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MODEL OF THE PROCESS OF GEOSPATIAL MULTI-CRITERIA DECISION ANALYSIS FOR TERRITORIAL PLANNING

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ABSTRACT

Context. The process of multi-criteria decision analysis for territorial planning and rational placement of spatial objects, based on modeling the properties of the territory, is considered.

Objective. Development of technology for multi-criteria decision analysis for territorial planning based on the apparatus of the theory of fuzzy sets and functions of geoinformation analysis.

Method. An object-spatial approach to the formation of a set of alternatives and criteria is proposed, according to which the process of multicriteria decision analysis is divided into two stages: macro- and microanalysis.The macroanalysis stage involves the assessment of the ecological and socio-economic properties of the territory using geomodeling functions. The paper provides a formalized description of the macroanalysis stage, including methods for assessing the qualitative and quantitative impact of spatial objects on the properties of the territory and decomposing objects into thematic layers of criteria. At the stage of microanalysis, the ranking of alternatives is performed taking into account the chosen decision-making strategy. The method of standardization of criteria attributes using fuzzy set membership functions and the modification of the method for calculating the coefficients of relative importance (weights) of criteria, taking into account the spatial heterogeneity of the preferences of the decision maker, are considered. A comparative analysis of the methods for aggregating the estimates of alternatives according to different criteria has been carried out. A feature of the presented technology of geospatial multi-criteria decision analysis of decisions for territorial planning is the possibility of its integration into modern geographic information systems.

Results. The procedure of geospatial multi-criteria decision analysis was implemented in the environment of the geographic information system ESRI ArcGIS 10.5 and was studied in solving the spatial problem of rational location of an enterprise.

Conclusions. The proposed object-spatial approach to multi-criteria decision analysis makes it possible to explicitly take into account the spatial heterogeneity of geographic data, which is the result of the influence of geographic objects on the properties of the territory. The developed technology can be used to solve a wide range of problems related to determining the most rational placement of various capital construction and infrastructure facilities.

KEYWORDS: geographic information systems, spatial modeling, multicriteria decision analysis, fuzzy sets.

ABBREVIATIONS

AHP is an analytic hierarchy process;
DEM is a digital elevation model;
DM is a decision maker;
DSS is a decision support system;
FAHP is a fuzzy analytic hierarchy process;
GIS is a geographic information system;
LMCA is a local multicriteria analysis;
MF is a membership function;
OAT is one-at-a-time
WLC is a weighted linear combination.

NOMENCLATURE

A is a set of alternatives;
$\tilde{A}$ is a fuzzy set;
At is a set of attribute data;
C is a set of evaluation criteria;
D is a decision rule that specifies the order in which actions are performed on a set of alternatives (selection, ranking, sorting of alternatives);
d_{ik} is a distance between the i-th alternative and the k-th reference location;
d_{Sik} is a standardized distance for a pair of locations i and k;
F is a procedure for criteria-based evaluation;
F_v is a function of territorial influence;
Fv_j is a influence function of the j-th object;
$\{Fv_{ij}\}$ is a set of functions of the territorial influence of the j-th objects on the i-th local parts of the territory;
G is a decision maker's preference system;
Gm is a set of geometric properties of the object;
gl is a linear object;
gp is a point object;
$gpol$ is a polygon object;
$H = \{h_i\}$ is a set of local areas into which the territory is divided;
L is a set of coordinates defining the geometry of the object;
M is a number of territory objects;
N is a number of alternatives;
$O = \{o_j\}$ is a set of objects belonging to the territory;
P is a property of the territory;
P_i is a set of properties of local areas h_i of the territory;
P_{ij} is a value of the influence of the j-th object in the i-th point or local area h_i of the territory;
P_j is a value of the influence of the j-th object at its location;
Pr is a procedure for assessing the properties of the territory;
R is a number of properties of the territory that must be taken into account in the decision-making problem;
Rj is a influence range of the j-th object;
r_{ij} is a distance between the i-th point (local area) of the territory and the j-th object;
T is a territory as an object of management;

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t is a number of map layers;

$V()$ is a integral estimate of the alternative;

w_j is a global weight of the j-th criterion;

w_{ij} is a local weight of the i-th decision alternative according to the j-th criterion;

X is a universal set;

X_i are the sets of characteristics of the territory that are significant for solving the spatial problem;

$\mu_a(x)$ is a fuzzy set membership function;

$v()$ is a evaluation of the alternative by the criterion;

$\Phi_{AGG}()$ is a function of aggregating the influence of objects in the i-th point of the territory.

INTRODUCTION

Modern GIS are an important component of DSS due to the advanced functions of storing, processing and analyzing geodata, modeling tools and visualization tools. Spatial problems, in particular the problem of determining the suitability of territories for accommodating enterprises, capital construction facilities and infrastructure, are always multi-criteria in nature [1], therefore, spatial DSS are often used in cases where a large number of alternatives must be evaluated based on a set of conflicting and incommensurable criteria .

GIS allows for the process of making optimal spatial decisions due to the available functions of geoinformation data processing. The capabilities of a GIS to generate a set of alternatives and select the best solution are usually based on the operations of Surface analysis, Proximity analysis, and Overlay analysis.

Overlay operations allow you to define alternatives that simultaneously satisfy a set of criteria in accordance with the decision rule, but they have limited ability to include the preferences of DM.

A feature of the spatial problems of territorial planning is the need to take into account the complex environmental and socio-economic properties of the territory, as well as the impact of objects on the natural and anthropogenic environment. This justifies the need to take into account expert knowledge and use methods based on expert assessments. The integration of multi-criteria decision-making methods allows expanding the capabilities of GIS, structuring the problem in geographic space, taking into account both qualitative and quantitative evaluation criteria and value judgments (i.e., preferences for criteria and/or alternatives) [2–4].

Geospatial multicriteria decision analysis will be considered as a combination of spatial modeling tools with multicriteria decision making methods for evaluating and analyzing alternative solutions to a spatial problem. It is assumed that the problem is characterized by a finite, explicitly given set of alternatives. The goal of multi-criteria analysis is to rank alternatives by a finite number of attributes. At the same time, it is necessary to know the importance (weight) of attributes and the evaluation of alternatives regarding attributes. Most modern GIS do not contain built-in full-featured tools that can implement the complex procedure of multi-criteria decision analysis. Separate attempts to fully integrate tools for multi-criteria decision analysis and GIS within the framework of a universal interface have revealed problems associated with the lack of flexibility and interactivity of such systems, which cannot provide the required freedom of action for analysts [5]. Therefore, the development of a universal technology for geospatial multicriteria decision analysis that provides a solution to this problem is an urgent task for researchers.

The object of study of this work is the decision support process for territorial planning.

The subject of the study is object-spatial models and methods for assessing the properties of the territory and geospatial multi-criteria decision analysis for territorial planning.

The aim of the study is to develop a technology for multi-criteria decision analysis for territorial planning based on the apparatus of the theory of fuzzy sets and the functions of geoinformation analysis.

1 PROBLEM STATEMENT

When performing a geospatial multi-criteria analysis of decisions at the macro and micro levels, territorial spatial factors or conditions in which the processes under study take place should be taken into account. It is advisable to consider the territory as a complex system, and the model for assessing the state (properties) of the territory, formed as a result of the impact of objects located on it, as the basis for decision-making. At the same time, the objectives of the assessment, methods and scales of assessment, assessment criteria $C=\{C_1,C_2,\ldots,C_n\}$, alternatives $A=\{a_1,a_2,\ldots,a_m\}$ and the procedure for criteria-based assessment F should be defined. In this regard, the procedure for estimating the properties of the territory Pr, which determines the data representation model and the semantics of the spatial relations of objects, should be developed and included in a formalized record of the geospatial multi-criteria decision analysis:

$$\langle A, C, Pr, F, G, D \rangle. \quad (1)$$

Most of the traditional approaches to the analysis of spatial issues are extensions and adaptations of existing decision making methods. As a rule, they take into account spatial variability only implicitly and assume the spatial homogeneity of preferences and value judgments of DM. For instance, when aggregating estimates of alternatives using the weighted sum method, it is customary to calculate one weight for each criterion, despite the fact that in spatial problems the weight of the criterion often depends on the location of the alternative and may have a local value at different points in the territory. For example, the relationship between two properties of a territory may be markedly different in one region compared to another.

Based on the presence of the local weight w_{ij}, assigned to the i-th solution alternative (in the i-th location with

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coordinates x_i, y_i) according to the j-th criterion, the aggregation of the estimates of the alternatives $v(a_{ij})$, for example, using the weighted sum method, should look like:

$$V(A_i) = \sum_{j=1}^{N} w_{ij} v\left(a_{ij}\right). \qquad (2)$$

At the same time, an important task remains the development of methods for determining the local weighting coefficients of criteria that will take into account the spatial heterogeneity of the territory.

2 REVIEW OF THE LITERATURE

An analysis of recent studies and publications demonstrates that the synergy of multi-criteria decision making methods and GIS is a fundamental tool for solving spatial problems in many areas [6–8]. Over the past few decades, significant progress has been made in the development of methods for multicriteria analysis of the suitability of territories [9, 10] and the choice of locations for spatial objects [11–13]. This study continues the cycle of works devoted to the problems of integration of geoinformation technologies and methods of multi-criteria decision making for solving problems of management and territorial development [14–18]. They raise the issues of creating, applying and optimizing the technology of geospatial multi-criteria analysis of solutions for GIS applications.

Spatial problems are often characterized by incompleteness and fuzziness of the initial data, as well as criteria represented by qualitative values that are difficult to formalize. Uncertainties arise due to the use of discretization operations and generalization of a set of geographic data. In addition, there are uncertainties in the value judgments and preferences of DM. The most attractive approach to solving such problems is the use in the methods of multicriteria analysis of the solutions of the «soft» computing apparatus, the theory of fuzzy sets [19].

A review of scientific research over more than 20 years [3] showed that the following multi-criteria methods are most often used in GIS applications: weighted WLC [20], AHP [21], reference point methods [22] , and outranking methods [23]. One of the most popular is the AHP method, which is based on pairwise comparisons on a ratio scale. In [24], its FAHP is presented, in which triangular fuzzy numbers are used to account for uncertainty in expert comparisons, and two approaches of FAHP means Fuzzy Extent Analysis and α-cutbased method.

As a rule, the greatest contribution to the uncertainty when using the AHP method is made by the criteria weights determined by pairwise comparison. Weights can be changed during analysis. Corresponding weight sensitivity on multi-criteria evaluation results is generally difficult to be quantitatively assessed and spatially visualized. In [25] developed a unique methodology to analyze weight sensitivity caused by both direct and indirect weight changes using the OAT technique (mostly known as local sensitivity analysis). The method was integrated into a comprehensive framework in the GIS environment. The framework was implemented as AHP-SA2 tool with spatial visualization capability.

In [26] spatial uncertainty and sensitivity analysis of land suitability maps is proposed. The resulting sensitivity maps delineate regions of weight dominance, where a particular weight greatly influences the uncertainty of suitability scores.

As noted earlier, most studies did not take into account the spatial heterogeneity of geographic data inherent in decision-making, especially in the area of territory management. In recent years, new research trends have emerged associated with a paradigm shift from spatial implicit to spatially explicit multicriteria analysis [27]. LMCA introduces the concept of spatial weight and spatially explicit value function [28, 29]. In [30], the OWA method is proposed, which can be used to take into account various risk-taking scenarios. In [31], local forms of reference point methods were developed. The weighting of criteria with a correction for proximity was proposed in [32]. The calculation of local weights is based on the idea of adjusting preferences according to spatial relationships between alternatives and some reference locations. Thus, the method explicitly recognizes the concept of spatial preference heterogeneity.

An analysis of publications shows that most of the works devoted to spatial multi-criteria analysis focus on the procedure for evaluating alternatives, taking into account the uncertainty and spatial heterogeneity of decision makers' preferences. However, while paying little attention to the preparation of initial data, namely the evaluation criteria and a variety of alternatives. To create a universal technology for multi-criteria analysis, it is necessary to have a formalized description of the process of decomposition of territory objects into separate thematic layers and the process of evaluating the properties of the territory as a result of the influence of objects located on them. This study describes the methodology and gives recommendations for the quantitative determination of the territorial influence of objects and the calculation of the integrated properties of the territory, as well as the ranking of alternatives, taking into account locally adapted decision-making methods.

3 MATERIALS AND METHODS

The properties of the territory can be considered as the result of the action (influence) of individual objects o_j located on local sections h_i into which the territory is divided. In this case, the territory T can be represented as $T \subset O \times H$.

One will consider the property of the territory P as a set of local or aggregated characteristics of the territory that are significant for solving the spatial problem, which can be obtained as a result of calculations or expert assessment. The set of connected objects of the territory influences the properties of the territory through the spatial influence functions F_v:

$$O \xrightarrow{F_v} P. \qquad (3)$$

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In general, P can be represented by a set of n sets X_i of characteristics of the territory that are significant for solving the spatial problem, for example, these can be indicators of the ecological, social or economic state of the territory:

$$P = \bigcup_{i=1}^{n} X_i . \quad (4)$$

Characteristics (or indicators for assessing the properties of the territory) can be local, complex or integral. According to their type, indicators can be divided into qualitative and quantitative, respectively, be measured or calculated or determined by experts. The qualitative composition and the number of local indicators by which the property of the territory is assessed can vary from several units to several tens, and depend on the nature of the spatial decision-making problem. For example, to determine the location of a solid domestic waste landfill, it is necessary to take into account more than several dozen quantitative and qualitative indicators of the properties of the territory, which may include landscape, environmental, economic, social, and other characteristics [15].

A property of a territory is defined as an ordered set of properties of local parcels:

$$P = \left\{ P_i \mid P_i = \left\{ P_{ij} \right\} \right\},\ i = 1 \div n,\ j = 1 \div m. \quad (5)$$

The magnitude of the influence of the j-th object at the i-th point or local area of the territory determined through the distribution function of the influence of this object as:

$$P_{ij} = P_j \cdot F_{vj} \left(r_{ij} \right). \quad (6)$$

The value of the influence function depends on the set of properties of the territory (relief, slope, soil type, etc.), as well as on the distance r_{ij} between the j-th object and the i-th point of the territory. The territorial influence function can be specified analytically, for example, on the basis of equations describing known physical processes (pollution transfer models, illumination distribution, etc.) or socio-economic impact models. The Fv function can be set as a value function built on the basis of expert estimates.

The impact of a set of objects O on the i-th point (local section) of the territory is determined by aggregating the values of the influence of individual objects:

$$P_i = \Phi_{AGG} \left(P_j \cdot F_{vj} \left(r_{ij} \right) \right). \quad (7)$$

In general, the influence aggregation function is nonlinear and may include logical operations.

Taking into account the representation of the territory property model as a two-dimensional discrete system consisting of a set of elementary sections h_i or points of the territory defined by x, y, coordinates, the property of the territory can be represented as a function of the surface $P_{x,y} = f_p(x, y)$. Thus, from the point of view of geoinformatics, each of the properties of the territory can be represented in in the form of a coordinate-defined surface (for example, transport accessibility, pollution of the territory, flood damage, etc.). The application of an approach based on the description of the properties of the territory by means of the surface function allows one to solve the problems of placing infrastructure objects at different levels in the same way.

In a geographical context, the process of multi-criteria analysis of spatial planning decisions includes a set of geographically defined alternatives, usually local areas (eg, land parcels) and a set of evaluation criteria, presented as thematic map layers. Estimates of alternatives according to different criteria (attributes of criteria) are determined in accordance with the model for evaluating the properties of the territory. The analysis consists in combining the attributes of the criteria in accordance with the preferences of the decision maker, using the decision rule (combination rule).

The diagram of the process of geospatial multi-criteria decision analysis is presented in Fig.1.

Provided that the criteria layers are represented in a raster data model, which has the form of a two-dimensional x×y discrete rectangular grid. Each raster cell is an alternative, which is described by its spatial data (geographic coordinates) and attribute data (criteria scores). The decision matrix in this case has the form shown in Table 1.

The macroanalysis stage (Fig. 1) provides for the procedure for assessing the properties of the territory using geomodeling functions. At this stage, data on the spatial problem is collected, the objects are decomposed into thematic layers, the qualitative or quantitative territorial impact of the objects is calculated, the properties of the territory are evaluated according to objects of the same type, many criteria and alternatives are formed, taking into account the restrictions imposed on the solution.

Microanalysis (Fig. 1) is a stage that involves the analysis of alternatives using the methods of multi-criteria decision making. At the stage of microanalysis, certain decision-making strategies are formed, taking into account the preferences of the decision maker. A feature of the stage is the integration of geomodeling functions and decision-making methods.

Recommendations – the stage of visualizing the results of the analysis of decisions and providing recommendations to decision makers. The results of the analysis, as a rule, are visualized in the form of a comprehensive map of a set of acceptable solutions formed in accordance with the chosen procedure for analyzing alternatives (selection, ranking, sorting, etc.).

Sensitivity analysis is crucial for model validation and calibration, it is used as a tool to check the stability of the final result to small changes in the input data (for example, criteria weights) and to reduce uncertainty in the process of geospatial multi-criteria decision analysis.

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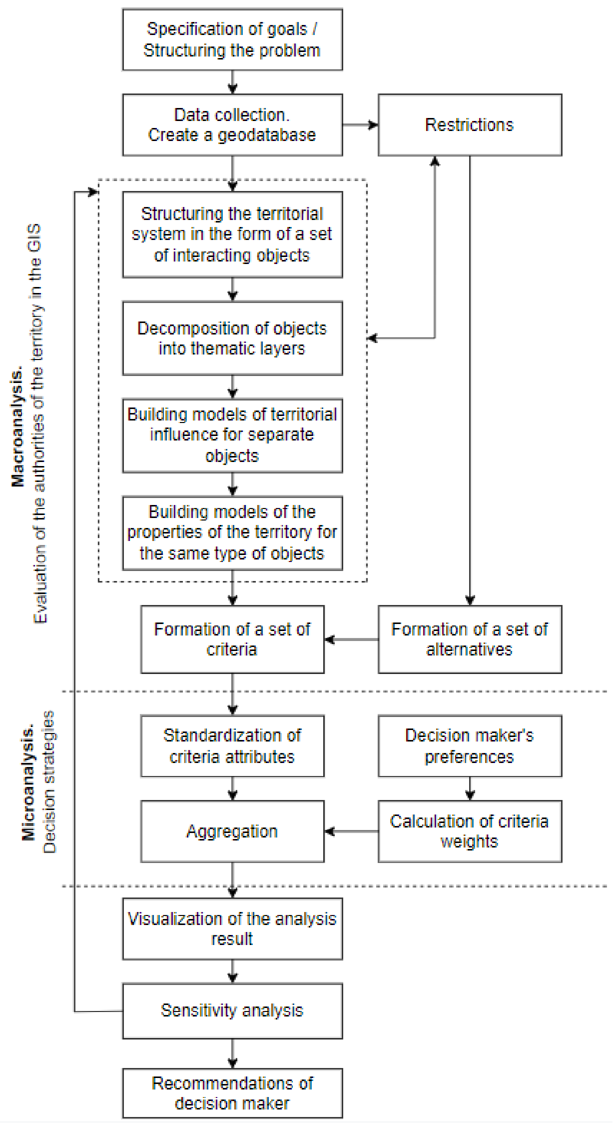

Figure 1 – Diagram of the process of geospatial multi-criteria decision analysis

Table 1 – Decision Matrix

Alternative	Coordinates		Criterion/attribute, C_j			
A_i	X	Y	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_{ij}		w_1	w_2	…	w_n

Let us consider in more detail the stage of macroanalysis of the process of geospatial multi-criteria analysis of solutions (Fig. 1). Structuring a territorial system in the form of a set of interacting objects involves the representation of an object in the form of a tuple of sets of homometric, spatial and attributive properties, taking into account the influence of *Fv* that it exerts on the territory:

$$O = \langle Gm, L, At, F_v \rangle. \quad (8)$$

Let's take a closer look at the procedure for decomposing territory objects into thematic layers. Let be given some finite set of objects *O* belonging to the territory. It is necessary to select from the set of objects *O* a subset of objects $O_p \in O$, which determine the properties of the territory in accordance with the spatial problem being solved. Further, the set of objects O_p should be decomposed into subsets of objects O_r, which by their influence determine the properties of the territory that are important for the task (for example, the development of the transport network, soil type, environmental safety, etc.), which need to be combined into separate thematic layers of criteria:

$$O_p = \bigcup_{r=1}^{R} O_r, \quad \bigcap_{r=1}^{R} O_r \neq \varnothing. \quad (9)$$

The decomposition of objects is performed based on the analysis of their spatial and attribute information, as well as the functions of influence on the territory.

The geometric properties of objects have the highest priority in decomposition $Gm = \{gp, gl, gpol\}$. The entire set of objects O_p is divided into three classes of point objects according to a geometric featureK_1, linear K_2 and polygonal K_3 objects. A thematic layer can only contain objects of the same geometric type (an object cannot be both a point and a polygon), so classes have the following properties: $O_p = K_1 \cup K_2 \cup K_3$, $K_1 \cap K_2 \cap K_3 = \varnothing$, where

$$K_i = \{o_j \in O \mid o_j \sim k_i\},\ i = 1,2,3, \quad O_p = \bigcup_{j=1}^{3} O_j. \quad (10)$$

The priority of attribute properties of objects is next after geometric ones. Each of the subset of objects O_j belonging to a certain geometric type which is further decomposed by the attribute criteria $At = \{Q, N\}$. Attribute information consists of a set of qualitative properties *Q*, which determine whether an object belongs to a certain thematic group (transport infrastructure, water bodies, settlements, etc.) and *N* – a set of quantitative characteristics of the properties of the object. For example, for objects belonging to the thematic group "Settlements", you can perform a decomposition by population.

At the last step, the decomposition is performed according to a variety of types of *Fv* influence functions, i.e. by functional attribute. At the same time, the type of influence that can be both positive and negative should be taken into account.

After the decomposition of objects, an *Mp* map can be obtained, which is a set of thematic layers L_i:

$$Mp = \{L_i\}, i = \overline{1,t}, \quad (11)$$

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$$L_i = \left\{ O_j^i \right\},\ j = \overline{1,n}. \tag{12}$$

Each thematic layer is a criterion for the decision-making task (Table 1). Schematically, the decomposition of a set of objects into thematic layers is shown in Fig. 2.

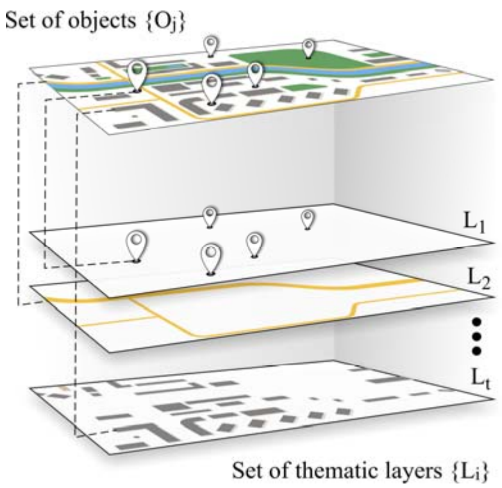

Figure 2 – Diagram of the decomposition of objects into thematic layers

We will consider a stationary model of territories with constant properties, in which P_j = const and F_v = const, that is

$$P_{ij} = P_j \cdot F_v\left(R_j\right). \tag{13}$$

To build models of territorial influence, various types of influence functions can be used, the parameters of which can be determined from the physical principles of distribution, experimentally or expertly. Often, a normal distribution law is used for this, which accurately describes the spatial impact caused by a large number of poorly correlated factors.

Expert assessment methods are most often used to determine the parameters of models reflecting the spread of social or economic properties of the territory.

The most effective mechanism for the formal description of models based on expert opinions is the theory of fuzzy sets [19]. A fuzzy set of a universal set X is defined as a set of ordered pairs:

$$\tilde{A} = \left\{ \left(x, \mu_a\left(x\right)\right) \mid x \in X \right\}, \mu_a\left(x\right) : x \to \left[0,1\right]. \tag{14}$$

Membership function indicates the degree to which element x belongs to a fuzzy subset $\tilde{A}$. The larger the $\mu_a(x)$, the more the element of the universal set corresponds to the properties of a fuzzy subset. The specific value of the membership function is called the degree or coefficient of membership. This degree can be defined as a functional dependency. The definition of the territorial influence model is, in fact, the definition of the influence of an object on a nearby territory in the form of an affiliation function $F_v\left(r_{ij}\right) = \mu\left(r_{ij}\right)$. We will consider the membership degree as the intensity of the manifestation of the function of territorial influence at a certain point of the local area of the territory.

One of the simplest membership functions is a piecewise linear (triangular and trapezoidal) function. Expert parameters of such membership function (territorial influence) are the easiest to determine. It is sufficient to determine the value of the distance r_{ij}, at which the influence of the object is practically unchanged, and the distance R, at which the influence of the object can be neglected. A continuous membership function approximating a trapezoidal one is a Gaussian-type curve. The generalized Gaussian function has the greatest versatility, examples of which are shown in Fig. 3.

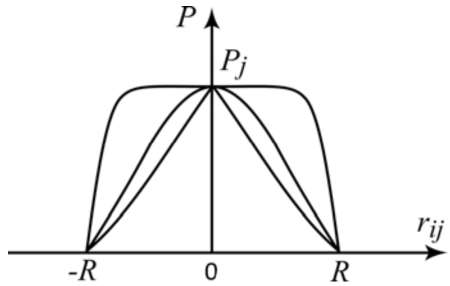

Figure 3 – Examples of graphs of territorial influence functions based on the generalized Gaussian function

Defining the influence functions as the membership degree to a fuzzy set makes it possible not to further standardize the attributes of alternatives, since their values are already in the range [0, 1].

The impact of multiple objects O on the $i$point (local area) of the territory is determined by aggregating the impact values of individual objects (7). The function of aggregating the impacts of objects at the i point of the territory can have a different form and, as a rule, is determined from the context of a spatial problem.

The task of aggregating estimates can arise in two cases: firstly, if necessary, to aggregate the influence of the same type of objects forming a certain property of the territory; secondly, to aggregate the influence of various objects to obtain a comprehensive property of the territory. The same aggregation approaches can be used for both cases.

Fuzzy logic operations can be used to determine the resulting impact of objects belonging to the same class.

The fuzzy union (or OR) of the influences of objects (Fig. 4 a) is defined as:

$$\bigcup_{i=1}^{n} P_i = \max\left(P_1, P_2, \ldots, P_n\right). \tag{15}$$

The fuzzy intersection (or AND) of the influences of objects (Fig.4 b) is defined as:

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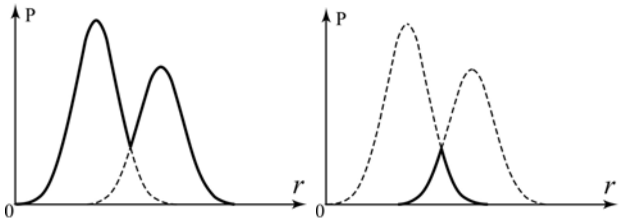
$$\bigcap_{i=1}^{n} P_i = \min\left(P_1, P_2, ..., P_n\right). \quad (16)$$

The use of the fuzzy intersection operation (16) leads to the evaluation of the property based on the lowest value of the influence of objects, the fuzzy union operation (15) takes into account only the maximum values of the influence of objects on the nearby territory.



a b

Figure 4 – Graphs of the resulting model: a – by the maximum value of influence from individual objects; b – by the minimum value of influence from individual objects

To obtain a complex (integral) assessment of the properties of a territory from objects belonging to different classes and having certain weights of importance, the weighted sum (2) operation adapted to the model of the properties of territories, that is, taking into account spatial variations and the division of the territory into local areas, can be used.

For the h surrounding and the local weight w^h_j for the j criterion, a local form of the weighted sum operator of the form can be determined:

$$P(A_i^h) = \sum_{j=1}^{n} v(a_{ij}^h) w_j^h. \quad (17)$$

The diagram of the process of assessing the properties of the territory is shown in Fig. 5. It reflects the main stages of the process, starting with the decomposition of all objects significant for the spatial problem into layers before constructing integral layers of the territory properties. If the objects of the same type of thematic layer have different influence functions, then it is assumed that a set of layers of territory properties is built separately for each object, followed by their combination by one of the aggregation operators to obtain an integral thematic layer.

At the stage of microanalysis, a wide range of decision-making methods can be applied. The main steps of the stage are determining the weights of criteria and aggregating the attributes of alternatives, which are estimates of alternatives according to different criteria (properties of the territory), into a general integral assessment. At the same time, it is important to take into account the preferences of decision-maker, which can be characterized by subjectivity, uncertainty and different attitudes to risk. In addition, local adaptation of methods may be necessary, in the case when there is a spatial heterogeneity of decision-maker's preferences in the problem.

4 EXPERIMENTS

Let's consider an example of using geospatial multi-criteria decision-making to select a suitable location for an enterprise. Let's assume that the main goals are to reduce construction costs and provide the enterprise with human resources (labor). We will identify as the main factors that can affect the reduction of construction costs, the slope of the territory and the proximity of the transport network. Potential sources of labor are nearby settlements, while the main source is a large district center with the largest population. Thus, in order to provide the enterprise with cheap labor, it is advisable to place it as close as possible to populated areas, which will additionally make it possible to reduce transportation costs for the delivery of workers.

The decomposition of the territory objects important for solving the problem according to geometric, attributive and functional features leads to the formation of three thematic layers:

1) DEM is a raster layer, which is a representation of the earth surface of the territory, in the form of a matrix of cells, each of which is characterized by a certain height;

2) transport network – a layer of linear objects, representing paved roads;

3) settlements – a layer of polygonal objects representing the administrative boundaries of settlements located on the territory under consideration.

Next, it is necessary to assess the functional impact of these objects on the territory.

The slope is determined by the steepness in each cell of the raster surface. The smaller the slope value, the flatter the earth's surface is. In GIS, the slope can be calculated as the rate of elevation change from one DEM cell to another.

The Euclidean proximity metric can be used to determine the distance to roads and settlements. In GIS, the Euclidean distance between two objects $O_1(x_1, y_1)$ and $O_2(x_2, y_2)$ is defined as:

$$d(O_1, O_2) = \sqrt{\left(x_1 - x_2\right)^2 + \left(y_1 - y_2\right)^2}. \quad (18)$$

Performing the calculation according to (18) transforms the vector layer of objects into a raster layer, which is a continuous surface of a given property.

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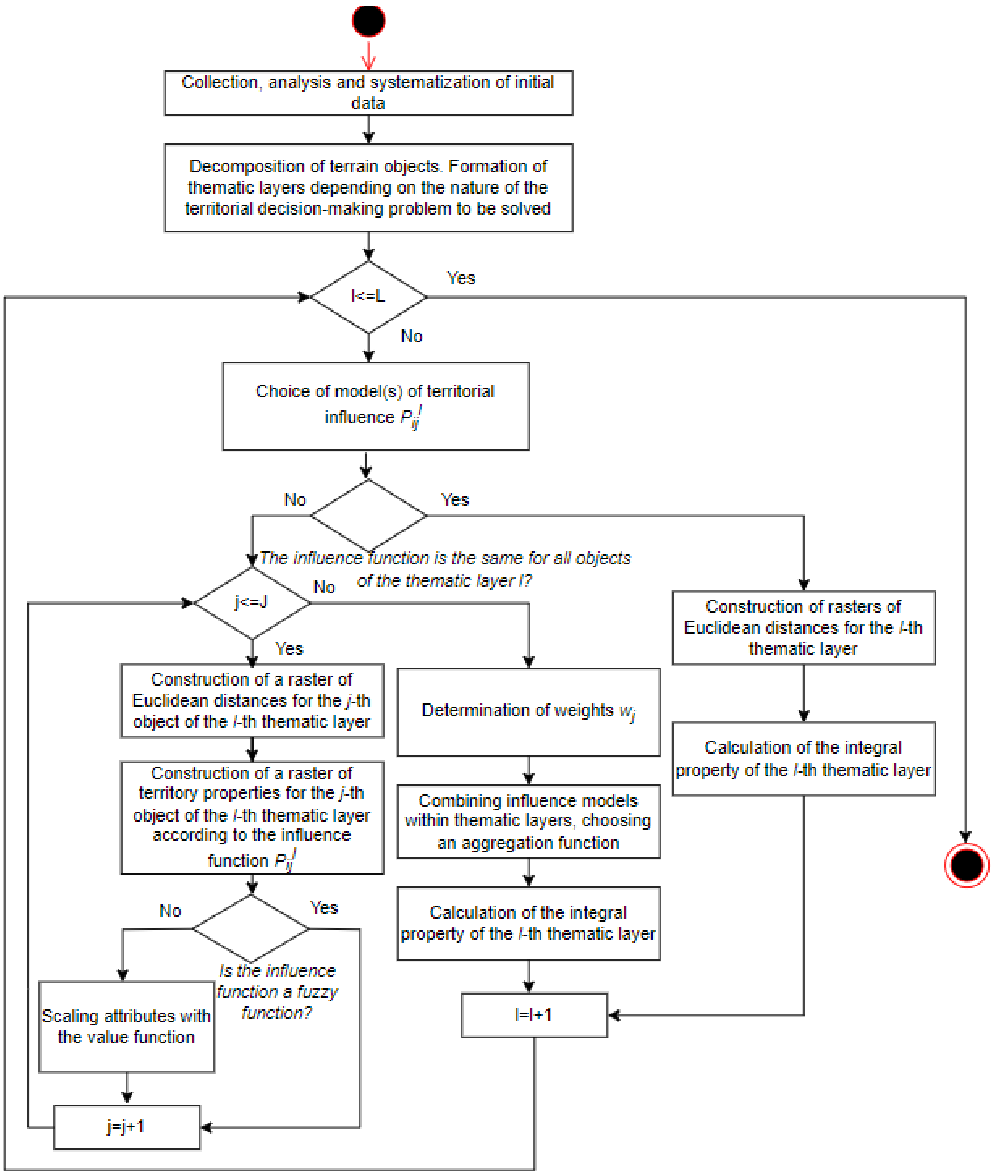

Figure 5 – Diagram of the assessing process of the territory properties

Let's standardize the raster layers of criteria using the fuzzy set membership functions built on the basis of expert evaluation. The values of the alternative attributes will be transferred to the range [0, 1], where the unsuitable areas are marked with zero, and the areas with the maximum degree of suitability are marked with 1. A general view of the membership functions used in the experiment is shown in Fig. 6. Detailed information about thematic layers, influence functions, control points of membership functions used to standardize attributes, as well as weights of the importance of criteria is given in Table 2.

Let's consider two scenarios of multi-criteria analysis of solutions. In the first scenario, the global weight of the importance of the criteria will be used, i.e. a constant weight w_j is set for the j criterion (Table 2). The integral estimate will be obtained by the weighted sum method:

$$V(A_i) = \sum_{j=1}^{N} w_j v\left(a_{ij}\right). \tag{19}$$

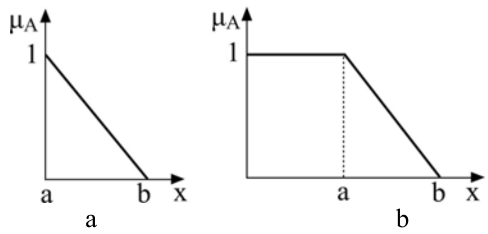

Figure 6 – Membership functions used to standardize attributes: a – linear monotonically decreasing; b – piecewise linear decreasing

In the second scenario, local importance weights will be used [32]. So the weight distribution of the "Slope" criterion will be recalculated depending on the distance

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from the transport network. In this case, the location of the linear road object is the reference location. Similarly, the weight of the criterion "Distance to settlements" will have a local value, depending on the proximity of the district center (reference location).

The weight of the proximity-adjusted criterion, w_{ij}, assigned to the i alternative of the relative j criterion is defined as:

$$w_{ij} = w_j \frac{d_{ik}^S}{1/n \sum_{i=1}^{m} d_{ik}^S}. \quad (20)$$

Standardized distance for a pair of locations i and k:

$$d_{Sik} = \frac{\min_i \{d_{ik}\}}{d_{ik}}. \quad (21)$$

The distances to the reference locations will be calculated using the Euclidean distance metric.

Thus, the local weight will be obtained by modifying the global weight of the criterion, taking into account the distance d_{ik}, normalized by the average distance of all alternatives to the reference location. An example of calculating local weights for five alternatives is given in Table 3. According to (20), the global weight of the criterion is changed by redistributing the total weight nw_j, depending on the spatial relationship (proximity) between the reference location and the alternative solution.

Local weights will be used to calculate the integral evaluation of alternatives using the weighted sum aggregation operator (2).

5 RESULTS

Scenario 1 and scenario 2 were implemented in the ArcMap 10.5 GIS environment. The results of geospatial modeling are presented in Fig. 7. Thematic layers of criteria (Table 2) based on the proposed influence functions and in accordance with the macroanalysis procedure (Fig. 1 and Fig. 5) were transformed into raster layers of slope, distance to the transport network and distance to settlements. Next, the layers were standardized in accordance with the membership functions shown in Figure 6. Standardization was performed using the functions of Raster Calculator and Reclassify of the Spatial Analyst library. As a result, a standardized slope raster (Fig. 7 a), a standardized distance raster to the transport network (Fig.7 b) and a standardized distance raster to settlements (Fig.7 c) were obtained.

The complex applicability map according to scenario 1 (Fig. 7 d) is constructed using the weighted sum operator based on the global weights of the criteria given in Table 2.

Scenario 2 assumed the calculation of local weights. Standardized rasters of the distances of alternatives to the district center and the transport network were obtained based on the expression:

$$d_{Sik} = \frac{\max_i \{d_{ik}\} - d_{ik}}{\max_i \{d_{ik}\} - \min_i \{d_{ik}\}}. \quad (22)$$

Table 2 – Characteristics of thematic layers (criteria) of a spatial decision-making problem

Criterion	Thematic layers	Influence function	Standardization: control points of the membership function (Fig. 6)		Weight
			a	b	
Slope	raster	$F_v = f'(x,y)$	5%	15%	0,4
Distance to transport network	linear	$F_V = \sqrt{(x-x_{gl})^2 + (y-y_{gl})^2}$	0	500 m	0.3
Distance to settlements	polygonal	$F_V = \sqrt{(x-x_{gpol})^2 + (y-y_{gpol})^2}$	0	10 km	0.3

Table 3 – Proximity-adjusted weights

Alternatives	Euclidean distance d_{ik}	Standardized distance d_{Sik}	Weight: global w_j	local w_{ij}
A1	6	0.33	0.3	0.172
A2	3	0.67	0.3	0.345
A3	5	0.40	0.3	0.207
A4	2	1.00	0.3	0.517
A5	4	0.50	0.3	0.259
Mean	4	0.58		
Minimum	2	0.33		
Sum (w_j)			1.5	1.5

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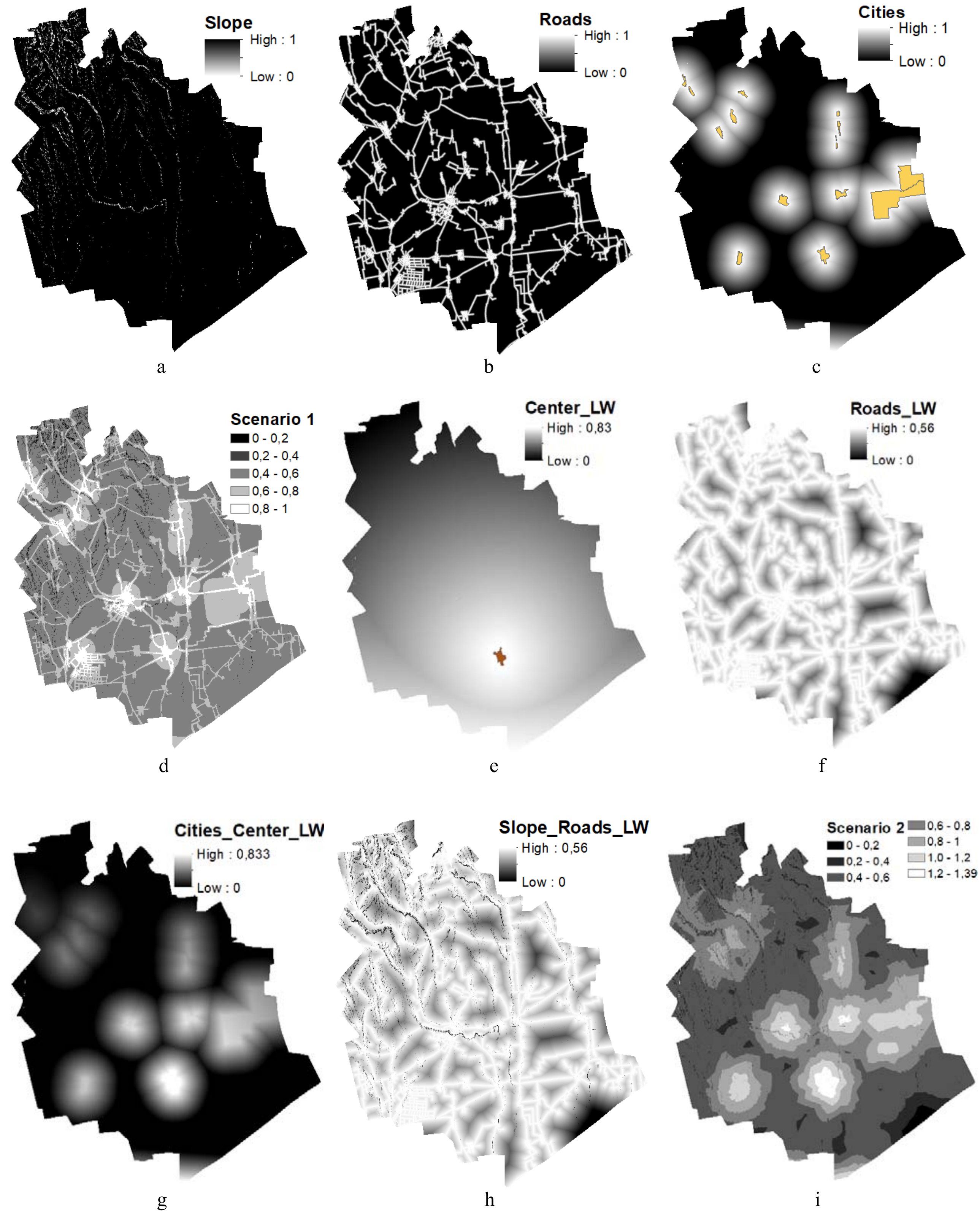

Figure 7 – Results of spatial modeling in accordance with the initial data of scenario 1 and scenario 2: a – standardized layer of the slope of the territory; b – standardized layer of distances to the transport network; c – standardized layer of distances to settlements; d – integrated suitability map (scenario 1); e – raster of local weights of the criterion "Settlements adjusted for the proximity of the district center"; f – raster of local weights of the criterion "Slope adjusted for the proximity of the transport network""; g – estimates of alternatives according to the criterion "Slope adjusted for the proximity of the transport network"; h – estimates of alternatives according to the criterion "Settlements adjusted for the proximity of the transport network"; proximity of the district center; i – comprehensive applicability map (scenario 2)

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The minimum distance $\min_i \{d_{ik}\}$ taken as the size of the raster cell, which, when modeled for all maps, is 27 m. The average value of standardized distances is obtained using the Get Raster Properties tool of the Data Management library. The global weight w_j (20) for the criteria of scenario 2 is assumed to be 0.5. The field of local weights for the criterion "Settlements adjusted for the proximity of the district center" is shown in Fig. 7 e, and for the criterion "Slope adjusted for the proximity of the transport network" in Fig. 7 f.

Estimates of alternatives according to the criteria "Slope" and "Settlements" were multiplied by the corresponding local weights adjusted for proximity, the results are presented in Fig. 7 g and Fig. 7 h respectively. The final complex applicability map was obtained using a locally adapted version of the weighted sum operator (2) and is shown in Fig. 7 i.

6 DISCUSSION

For all scenarios of geospatial analysis, the previously considered macroanalysis procedure was applied (Fig. 1), which includes the decomposition of objects into thematic layers and the assessment of the properties of the territory based on the model of the territorial influence of objects. Scaling of criteria is performed using piecewise linear membership functions. As a result, the values of the criteria attributes were transferred to the range [0, 1], where 1 is the highest, and 0 is the lowest degree of suitability of an alternative according to a given criterion (Fig. 7 a, b, c). This makes it possible to further aggregate alternative estimates by various methods, such as using fuzzy overlay (union or intersection operations) so with the weighted sum operator.

In scenario 1, the weighted sum and global weights method is used for aggregation. The weight of the "Slope" criterion is assumed to be 0.4, however, as can be seen in Fig. 7, and most (92.6%) of the studied territory has a degree of suitability equal to 1 according to this criterion, therefore it has little influence on the final result. The criteria "Distance to the transport network" and "Distance to settlements" have an equal weight of 0.3 and have the same effect on the prioritization, which leads to a scattered distribution of alternatives with a high rating throughout the territory. As a result, alternatives with high suitability were concentrated around sections of the road network located within the boundaries of settlements (Fig. 7 d). The plots with a degree of suitability of 0.8 and higher accounted for 5.56% of the entire research area.

The results of the experiment in scenario 2 showed that the local weights calculated for the criteria "Slope adjusted for the proximity of the transport network" and "Settlements adjusted for the proximity of the district center" have a significant impact on the ranking of alternatives. They allow us to quantify the spatial displacement to the focal (important for decision-making) objects. Thus, in the considered spatial problem, the solutions with a high rating shifted towards the district center (Fig. 7 i).

The proposed algorithm made it possible to calculate the local weight at each point (section) of the territory, redistributing the global weight of the criterion depending on the spatial relationship (proximity) between the focal location and the alternative solution. The resulting raster of weights is then used to aggregate estimates of alternatives by the weighted sum operator. Note that an important parameter of modeling is the size of the raster cell. It is assumed that it must be the same for all criteria for correctly performing the overlay operation. It should be chosen taking into account the analyzed distances and the necessary modeling accuracy. Thus, for scenario 2, plots with a high degree of suitability of more than 1.0 accounted for 6.59%, and more than 1.2–0.98% of the entire study area.

The use of local weights provides an alternative representation of complex preferences and reduces the number of criteria, which in turn significantly simplifies the stage of microanalysis and integration of the model into the GIS environment. In addition, the approach based on local weights simulates cognitive reasoning, which makes the analysis procedure more transparent and understandable for the decision-maker.

CONCLUSIONS

The urgent task of developing a model of the process of geospatial multi-criteria analysis of decisions on territorial planning and rational placement of capital construction and infrastructure facilities has been solved.

The scientific novelty of the obtained results lies in the fact that an approach to multi-criteria decision analysis is proposed, which is based on a model for assessing the properties of territories and spatially adapted decision-making methods. The properties of the territory are evaluated based on the influence functions of adjacent objects. A universal technology has been proposed that allows for spatial analysis without restrictions on the maximum and minimum sizes of land plots. Taking into account the spatial variation of the properties of the territory and the different degrees of detail of objects, allows to increase the accuracy of spatial analysis, as well as its practical value.

The practical significance of the results obtained lies in the fact that the technology of geospatial multi-criteria analysis of solutions has been developed, which is based on existing functions of information geoprocessing and can be fully integrated into the GIS environment. The results of the simulation allow us to recommend the proposed model for use in practice, in particular for the tasks of rational placement of important infrastructure facilities.

The prospects for further research are to improve the model of the geospatial multi-criteria decision analysis process in order to take into account various decision-making strategies, in particular in conditions of risk and uncertainty.

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МОДЕЛЬ ПРОЦЕСУ ГЕОПРОСТОРОВОГО БАГАТОКРИТЕРІАЛЬНОГО АНАЛІЗУ РІШЕНЬ З ТЕРИТОРІАЛЬНОГО ПЛАНУВАННЯ

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АНОТАЦІЯ

Актуальність. Розглянуто процес багатокритеріального аналізу рішень з територіального планування та раціонального розміщення просторових об'єктів, заснований на моделюванні властивостей території. Мета роботи – розробка технології багатокритеріального аналізу рішень з територіального планування на основі апарату теорії нечітких множин та функцій геоінформаційного аналізу.

Метод. Запропоновано об'єктно-просторовий підхід до формування множини альтернатив та критеріїв, відповідно до якого процес багатокритеріального аналізу рішень розбивається на два етапи: макро- та мікроаналіз. Етап макроаналізу передбачає оцінювання екологічних та соціально-економічних властивостей території за допомогою функцій геомоделювання. У роботі дано формалізований опис етапу макроаналізу, включаючи методи оцінки якісного та кількісного впливу просторових об'єктів на властивості території та декомпозиції об'єктів на тематичні шари критеріїв. На етапі мікроаналізу виконується ранжування альтернатив з урахуванням обраної стратегії прийняття рішень. Розглянуто метод стандартизації атрибутів критеріїв за допомогою функцій належності до нечіткої множини, а також модифікація методу розрахунку коефіцієнтів відносної важливості (ваг) критеріїв з урахуванням просторової неоднорідності переваг особи, яка приймає рішення. Проведено порівняльний аналіз методів агрегування оцінок альтернатив за різними критеріями. Особливістю представленої технології геопросторового багатокритеріального аналізу рішень з територіального планування є можливість її інтеграції у сучасні геоінформаційні системи.

Результати. Процедура багатокритеріального аналізу рішень реалізована у середовищі геоінформаційної системи ESRI ArcGIS 10.5 та досліджена при вирішенні просторової проблеми раціонального розміщення підприємства.

Висновки. Запропонований об'єктно-просторовий підхід до багатокритеріального аналізу рішень дозволяє явно враховувати просторову неоднорідність географічних даних, яка є результатом впливу на властивості території розміщених на ній географічних об'єктів. Розроблена технологія може бути використана при вирішенні широкого кола проблем, пов'язаних з визначенням раціонального розміщення різних об'єктів капітального будівництва та інфраструктури.

КЛЮЧОВІ СЛОВА: географічні інформаційні системи, просторове моделювання, багатокритеріальний аналіз рішень, нечіткі множини.

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МОДЕЛЬ ПРОЦЕССА ГЕОПРОСТРАНСТВЕННОГО МНОГОКРИТЕРИАЛЬНОГО АНАЛИЗА РЕШЕНИЙ ПО ТЕРРИТОРИАЛЬНОМУ ПЛАНИРОВАНИЮ

Кузниченко С. Д. – канд. геогр. наук, доцент, декан факультета компьютерных наук, управления и администрирования Одесского государственного экологического университета, Одесса, Украина.

АННОТАЦИЯ

Актуальность. Рассмотрен процесс многокритериального анализа решений по территориальному планированию и рациональному размещению пространственных объектов, основанный на моделировании свойств территории. Цель работы – разработка технологии многокритериального анализа решений по территориальному планированию на основе аппарата теории нечетких множеств и функций геоинформационного анализа.

Метод. Предложен объектно-пространственный подход к формированию множества альтернатив и критериев, в соответствии с которым процесс многокритериального анализа решений разбивается на два этапа: макро- и микроанализ. Этап макроанализа предполагает оценивание экологических и социально-экономических свойств территории с помощью функций геомоделирования. В работе дано формализованное описание этапа макроанализа, включая методы оценки качественного и количественного влияния пространственных объектов на свойства территории и декомпозиции объектов на тематические слои критериев. На этапе микроанализа выполняется ранжирование альтернатив с учетом выбранной стратегии принятия решений. Рассмотрен метод стандартизации атрибутов критериев с помощью функций принадлежности к нечеткому множеству, а также модификация метода расчета коэффициентов относительной важности (весов) критериев, с учетом пространственной неоднородности предпочтений лица, принимающего решения. Проведен сравнительный анализ методов агрегирования с различной формой компромисса между оценками альтернатив по разным критериям. Особенностью преставленной технологии геопространственного многокритериального анализа решений по территориальному планированию является возможность ее интеграции в современные геоинформационные системы.

Результаты. Процедура геопространственного многокритериального анализа решений реализована в среде геоинформационной системы ESRI ArcGIS 10.5 и исследована при решении пространственной проблемы рационального размещения предприятия.

Выводы. Предложенный объектно-пространственный подход к многокритериальному анализу решений позволяет явно учитывать пространственную неоднородность географических данных, которая является результатом влияния на свойства территории расположенных на ней географических объектов. Разработанная технология может быть использована при решении широкого круга проблем, связанных с определением наиболее рационального размещения различных объектов капитального строительства и инфраструктуры.

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КЛЮЧЕВЫЕ СЛОВА: географические информационные системы, пространственное моделирование, многокритериальный анализ решений, нечеткие множества.

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