.3); C_3 – Distance from residential and public building (w_3=0.2). The attributes of the criteria are standardized by an expert assessment of their fuzzy membership functions. As an aggregation operator, we use the weighted sum (7).

In Fig. 5, alternative models of suitability for the placement of a SW landfill for different threshold values are given (α_1, α_2, α_3).

Characteristics of the implementation of models in the GIS environment are presented in Table II.

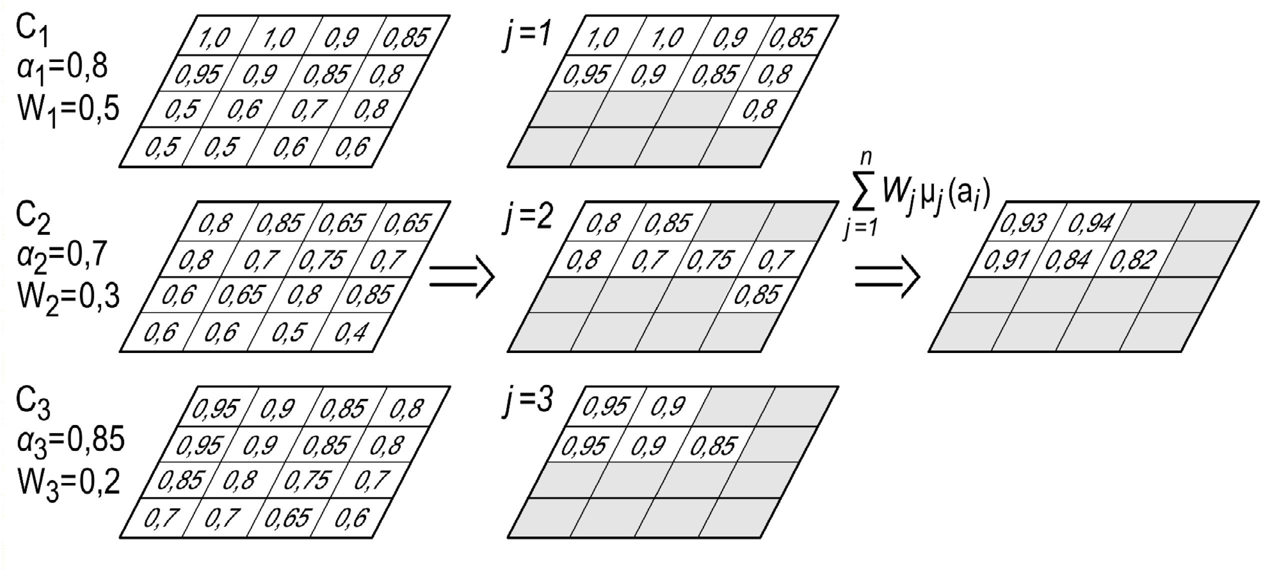

Fig. 4. An example of implementing an algorithm for screening alternatives for three criteria

Table 2. Characteristics of implementation of models in gis

The values of the thresholds α-cuts (α_1, α_2, α_3)	Number of alternatives (raster cells with value)	Time to perform a weighted sum operator
(0, 0, 0)	6900583	4 870 ms
(0.2, 0.35, 0.3)	4084035	4 800 ms
(0.3, 0.5, 0.45)	3540798	4 760 ms
(0.8, 0.85, 0.9)	1079139	4 580 ms

Combined maps of suitability for placement of a landfill of solid waste, shown in Fig. 5, are constructed for four different set of thresholds α-cut of fuzzy sets of criteria. The higher the threshold value, the less the number of alternatives remains for further analysis and the faster the weighted sum operator performs (the operator's execution time is calculated for the ArcGIS 10.5 environment and computer system containing OS Windows 10, Intel Core i3-7100 Kabylake, RAM 8Gb).

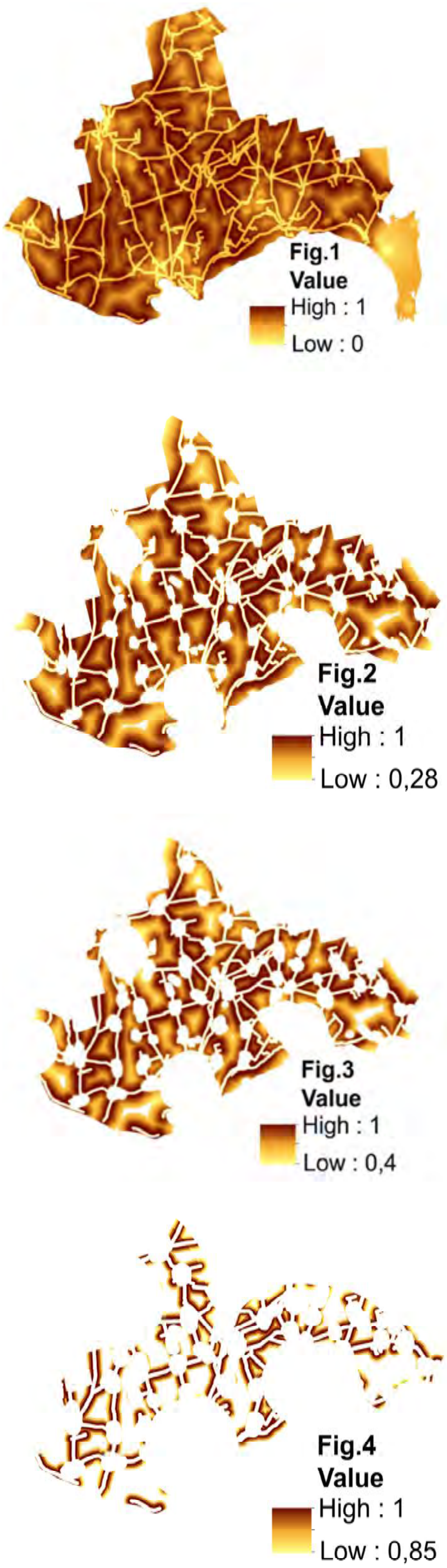

Fig. 5. Combined suitability maps for the placement of a solid waste landfill for different values of α-thresholds of fuzzy sets

CONCLUSIONS

Using in multi-criteria analysis of a raster data model allows you to display continuous surfaces, analyze them and perform overlays using complex data sets. In the study of large areas, the sets of raster data can be large enough, which leads to a significant increase in data volumes and a decrease in the processing speed. Adding to the procedure of multicriteria analysis of the additional stage of filtering alternatives, by specifying on the basis of the advantages of the DM thresholds of the level α_j by which the fuzzy set of α-levels is constructed in accordance with (5), enables to reduce the number of alternatives, and in the subsequent and the processing time of the criteria layers by the aggregator operators. The proposed algorithm for screening alternatives can be performed in a GIS environment using Fuzzy Membership, Overlay and Raster calculators tools.

Alpha cuts play a crucial role in many fuzzy models by removing unnecessary noise and specifying a degree of confidence necessary in the model to effect a correct outcome. Thresholds must be used with care, however, in that very high alpha cuts (higher than the crossover point) can have serious deleterious effects on a model's performance.

The application of the apparatus of the theory of fuzzy sets and methods of decision-making allows to take into account expert knowledge and judgments, as well as to obtain a more informative map of suitability by determining the rank of suitability of alternatives.

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