Development of a Spatial Decision-Making Support System for yhe Location of Technogenic Hazard Objects

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Abstract

The paper proposes an approach to the development of a spatial decision-making support system for the location of technogenic hazard objects. To solve the problem of ranking the territory according to the degree of suitability for placing hazard objects, methods of multiple-criteria decision-making and fuzzy models of spatial data processing are used. The use of the apparatus of fuzzy logic allows taking into account expert knowledge and judgments, partially compensates for the uncertainty of the initial information. During building the database, the concept of fuzzy relational databases was used, which allows you to extend the relational model to represent fuzzy data. This approach allows using relational structures to store the judgments of experts using the apparatus of fuzzy sets in GIS.

Keywords

Geographic information system, multiple-criteria decision analysis, fuzzy sets, site selection analysis.

1. Introduction

Modern geoinformation systems (GIS) are an essential component of decision support systems (DSS) due to the advanced functions of storage, processing and analysis of geodata, modeling tools, and the availability of visualization tools. Spatial problems, in particular the problem of determining the suitability of sites for construction objects, are by their nature always multiple-criteria [1]; therefore spatial DSSs are often used in cases when a large number of alternatives must be assessed on the basis of several criteria..

GIS capabilities to generate a set of alternatives and select the best solution are usually based on surface analysis, proximity analysis, and overlay analysis. Overlay operations allow us to identify alternatives that simultaneously meet a set of criteria according to the decision rule, but they have limited opportunities to include the preferences of a decision-maker (DM). In addition, the complexity of spatial relations in some problems cannot be represented cartographically. Therefore, for the last 20 years, GISs have been actively integrating multiple-criteria decision analysis (MCDA) methods [2-4] which expand the capabilities of GISs.

Methods of multiple-criteria decision analysis (MCDA) allow to structurize the problem of decision-making in the geographical sphere, take into account value judgments (i.e., preferences for criteria and/or alternative solutions), provide transparency of decision-making for a DM, and the ability to take into account both qualitative and quantitative criteria evaluation of all alternative solutions.

It should be noted that the major part of modern general-purpose GISs does not contain built-in full-featured tools that can fulfill a complex MCDA procedure. The use of separate software and tools and the lack of a single system for processing expert knowledge increases the duration of pre-project work, i.e., increases the life cycle of decision-making and consequently increases the probability of erroneous results at different stages. One of the possible ways to overcome the above-mentioned problems is the development and integration of software that implements the MCDA procedures into GISs.

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Individual attempts to fully integrate MCDA and GIS tools within the common interface have identified problems due to the lack of flexibility and interactivity of such systems, which cannot provide the needed freedom of action for analysts [5]. Therefore, the choice of procedure and appropriate methods of MCDA, which can provide a better solution to a particular problem, is an urgent task for developers.

Analysis of recent research and publications shows that the combination of MCDA and GIS is a fundamental tool for solving spatial problems in many areas [6-9]. Over the last few decades, significant progress has been made in the development of methods for the multiple-criteria analysis of the suitability of territories [10-12] and the choice of locations for spatial objects [13-15].

The peculiarity of the multiple-criteria decision analysis on the location of man-made hazardous and industrial objects is the need to take into account the ecological status and prospects of the socio-economic development of the region, the impact of this object on the environment and anthropogenic environment, as well as the current environmental legislation and sanitation. Preliminary examinations, in particular, ecological examinations at the site of the planned location of the object, are a mandatory condition. This justifies the need to take into account expert knowledge and use methods based on expert assessments.

In addition, we have to often encounter inaccuracies in the source spatial information and the need to use criteria that cannot be formalized, as well as uncertainty among experts as to the relative importance of the criteria and the acceptable decision strategy, i.e., compromise between the alternatives assessments according to different criteria. To take into account such uncertainties, an approach based on the use of "soft" computing and fuzzy set theory in MCDA methods is considered suitable [16]. Thus, in the information system based on the processing of geospatial information, in order to support decision making on the location of spatial objects, the following tasks must be solved:

- automated processing of the source heterogeneous geospatial information;
- ranking of territories according to the degree of suitability for placement of objects on the basis of a combination of processing of the geospatial information with estimates and judgments of experts with the help of the MCDA methods using the instrument of fuzzy set theory and fuzzy logic;
- visualization of modeling results for different decision making strategies in the form of a comprehensive suitability map.

2. The main research material

2.1. Multiple-criteria model of technogenic hazard objects location based on fuzzy logic

Let us formulate the problem to determine the degree of suitability of the territory for the location of man-made hazardous objects on it [15]:

$$\langle A, C, F, P; D \rangle, \tag{1}$$

where A = {a1, a2,…, am} is a finite set of alternatives; C = {C1, C2,…, Cn} – a set of criteria by which alternatives are assessed; F – criteria-based assessment procedure; P – a system of the DM preferences, contains information on the alternatives assessments for each criterion; D – the decisive rule, specifies the procedure for performing the desired action on a set of alternatives (selection, ranking, sorting of alternatives).

In the geographical context, the MCDA process includes a set of geographically defined alternatives (e.g., land plots) and a set of assessment criteria presented as map layers. The analysis is to combine the criteria attributes according to the DM preferences using the decision rule (combining rule).

It is assumed that the criteria layers are represented in a raster data model that has the form of a two-dimensional discrete rectangular grid x×y. Each raster cell is an alternative that is described by its spatial data (geographical coordinates) and attribute data (criteria values). Let us write a set of alternatives A assessed by the criteria Cj:

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

where aij – the value of the alternative attribute, i.e., the value of the attribute according to the j-th criterion and the i-th alternative; n – a number of criteria; m = mx•my – the number of alternatives (raster cells).

The MD preferences for the criteria assessment are determined by assigning the criteria weights wj, where j = 1, 2, ..., n.

A complete multiple-criteria mathematical model of the location of man-made hazardous objects based on the fuzzy logic is given in [17]. The model is adapted to the location of landfills for solid domestic waste (SDW). Landfills are designed in accordance with state construction standards, which are given in Table 1.

It should be noted that the designed model allows us to enter an unlimited number of criteria, such as the prevailing wind direction, surface slope, etc

Table 1
Requirements for the construction of landfills SDW according to DBN V.2.4-2

Criterion	Thresholds
Distance from airports and airfields	15 km
Distance from the edge of open reservoirs, reserves, seacoast	3000 m
Distance from bridge border	1000m
Distance from residential and public buildings	500 m
Distance from agricultural land, road and railways	200 m
Distance from the border of the forest and forest plant	50 m
Depth of soil water	at least 2 m

One of the important stages of the MCDA is criteria standardization – the transformation of criteria attributes into comparative units, usually in a range of [0,1]. In [17], a procedure for the criteria fuzzification, i.e., transformation into a fuzzy set, is proposed for this purpose based on an expert assessment of the fuzzy membership function.

Thus, the description of spatial information based on the instrument of fuzzy set theory is based on the transformation of the attribute values of the k-th layer into the value of the membership degree of the fuzzy set Ṽk:

$$\tilde{V}_k = \left\{(a, \mu_v{}^k(a)) \mid a \in U\right\}, \mu_v{}^k(a) : a \to [0,1], \quad (3)$$

where a – the value of the attribute, U – a continuous set of attribute values.

As a rule, the membership function is built with the participation of an expert (group of experts) so that the membership degree is approximately equal to the intensity of the manifestation of some factor. In practice, the following types of membership functions are used (Fig. 1):

- triangular and trapezoidal (piecewise linear);
- nonlinear (Gaussian function, sigmoidal function, spline);
- LR-representation of membership functions.

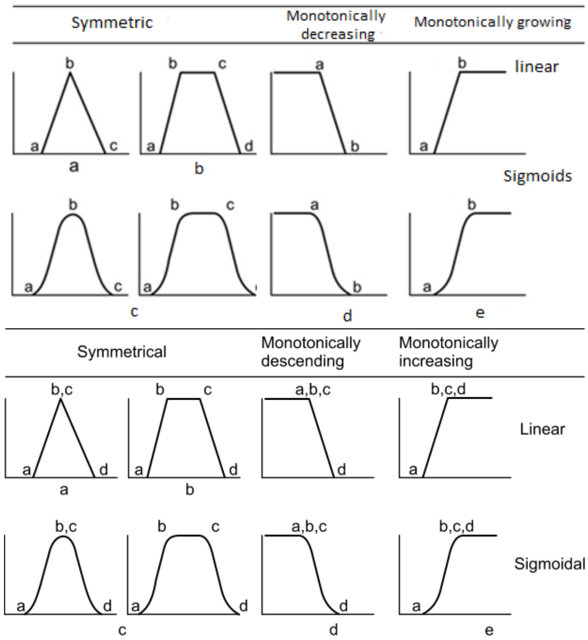

Figure 1: Types of membership functions: a) triangular; b) trapezoidal; c) U-shaped; d) Z-shaped; e) S-shaped

Trapezoidal MF in the general case can be given analytically by the expression:

$$f_T(x; a,b,c,d) = \begin{cases} 0, x \le a \\ (x-a)/(b-a), a < x \le b \\ 1, b < x \le c \\ (d-x)/(d-c), c < x \le d \\ 0, d < x \end{cases} \quad (4)$$

where a, b, c, d – some numerical parameters that take arbitrary real values and are ordered by the relation: $a \le b \le c \le d$.

The use of these functions reduces the numerical calculations and, correspondingly, the computational resources required to store individual values of the membership function.

Criteria fuzzification allows for the further combining of the criteria using fuzzy derivation rules. Fuzzy arithmetic intersection or combining operations can be used, which in this case can be considered as non-compensatory aggregation methods.

Thus, the use of fuzzy set theory to standardize the instrument criteria layers allows to take into account the uncertainty of the source information and the experience and judgment of experts, as well as to obtain a more informative map of suitability by determining the suitability of alternatives: from 0 – "unsuitable," to 1 – "absolutely suitable". The higher the suitability rank of the alternative, the more suitable the alternative is for the object location.

2.2. Designing of the structure of spatial DSS for the location of hazardous objects

The decision support system (DSS) for the location of spatial objects was implemented as a GIS application based on the ArcGIS for Desktop platform by ESRI, which can be published on the Internet as a web service for use by an unlimited number of desktop and mobile clients using ArcGIS for Server server software.

The DSS structure is shown in Fig.2. The information needed to ensure the functioning of the system is stored in separate databases: cartographic – in a specialized geodatabase (GDB), expert information needed to process spatial data with the MCDA – in a database (DB) managed by the Microsoft SQL Server DBMS.

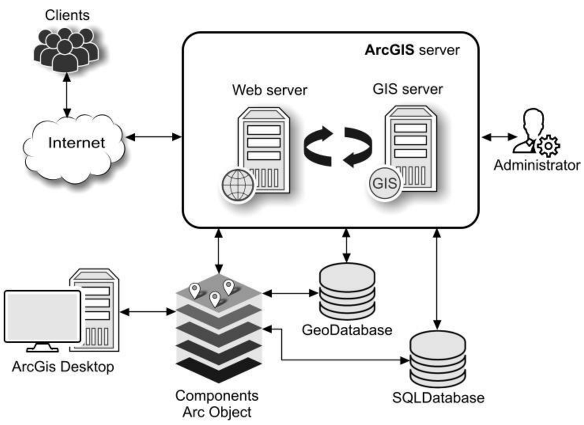

Figure 2: The structure of the spatial DSS for the location of technogenic hazard objects

The geodatabase of the system consists of vector layers at a scale of 1:100000. Vector maps of land use, water bodies, settlements, railways, and highways are obtained by importing the Open Street Map database. Maps of agricultural lands, reserves, housing, forests, and afforestation were obtained by using SQL queries to the land use map attribute table. Digital terrain model (DTM), as well as the derived slope and exposure maps, were built according to ASTER space images with a raster cell size of 27 m. Depending on the specifics of the tasks, additional specialized layers can be used (especially protected areas, fisheries, etc.).

Individual workflows have been designed as in-house tools using the ModelBuilder visual constructor and Python programming scripts.

To provide the GIS application with the necessary features and business logic, the ArcObjects SDK extension for .NET was used, with the help of which additional modules (add-ons) that perform fuzzy spatial data processing models, methods and algorithms of the MCDA procedure were developed based on C# and Windows Forms technology.

2.3. Development of a fuzzy database model

The concept of fuzzy relational databases was used in the building of the DSS database [18], which allows to expand the relational model for the presentation of fuzzy data. This approach allows storing expert judgments with the help of relational structures, using the instrument of fuzzy sets as a basis for managing certain types of uncertainty in GIS.

Fuzzy data is represented by membership functions, which can usually be determined by several numerical parameters (Fig. 1). By storing these parameters so that the requirements of adequacy and integrity are met, one can manage fuzzy data in a relational database. To do this, a fuzzy metamodel is proposed, which manages fuzzy data and connects with relational tables of real objects (Fig. 3).

The is_fuzzy table indicates which attributes and in which database tables are fuzzy. The fuzzy_link table connects the MF type with an attribute in a relational model of real objects. The fuzzy_type table defines the type of MF: triangular, trapezoidal, Z-shaped, S-shaped.

For the criteria attributes fuzzification, the system involves linear MF, each of which is presented by the numerical parameters in a separate table. For example, the trapezoidal table has the following attributes (fuzzy_id, a, b, c, d) to control the storing of trapezoidal fuzzy data. The triangular table has the (fuzzy_id, a, b, c) attributes correspondingly.

The connection of the database fuzzy metamodel with the geodatabase is shown in Fig. 4. The survey_area table contains information about the thematic raster layers of the studied area that need fuzzification.

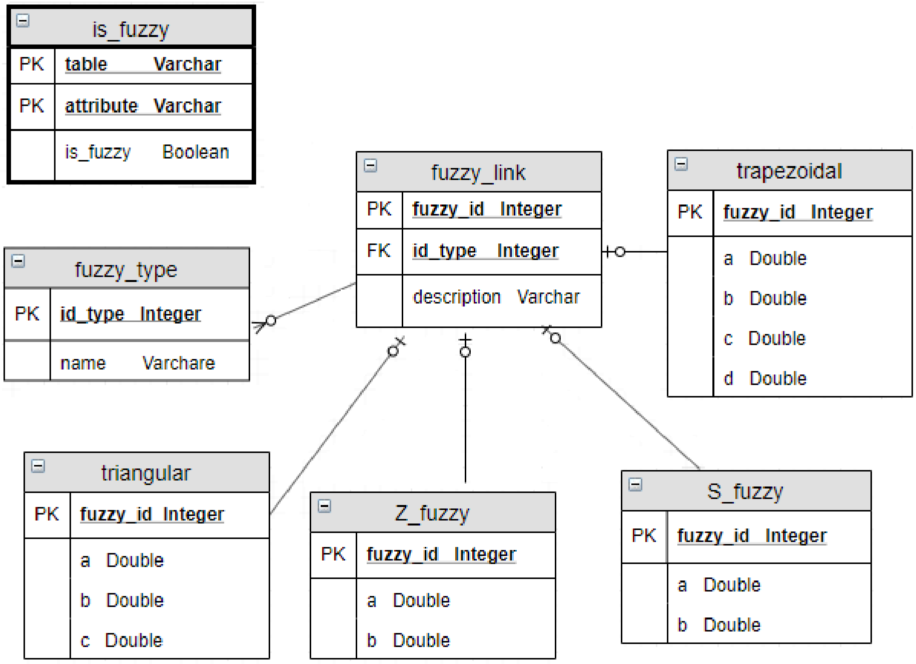

Figure 3: Fuzzy metamodel of a relational database

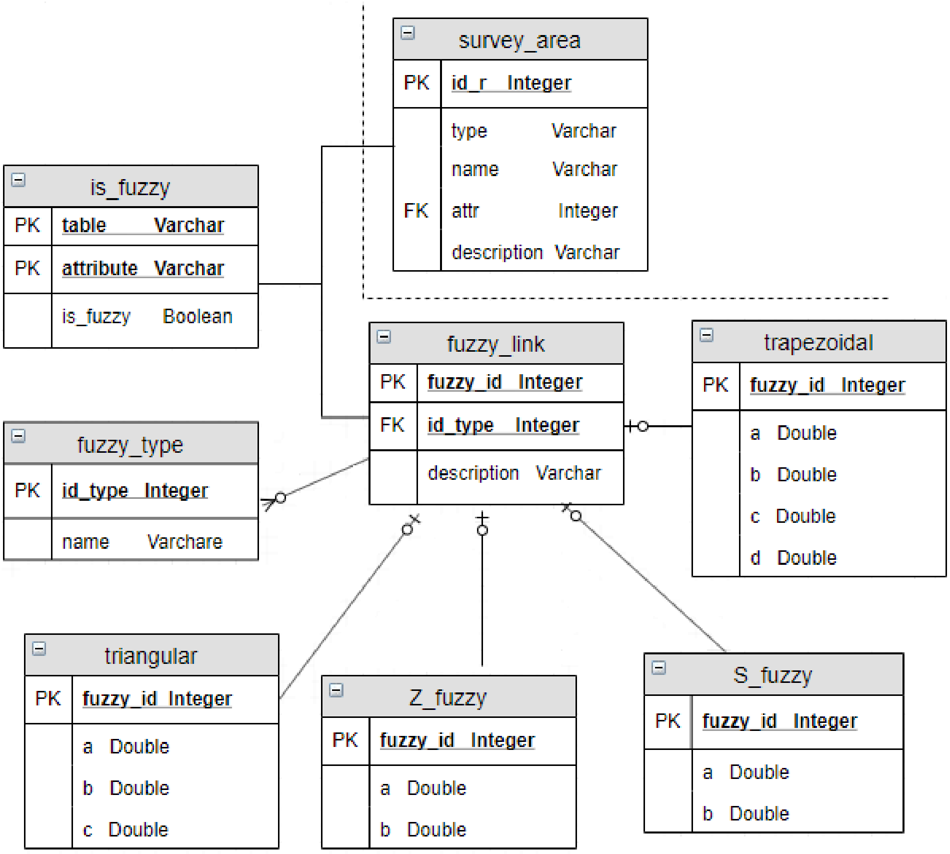

Figure 4: Informational model of fuzzy information storing in a relational database system

survey_area

id_r	type	name	attr	description
1	raster	Road	1101	distance from roads
2	raster	Cities	1102	distance from cities
3	raster	Residential	1103	distance from buildings
...	...	...	...	...

is_fuzzy

table	attribute	is_fuzzy
survey_area	type	0
survey_area	name	0
survey_area	attr	1
survey_area	descrition	0
...	...	...

fuzzy_link

fuzzy_id	id_type
1101	trapezoidal
1102	trapezoidal
1103	s
...	...

S_fuzzy

fuzzy_id	a	b
1103	500	1500
...	...	...

trapezoidal

fuzzy_id	a	b	c
1101	200	500	1000
1102	1000	10000	20000
...	...	...	...

Figure 5: The structure of the spatial DSS for the location of technogenic hazardous objects

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Using the is_fuzzy and fuzzy_link tables, each raster of the GDB gets an assigned certain type of MF. A relational example of a fuzzy relational database is shown in Fig. 5.

From the tables shown in Fig. 5, one can recover all fuzzy as well as clear data. For example, the raster layer of distances from the transport network in the geodatabase of the system is named Road. For the fuzzification of its attributes, the trapezoidal MF will be used with numerical parameters a = 200 m, b = 500 m, c = 1000 m, d = 5000 m, i.e., the greatest degree of suitability according to this criterion will have alternatives located at a distance of 500 to 1000 m from railways and highways. Based on the available numerical parameters of the trapezoidal MF according to (4), the corresponding fuzzy values can be obtained for the entire range of clear values of the criteria attributes, and a table is formed for reclassification of the raster by the Reclassify geoprocessing ArcToolbox tool.

3. Conclusions

The paper presents a multiple-criteria decision analysis model, and the structure of the spatial decision support system for the location of hazardous objects in the form of a GIS application is developed. The use of fuzzy logic allows one to take into account expert knowledge and judgments, which partially compensates for the uncertainty of the source information through the use of expert experience, as well as to obtain a more informative map of the suitability of territories by determining the suitability of alternatives.

A metamodel of building a spatial decision support system for the location of hazardous objects, which extends the relational model for the presentation of fuzzy data, is proposed. The metamodel allows using relational structures to store attributive information, membership functions and expert judgments, using the instrument of fuzzy sets as a basis for managing certain types of uncertainty in GIS. The relational approach to the organization of fuzzy database makes it possible to use it as part of an organized storage structure, as well as to ensure the interaction of spatial and attributive data and fuzzy database based on the use of queries received in the system, which greatly facilitates system implementation and ensures integrity and consistency of all accumulated information about hazardous objects to be located.

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