Iryna BUCHYNSKA[1]

Scientific Supervisor: Svitlana KUZNICHENKO[2]

SYSTEM WSPOMAGANIA DECYZJI Z ZASTOSOWANIEM GIS DO WYBORU LOKALIZACJI WYSYPISKA ŚMIECI

Streszczenie: W artykule przedstawiono metodę formalnego opisu przestrzennego lokalizacji wysypiska śmieci stałych pochodzących z gospodarstw domowych. W opracowanym systemie użyto metodę logiki rozmytej. W logice rozmytej reprezentuje się funkcje przynależności charakteryzujące względne położenia obiektów na mapie. System ten umożliwia przetwarzanie wiedzy ekspertów dotyczącej możliwych położeń wysypisk śmieci pochodzących z gospodarstw domowych - poprzez różnorodne analizy przestrzenne. W opracowanych modelach przetwarzano dane przestrzenne za pomocą specjalistycznego oprogramowania tj. ArcGIS Model Builder.

Słowa kluczowe: geograficzny system informacji, logika rozmyta, system wsparcia decyzji, wysypiska śmieci stałych, lokalizacja miejsca.

A GIS-BASED DECISION SUPPORT SYSTEM FOR PLACING SOLID WASTE LANDFILL

Summary: The paper presents a method of describing spatial information about the facilities of solid household waste disposal based on fuzzy logic methods, which is to represent the membership functions that characterize the relative position of facilities on the map. The ability to process expert knowledge about the disposal of household waste is shown by spatial analysis. A model for processing spatial data in ArcGIS Model Builder.

Keywords: geographic information system, fuzzy logic, decision-support system solid waste landfill, site location.

1. Introduction

The most important factor affecting the man-made hazard is the proper placement of waste landfills. Currently, Ukraine is experiencing a steady increase in waste generation rates, corresponding to the dynamics of the increase in the welfare of the population. Despite the fact that the state policy is aimed at the transition to a system of rational management of solid waste through the introduction of sorting and recycling of waste, there is still a need to organize additional sites for the disposal of solid waste. When designing and searching for the best option for placing solid

[1] Odessa State Environmental University, Dept. of Information Technologies, Postgrad (PhD) Student, buchinskayaira@gmail.com
[2] Ph.D., Odessa State Environmental University, Dept. of Information Technologies, skuznichenko@gmail.com

waste landfills, restrictive selection criteria should be evaluated and taken into account. Therefore, the use of spatial analysis methods in the GIS environment is most preferable for processing spatial information and providing support for making decisions on placing of solid waste landfills.

The design of solid waste landfills is carried out in accordance with state construction codes [1], which impose a number of restrictions on the suitability of the territory:

- distance from airports is at least 15 km;
- distance from the border of open water bodies for economic purposes and reserves is not less than 3,000 m;
- distance from the border of cities is not less than 1,000 m;
- distance from residential and public buildings is not less than 500 m;
- distance from agricultural land, transport network is not less than 200 m;
- distance from the border of the forest and forest plantations not intended for recreational use is at least 50 m;
- depth of groundwater is not less than 2 m.

Based on the technical requirements for the placement of solid waste landfills, limiting factors can be formulated that will allow to exclude from the set of alternatives those that do not satisfy the listed threshold values. In addition to these limiting factors, it is also necessary to take into account the features of the terrain and the morphology of the landscape, as well as socio-economic factors. Using strict rules reduces flexibility and has a limiting effect on management decision making. Due to the fact that the initial information and requirements for the placement of solid waste landfills are often vague and fuzzy, intellectual technologies based on attracting expert knowledge in the framework of fuzzy logic are developing more and more.

The study of the application of geo-information technologies to support decision-making in the management of processes of environmental impact, rational use of natural resources and territories, is the work of many authors, among which there are works [2-7], directly devoted to the problem of waste management.

Despite the fact that there is a sufficient amount of work exploring fuzzy sets and their application in multi-criteria decision-making under uncertainty, the problem of developing fuzzy models of spatial information processing based on GIS technologies is still a relevant scientific and technical task.

2. Multi-criteria mathematical model for placing of landfills based on fuzzy logic

Fuzzy sets [9, 10] are a natural generalization of ordinary sets, if we reject the binary nature of the characteristic function and assume that it can take any values on the interval [0,1]. In the theory of fuzzy sets, the characteristic function is called the membership function, and its value $\mu_A(x)$ – the degree of belonging of an element *x* to a fuzzy set *A*.

Thus, a fuzzy set *A* is called a collection of pairs

$$A = \{\langle x, \mu_A(x) | x \in X \rangle\} \quad (1)$$

where $\mu_A(x)$ – membership function, i.e. $\mu_A(x): X \to [0,1]$.

Formalization of fuzzy data, based on expert assessment methods, by describing each criterion k_i from a variety of criteria *K*, determining the suitability of the territory for the placing a landfill, using a fuzzy variable:

$$K_i = \langle N_i, X_i, A_i \rangle \quad (2)$$

where N_i – variable name, X_i – universal set (domain N_i), A_i – fuzzy set on X_i, describing restrictions on fuzzy variable values N_i.

The membership function $\mu_A(x)$ indicates the degree of membership of the element *x* to the fuzzy set A_i. The larger the value $\mu_A(x)$, the more the element of the universal set x corresponds to the properties of a fuzzy set. Typically, the membership function is built under participation of an expert (expert group), so that the degree of membership is approximately equal to the intensity of manifestation of some factor. In practice, following types of membership functions are applied: linear, triangular and trapezoidal (linear-lump); nonlinear (Gaussian function, sigmoid function, spline).

Fuzzification of criteria, that is, conversion of their attribute values to a fuzzy set, based on expert assessment of the fuzzy membership function, allows further combining the criteria with the help of fuzzy rules of output. Fuzzy logic operations such as intersection or union may be used for this purpose.

The standard fuzzy intersection of sets $A_1, A_2, \dots, A_n$ for all $x \in X$ is defined as follows:

$$\bigcap_{i=1}^{n} \mu_A^i(x) = \min[\mu_A^1(x), \mu_A^2(x), \dots, \mu_A^n(x)] \quad (3)$$

The standard fuzzy union of sets $A_1, A_2, \dots, A_n$ for all $x \in X$ is defined as follows:

$$\bigcup_{i=1}^{n} \mu_A^i(x) = \max[\mu_A^1(x), \mu_A^2(x), \dots, \mu_A^n(x)] \quad (4)$$

The use of a fuzzy intersection operation (3) leads to alternative ranking based on only the lowest rank, that is, it is a pessimistic approach to decision making. Fuzzy union operation (4) takes into account only best evaluations of all criteria.

Aggregation of criteria can be accomplished using various methods of multiple-criteria decision analysis, which are implemented in GIS. The easiest method is the weighted linear combination (WLC) method, which is based on finding of the average value. The membership function is calculated as follows:

$$\mu_A^{WLC}(x) = \sum_{i=1}^{n} w_i \mu_A^i(x) \quad (5)$$

where $\mu_A^i(x)$ is the function of the membership of the *i*-th criterion, and w_i is the normalized weight of the *i*-th criterion and $\sum_{i=1}^{n} w_i = 1$.

The easiest way to evaluate the importance of criteria is to rank, that is, to streamline criteria by an expert in order of importance. Once the rating is set, we can calculate weights according to the equation [11]:

$$w_i = \frac{n - r_i + 1}{\sum(n - r_j + 1)} \quad (6)$$

where w_i is the normalized weight for the *i*-th criterion, *n* is the number of criteria considered (*j = 1, 2, ..., n*), and r_i is the rank position of a criterion.

Weights of criteria can be found directly by experts on the basis of a given scale, for example, from 0 to 100. In this case, the normalized weight of a criterion is calculated as follows [11]:

$$w_i = \frac{w_i'}{\sum w'} \quad (7)$$

where w_i is the normalized weight for the *i*-th criterion, and w_i' is the score for the *i*-th criterion.

The normalized weights of criteria can be calculated by the Analytical Hierarchy Process (AHP) [12], which is based on a pair comparison of criteria using the 9-point fundamental Saaty scale of absolute numbers.
The criteria can be described by a linguistic variable, represented in the following way:

$$K_i = \langle A_i, X_i, T_i \rangle \quad (8)$$

where A_i – name of linguistic variable; X_i – universal set of input values; T_i – a set of terms of a linguistic variable, fuzzy variables of the form (2), which in the framework of the study on the placing of solid waste landfills can be represented by linguistic units "suitable", "unsuitable" and others. In this case, for the calculation of the initial parameter *y*, determining the degree of territory suitability for placing the solid waste landfill, which is also described by the linguistic variable, a base of fuzzy inference rules should be formed. Such rules are established using dependencies, which are logical statements of the form *if A then B, P:A→B*. This scheme refers to the well-known Mamdani's algorithm of fuzzy inference.
The construction of the membership function is carried out according to expert estimates. In this case, direct and indirect methods can be used. In the direct method, the expert directly sets the rules for determining the values of the membership function. These values are consistent with its preferences on set *X* as follows:

$$\forall\, x_1, x_2 \in X, \mu_A(x_1) < \mu_A(x_2)\,,\ \text{if}\ x_2\ \text{more suitable than}\ x_1$$
$$\forall\, x_1, x_2 \in X, \mu_A(x_1) = \mu_A(x_2)\,,\text{if}\ x_1 \text{and}\ x_2\ \text{equally suitable.} \quad (9)$$

In indirect methods, expert information is only the source for further processing. One of the indirect methods to determine the degree to which attributes of a criterion belong to a fuzzy set is based on their pairwise comparisons. It represents the processing a matrix of estimates reflecting the expert's opinion on the relative belonging of elements to the set or degree of a property manifestation formalized by a fuzzy set. The result of the expert survey is the matrix $M = \|m_{ij}\|,\ i, j = 1, n$, where n – the number of points, in which the equation is made. Number m_{ij} shows how many times according to the expert, $\mu_A(x_i)$ is more suitable than $\mu_A(x_j)$. The value of the membership function in points x_i, is determined by the ratio:

$$\mu_A(x_i) = \frac{m_{ij}}{\sum_i m_{ij}} \quad (10)$$

value *j* is chosen arbitrarily. For determining $\mu_A(x_i)$ it is necessary to fix a randomly selected column of the matrix *M* and calculate the ratios by the formula (10).

3. Solution example

In [6], the authors developed a multi-criteria decision-making model for the placing of solid waste landfills in the south of the Odessa region, which took into account physical, environmental and socio-economic factors. A total of 14 criteria were formulated, which were presented in the geo-database as vector and raster layers (Fig. 1). Various sources of geo-data were used: satellite imagery, cartographic services, monitoring data [8].

The model for fuzzification criteria used piecewise linear membership functions (Fig. 2). Triangular and trapezoidal functions are used to set such properties of sets that characterize uncertainty of the type: "approximately equal", "average value", "located in the interval", etc. Z-shaped membership functions set uncertainty of the type: "small number", "small value", "insignificant value", and S-shaped – "large number", "large value", "significant value".

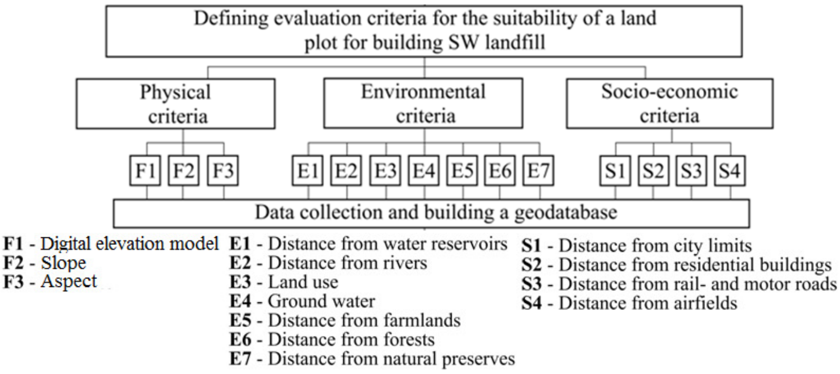

Figure 1. Model criteria expressed by linguistic variables

Consider the criterion expressed by the linguistic variable S4 = "Distance from rail- and motor roads". The membership function of the term "Suitable" for S4, formalized by the formula (11) and is shown in Figure 3.

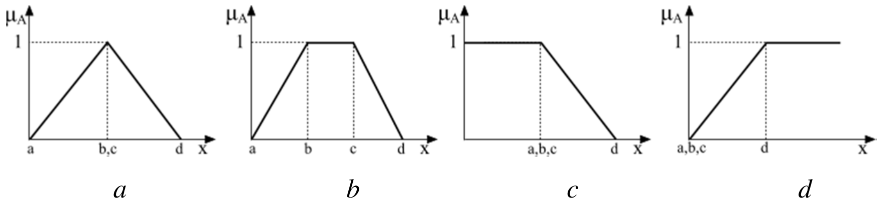

Figure 2. Piecewise-linear membership functions that were used for the fuzzification of criteria: a – triangular b – trapezoidal; c – monotonically descending; d – monotonically ascending

To implement the model in ArcGIS, thematic vector criteria layers were prepared. The decomposition of a set of objects belonging to the territory under study was performed. Decomposition was carried out in accordance with the geometric properties of objects (point, linear and polygonal) and attribute properties that determine the property of an object to a certain criterion (transport infrastructure, water bodies, settlements, etc.). The spatial processing algorithm consists of the following steps:

- Converting vector layers to rasters. In the model under consideration, the attributes of most criteria are values of distances from objects, therefore rasters of Euclidean distances were constructed for such criteria. For this, the ArcGIS ArcToolbox Euclidean Distance package geo-objects tool is used.
- Fuzzification of layers of criteria (translation of criteria attributes into a fuzzy form using the membership functions specified by experts). The Fuzzy

Membership geo-base tool is used. In the case when the membership function was not represented in the toolkit, Reclassify and Divide reclassification tools were used.

- Aggregation of criteria layers using different types of fuzzy overlay. Fuzzy Overlay tool is used.
- Presentation of results.

$$\mu_A(x) = \begin{cases} 0, & x \le 200 \\ \frac{x-200}{300}, & 200 < x \le 500 \\ 1, & 500 < x \le 1000 \\ \frac{5000-x}{4000}, & 1000 < x \le 5000 \\ 0, & 5000 < x \end{cases} \qquad (11)$$

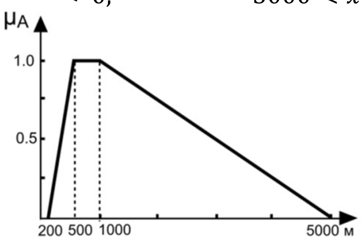

Figure 3. Membership function for linguistic variable «Distance from rail- and motor roads

To automate the processing of spatial information, a model has been developed in the environment called ArcGIS Model Builder (Fig.4).

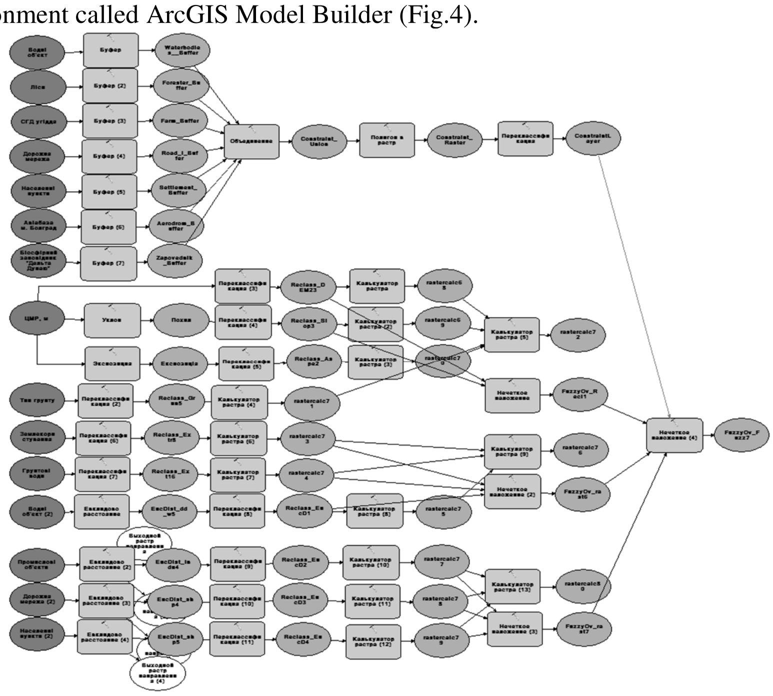

Figure 4. Data processing model in ARCGIS MODEL BUILDER

The result of the analysis of the degree of suitability of the study area for the placement of solid waste landfills, performed in the ArcGIS geographic information system, is presented in Fig. 5.

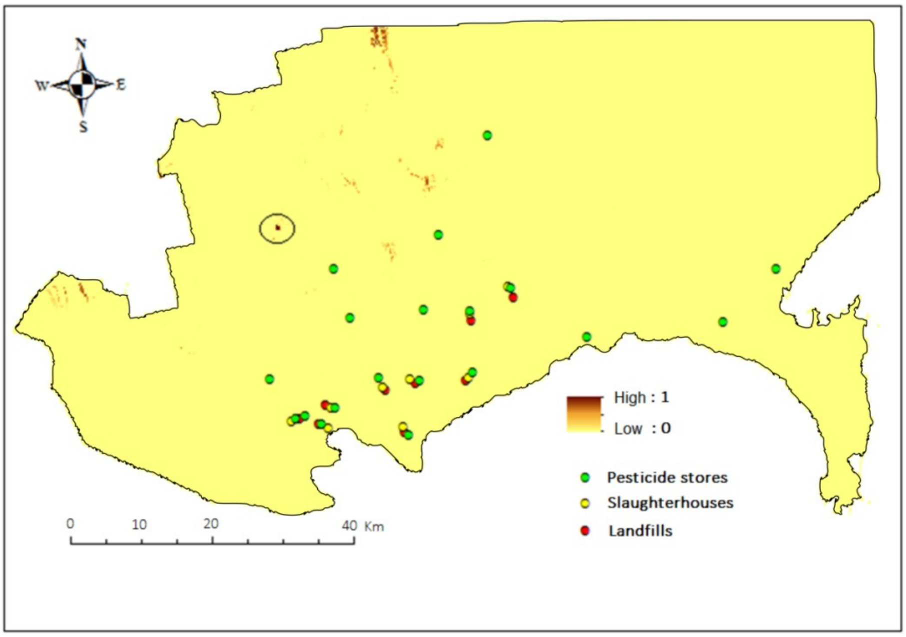

Figure 5. An example of the analysis of the degree of suitability of the territory for placing of solid waste facilities

As can be seen on the suitability map (Fig. 5), in the south of the Odessa region, there are almost no areas for the placing of solid waste landfills. This is understandable, strict requirements for its construction are difficult to fulfill, because the territory contains a large number of water bodies, agricultural land, planted forests and protected areas. The plots are either too small or of little value. The found plot (marked by a circle) has an area of 0.275 km^2. But despite the strict requirements for the construction of landfills, solid waste landfills, cattle burial grounds and pesticide depots are currently located in the study area. Fig. 5 shows the ratio of existing landfills and a suitability map constructed as a result of modeling.

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