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GIS-based Fuzzy Method for Urban Planning

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Abstract

Method for multiple assessments of land parcels on the base of fuzzy set theory integrated into geographic information systems (GIS) is developed. Numerical experiments for the application of the method in urban planning are carried out. Multiple assessments of land parcels in St.Petertsburg (Russia) suburbs is calculated and mapped. Complex evaluations of land parcels have been carried out by fuzzy model with the use of four criteria (technological, economical, ecological and social) for two special tasks: 1) ecological criterion is more important and 2) economical criterion is more significant. The results show the opportunity of the land parcels ranging for decision making support.

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Keywords: Urban planning; geoinformation systems; fuzzy set theory; multiple land parcels assessment

1. Introduction

There is a global trend of urban population growth. As a result, the spatial patterns of urban areas, by means of their limits and borders, are changing in a complex way [1]. The decision-making process for urban land use allocation has always been complicated. Cities that use arbitrary and less developed land use planning instruments face a particular developmental challenge [2]. Because of consistent changes in their structure and shape, urban areas are continuously at the epicenter of a wider scientific interest as the problems arising are complex and exceed the pure urban aspect. During the last decade a large number of spatial decision support systems have been developed to assist decision makers in the field of urban planning and other spatial planning issues [3].

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When alternatives or objectives are spatial, data are needed on the geographical locations of alternatives, spatial formulations of objectives and data on the spatial pattern of criterion values [4]. This requires a combination of multicriteria methods with a geographical information system (GIS) [5, 6]. Land-use planning may be defined as the process of allocating different activities or uses (such as residential areas, manufacturing industries, recreational activities) to specific units of area within a region [7]. As one of the core research aspect in urban planning, the optimal allocation of land use is soon becoming the key measure for sustainable land utilization [8]. It is impossible for an allocation to achieve a maximum benefit with respect to each land-use goal simultaneously [9].

Common used urban planning models can be classified to four types: mathematic quantitative optimization model, spatial optimization model, agent-based model and economic model. But they have some shortcomings, for example they cannot reflect the uncertainties in the land-use system [10]. In real world, there are many uncertainties existing in land-use system. An effective method to describe this type of uncertainty is fuzzy sets theory, which can use membership function to model the uncertainty. In addition, the quality or suitability of land may also be expressed as membership function [11, 12]. Therefore, modeling and simulation of complex dynamic systems such as urban areas could greatly benefit from the synergy of the methods and techniques of geographical information science with artificial intelligence techniques such as fuzzy logic [13].

Also in previous models many important ecological factors are not comprehensively considered, on the contrary economic benefits and political factors are always the main concern [14]. Therefore, various scenarios of violating ecological constraints and the trade-off between economic development and environmental protection must be discussed [15].

Urban planning with spatial multicriteria analysis typically starts with a set of land-use alternatives (land parcels) that is defined beforehand. This set of alternatives can be defined using the inputs from experts such as spatial planners or landscape architects [5] and land-use models [16]. This step usually includes screening procedures for selection from a large set of alternatives, a small subset of feasible alternatives to be further examined. The procedures are typically operationalized in GIS by means of exclusionary screening methods [17]. The procedures involve selection of the factors (evaluation criteria or attributes) which are important (e.g. topography, soils, water, vegetation, geology, transportation network, population distribution, etc.) using different approaches and models [18-20]. As a result it can be claimed that urban planning during site selection for city growing must have two phases: site screening and site selection. In this paper we are focused on the second phase.

Critical review of above mentioned scientific paper and other publication allows making some conclusions. Modern urban planning process involves many computer technologies including GIS and multicriteria analysis models. Many factors (criteria), which are usually taking into account during decision making, most of them are spatial. In can be summarized, that this hierarchical structure of the criteria has on his top level the following criteria: economical, ecological, social and technological. Mentioned criteria usually have been created by different specialist and sometimes have linguistic form presented by fuzzy membership functions [11]. It is a big problem is to create a complex assessment based on these 4 criteria. In this paper the fuzzy multicriteria analysis method for urban planning have been presented. This method is integrated with GIS and creates suitability maps to indicate grade to how land parcels analyzed meet decision making conditions.

2. Methodological base

Methodological basis of multiple assessments of landscape parcels is the section of fuzzy set theory devoted to multicriteria assessment and choice of alternatives [11, 21]. Let's A is a set of m land parcels under consideration:

$$A = \{a_1,\ a_2,\ \dots,\ a_m\} \tag{1}$$

A is a set of alternatives for decision making. Then for some particular criterion r can be considered fuzzy set:

$$R = \{\mu_r(a_1)/a_1, \mu_r(a_2)/a_2, \dots, \mu_r(a_i)/a_i\}, \quad \mu_r(a_i)/a_i \in [0,1] \tag{2}$$

where membership function $\mu_r(a_i)$ is evaluation for a_i under criterion r. Thus, we can determine how the alternative a_i meets the criterion r. If $\mu_r(a_i)=1$, then a_i is fully satisfied to criterion r, if $\mu_r(a_i)=0$, then alternative a_i did not meet the criterion r.

If we consider n criteria r_1, r_2, ..., r_n, the best alternative a_i must meets criterion r_1, and criterion r_2, and so on, and criterion r_n. Therefore, a rule for choosing the best a_i (in the conditions when the criteria are of equal importance) should be written as the intersection of the corresponding fuzzy sets:

$$X = R_1 \cap R_2 \cap \cdots \cap R_n \quad (3)$$

As the best alternative we must select element a^* from (1), which has the highest value of the membership function in the set X:

$$\mu_X(a^*) = \max_{j=1,m} \mu_X(a_j) \quad (4)$$

If criteria r_i have different importance (different weights), each of them is attributed with the coefficients of relative significance of these criteria $\alpha_1, \alpha_2, \dots, \alpha_n$ (the most important criteria have the largest α_i). In this case the rule should take the form:

$$X = R_1^{\alpha_1} \cap R_2^{\alpha_2} \cap \ldots \cap R_n^{\alpha_n}\,; \alpha_i > 0, i = 1, n; \frac{1}{n} \sum_{i=1}^{n} \alpha_i = 1 \quad (5)$$

Coefficients of relative significance α_i are found on the base of the Saaty's pairwise comparison method for deriving the criterion weights [22, 23]. In the beginning it is initially formed pairwise comparison matrix B. Elements of the matrix b_{ij} are defined in Table 1 and must meet the following conditions: $b_{ii} = 1$, $b_{ij} = 1 / b_{ji}$. At the same time b_{ij} can range from 1/9 to 9.

Table 1. Scale of evaluation of relative importance of criteria.

Relative importance of criteria C_i and C_j	Element b_{ij}
Equilibrium And an entry	1
Very of little importance	3
Of little importance	5
Importance	7
Great importance	9
Intermediate value	2, 4, 6, 8

After formation of matrix B for example on the base of expert opinions it is determined an eigenvector w of the matrix corresponding to the maximum eigenvalue of the matrix B ($Bw = \lambda_{max} w$). The solution for the desired values of the coefficients α_i are obtained by $\alpha_i = n\, w_i$ to meet the conditions (5), where n is the number of the criteria and w_i is the i-component of the eigenvector w of the matrix B.

3. Case study

Analysis of the real estate market of St. Petersburg is shown that the city cans effectively growth only on agricultural land in suburbs [24-26]. Various environmental and socio-economic conditions may lead to conflicts among stakeholders, local authorities, strategies and policies that simple traditional land management methods may not be effective for sound land-use planning. In the region under consideration all agricultural land has drainage systems, which cannot be divided. Therefore, it has been analyzed the land parcels with drainage systems in the nearest suburbs of St. Petersburg as a unit for urban planning. In the GIS database, it has been created a layer for these parcels with the attribute information about the results of the last land inventory. According to the proposed methodology of multi-criteria assessment, the parcels were considered as alternatives for the urban development.

For each of the parcels the membership function for sets "Land suitable for development of St. Petersburg" has been calculated. In the case when this function takes a value of 1, a parcel is definitely suitable for urban development, if this function takes a value of 0, then this parcels is not to be used for the development of the city. During the multicriteria calculation we used the following criteria represented by the membership functions in sets:

- set of parcels suitable for the development of the city from an environmental point of view (ecological factor - ECC);
- set of parcels suitable for the development of the city from an economic point of view (economic factor - EC);
- set of parcels suitable for the development of the city from a technological point of view (technological factor - TC);
- set of parcels suitable for the development of the city from the point of view of society (the human reaction) and the local people (social factor - SC).

These particular factors also take the value 1, if a parcel is in fully concordance with the relevant conditions and 0 if the contrary. Methods for calculating the values of these particular factors investigated in detail in the literature mentioned in introduction. Here we consider only the problem of forming a complex multicriteria evaluation on the basis of these particular factors.

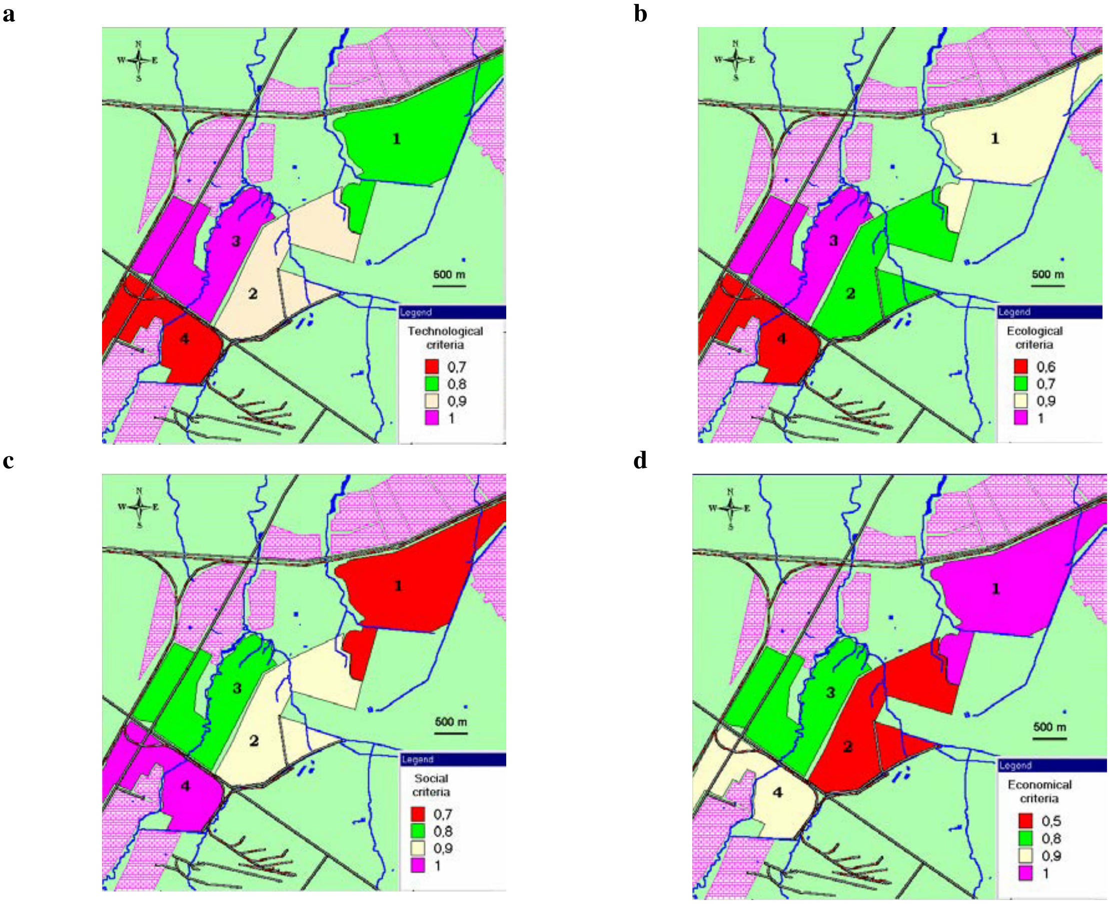


Fig. 1. Thematic maps with technological (a), ecological (b), social (c), and economical (d) factors.

GIS database has been modified by adding the appropriate fields in an attribute tables for the parcels, which were edited by responsible peoples from local authorities. The values for the ecological, economic, technological and social factors on each parcels shows by corresponding thematic maps on Fig. 1. For responsible decision maker we have been developed a tool for creation a multicriteria estimation according (4) – (5). Here it has been presented definition of the relative importance of criteria for two special tasks:

- ecological criterion is more significant (task #1);
- economical criterion more significant (task #2).

In Table 2 the results of pairwise comparison (matrix B1 and B2) for these two tasks has been presented. The values for matrix should takes from Table 1.

Table 2. The results on pairwise comparison.

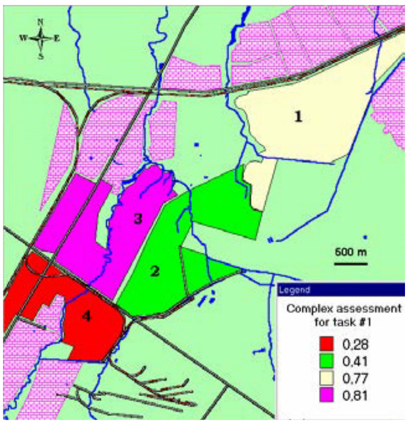
task #1	ECC	EC	TC	SC		task #2	EC	ECC	SC	TC
ECC	1	5	6	7		EC	1	4	6	7
EC	1/5	1	4	6		ECC	1/4	1	3	6
TC	1/6	1/4	1	4		SC	1/6	1/3	1	2
SC	1/7	1/6	1/4	1		TC	1/7	1/4	1/2	1

It can be calculated that for matrix of pairwise comparison B_1 for task #1 - $\lambda_{max} = 4.390$ and the components for corresponding eigenvector are following: $w_1 = 0,619; w_2 = 0,235; w_3 = 0,101; w_4 = 0,045$. The coefficients of relative significance: $\alpha_{ECC} = 2.48; \alpha_{EC} = 0.94; \alpha_{TC} = 0.4; \alpha_{SC} = 0.18$.

It can be calculated that for matrix of pairwise comparison B_2 for task #2 - $\lambda_{max} = 4.3102$ and the components for corresponding eigenvector are following: $w_1 = 0,617; w_2 = 0,224; w_3 = 0,097; w_4 = 0,062$ $(\alpha_{ECC} = 2.47; \alpha_{EC} = 0.896; \alpha_{TC} = 0.388; \alpha_{SC} = 0.248)$.

Multiple assessments of the parcels for urban development was carried out for two cases: ecological factor is more important (the first case), and economical factor is more significant (second case). These indices are calculated and mapped in MapInfo® environment. Result obtained is presented on Fig. 2. It is easy to see that the sequence of parcels suitability for urban development are different: task #1 – parcel #3 is more suitable and then #1, #2, #4; task #2 – parcel #1 is more suitable and then #4, #3, #2.

a



b

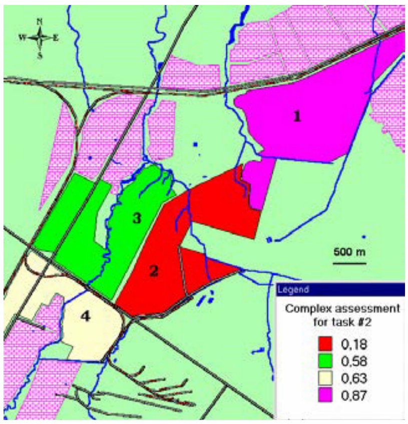


Fig. 2. Thematic maps during analysis of land parcels for task #1 (a) and task#2 (b).

(1)

4. Summary

The methodology of multiple assessments of landscape parcels based on use of GIS and fuzzy set theory have been designed. Numerical experiments for the study of the methodology are carried out. It is an appropriate method to support land suitability assessment, as demonstrated by example of practical implementation in the Saint-Petersburg suburbs.

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