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ASSESSMENT OF THE SUSTAINABILITY OF OBJECTS OF CULTURAL HERITAGE TO THE IMPACTS OF HAZARDOUS NATURAL PROCESSES WITH A CLIMATIC FACTOR

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Abstract

In the article, the authors propose an integrated approach to assessing the sustainability of cultural heritage objects under the influence of hazardous natural processes with a climatic factor. The approach is based on an integral indicator of the sustainability of a cultural heritage object, formed on the basis of three indicators (exposure to hazardous natural processes, physical condition and category of value of cultural heritage objects). This approach will make it possible to give a complex comprehensive assessment of a cultural heritage site and determine the weight of each factor in the formation of a common danger for such sites.

Keywords: object of cultural heritage, historical built-up areas, climate change, karst, landslide processes, flooding, sustainability of objects.

I. Introduction

Complex engineering and geological conditions of cities and modern climatic changes cause a high risk of initiation both new and activation of existing hazardous natural processes and phenomena. The consequences of data exposure have a negative impact on the state of objects of cultural heritage. Changes in the hydrogeological regime of groundwater, including those due to man-made loads and climate change, entailing the state, stability of buildings and structures [1,2]. The construction of new facilities on historical territories leads to flooding, which in turn initiates such dangerous processes as karst, landslide, and also reduce the bearing capacity of the soils of the foundations of structures [1, 2, 3]. As a result, emergency situations may occur in buildings, cracking of the walls of objects, additional wear of load-bearing structures, etc. [4,5,6].

For example, on the territory of the historical and architectural complex of the Kazan Kremlin (a UNESCO cultural heritage site), the following damage and deformations of its objects were recorded: deviation from the vertical of the curtain wall, erosion of the brickwork, cracks in the Kremlin walls, subsidence of soils of the foundations of structures, traces of wall soaking, stratification of the finishing layer (Fig. 1) [7,8].

Figure 1: *Deformations of the walls of the Kazan Kremlin (photo by the authors)*

This is due to the high intensity of natural and man-made impact on the hydrogeological environment near the Kremlin, as well as the intensification of a whole range of hydrogeological and engineering-geological processes, such as landslides, karsts, suffosions, river and ravine erosion, processing of the reservoir shore, natural and man-made flooding, subsidence phenomena in the soil [8].

The hydrogeological regime of the Kremlin Hill is determined by its geomorphology and features of the internal geological structure. Groundwater of the upper groundwater table type is almost ubiquitous at the top of the hill. Its source is atmospheric precipitation, irrigation and man-made waters. The share of the latter is especially significant in places where water utilities (water pipes, sewers) are laid and is largely associated with leaks, breakthroughs, etc. In the spring period of snowmelt and during heavy rains in the summer and autumn periods, the movement of groundwater only intensifies [7,8]. These processes of groundwater movement lead not only to flooding and liquefaction of the soils of the foundations of cultural heritage objects, but also to subsidence and uneven sedimentation of soils, a decrease in their bearing capacity and, as a result, deformation and destruction of objects occur, corrosion occurs, but also initiate other dangerous natural processes as ravine erosion, suffusion-karst and abrasion processes, landslides. In this regard, it is necessary to timely identify the negative manifestations of hazardous processes, conduct regular assessments of buildings and structures in historical territories.

Along with a number of well-known approaches to assessing sustainability [9], there is a need to develop an integrated approach by introducing an integral indicator that takes into account both the exposure of the object to hazards and the physical state of the object, the age of the object, the presence of deformation, cracks in the walls of the building.

All of the above requires the development of an integrated approach to assessing the sustainability of cultural heritage objects when exposed to hazardous natural processes with a climatic factor, aimed at preserving the architectural ensemble. Which will solve the problem of preventing the negative impact of active hazardous natural processes on historical architectural buildings and structures.

II. Development of a fuzzy model for calculating the integral indicator of sustainability of cultural heritage objects

A fuzzy controller of the Takagi-Sugeno-Kang type is a fuzzy inference system, the rule base of which contains linear analytical functions from the values of input variables in the conclusions of each rule [10,11]. The input information for the system is data on each factor of hazardous natural processes in the study area of cultural heritage objects (flat and ravine erosion, landslides, karst, reworking of the banks of reservoirs, flooding of the territory), and the result of the system is the numerical value of the integral hazard characteristic for the entire object for all factors in general. At the same time, the fuzzy nature of the degree of danger of each factor is taken into account, as well as the subjectivity of the assessment by experts in the subject area.

An integral indicator for assessing the sustainability of a cultural heritage object will be considered an indicator - G. This is a dimensionless value that can be expressed, for example, as a percentage or in fractions of a unit. The greater the G value, the greater the danger to the object and the less the sustainability of the cultural heritage object. To derive a complex integral sustainability indicator G, we define three particular indicators (Y1, Y2, Y3), on which the indicator G depends:

1. Y_1 – indicator of the object's exposure to hazardous natural processes with a climatic factor.

2. Y_2 – an indicator of the physical condition of the object (wear of structures, the presence of cracks, tifts, etc.).

3. Y_3 – indicator of the category of historical and cultural significance of a cultural heritage object.

As input variables for determining the integral indicator (Y_1), we use data from Appendix 3 of the Methodological Recommendations on Climate Adaptation [12], while taking into account those types of hazardous natural processes that are characteristic of the specific studied territory of the cultural heritage object.

To evaluate the indicator (Y_2), the initial data are indicators of the physical state of the cultural heritage object, obtained from the results of the state historical and cultural expertise (building tilt, relative difference in settlement, peeling of the lining, wear of the structure, cracks in the masonry from uneven settlement of the building (crack length)) in accordance with the category of the technical condition of the building and structure.

And when calculating the indicator (Y_3), we take into account data on the category of historical and cultural significance of a cultural heritage object.

To build a fuzzy model for evaluating the indicators (Y_1, Y_2, Y_3) of a cultural heritage object under the influence of dangerous natural processes, including with a climatic factor, it is necessary to form the left and right parts of fuzzy rules of logical inference of the form [13]. Let us consider the rules of logical inference for Y_1:

$$R_1\text{: IF } x_1 \text{ is } A_{11} \dots \text{ AND } \dots x_n \text{ is } A_{1n}\text{, THEN } y_1 \text{ is } B_1 \quad (1)$$

$$R_i\text{: IF } x_{i1} \text{ is } A_{i1} \dots \text{ AND } \dots x_{in} \text{ is } A_{in}\text{, THEN } y_i \text{ is } B_i \quad (2)$$

$$R_m\text{: IF } x_{m1} \text{ is } A_{m1} \dots \text{ AND } \dots x_n \text{ is } A_{mn}\text{, THEN } y_m \text{ is } B_m, \quad (3)$$

where x_k (k=1..n) – input variables;

y_i – output variable, i=1,m;

A_{ik} – given fuzzy sets with membership functions;

R_i – i-th inference rule.

It is necessary to build two fuzzy inference systems: Mamdani and Sugeno, to calculate the output parameters (Y_1, Y_2, Y_3) depending on the values of the input parameters for each particular indicator.

Provided that the membership functions are set for each qualitative assessment of the input and output parameters, it is possible to build the Mamdani system and calculate the value of the private indicator. However, the Mamdani system has a number of disadvantages, first of all, the impossibility of its retraining on the available initial data. These shortcomings can be avoided by a Sugeno-type system, which differs from Mamdani in the way in which the right parts of the rules are specified. In the Sugeno system, the right-hand sides are linear polynomials with respect to the input parameters with given coefficients.

To form the Sugeno system, it is necessary to use the same set of rules, however, a linear expression is written as an output parameter [13].

III. Results

As a result, a model of a three-level cascade was constructed from Neuro-Fuzzy systems of the Takagi-Sugeno-Kang type, which allows one to consistently determine all three initial partial indicators affecting the factor G (Y_1, Y_2, Y_3) (Fig. 2) [13].

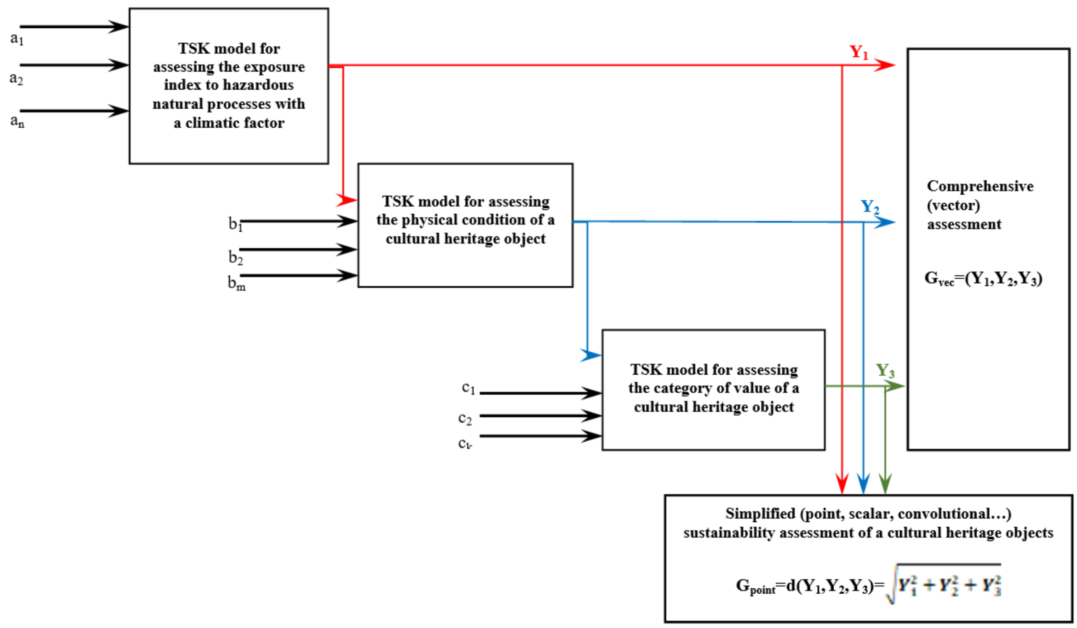

Figure 2: *Cascade Neuro-Fuzzy model of integral assessment of the sustainability index of cultural heritage objects*

The authors propose two approaches for calculating the estimate G based on the partial indicators Yi obtained at the previous stage. The first approach is to represent the quantity G as a three-dimensional vector of found Yi:

$$G = (Y_1, Y_2, Y_3) \tag{4}$$

The second approach is to calculate G as a linear convolution of the criteria Yi and obtain a scalar value of the sustainability index. Such an estimate can be obtained, in particular, as the length of the vector (Y_1, Y_2, Y_3):

$$G = \sqrt{Y_1^2 + Y_2^2 + Y_3^2} \tag{5}$$

Such a point estimate, although simplified, allows us to obtain an easily interpretable result.

To form the Sugeno system, a linear expression (function) is written: the dependence of the parameter (Y1) on the input parameters Erosion (E), Landslide (O), Karst (K), Flooding (P), Retreat (S). There should be four such functions in total - according to the number of possible qualitative estimates of the output parameter (Y1).

The function has a general form:

$$Y1=a1\ E+a2\ O+a3\ K+a4\ P+a5\ S \tag{6}$$

Thus, to determine function (6), it is necessary to calculate five unknown coefficients: a1, a2, a3, a4 and a5. In this expression, the free term a0 is omitted, since if it is present, the linear function degenerates into a singleton when calculating the coefficients according to the principle a0 = "middle of the range for a given qualitative value of the output parameter", and all other coefficients become equal to 0.

For further formation of systems of linear equations, it is necessary to have quantitative representations of the qualitative values of input and output parameters.

To determine the unknown coefficients of the linear function (4) for each qualitative value Y1* (for Y1*= "UO", "Op", "VO", "Kr"), we will develop the following procedure:

1. From Table 1, we select 5 rules so that the output value on the right side of the rule is equal to the given qualitative value Y1*, and the left side contains the maximum variety of combinations of input parameters.

2. For each selected rule, we write expression (4), replacing the parameters E, O, K, P and S with the average values of the ranges corresponding to the qualitative description from Appendix 3 of the Methodological Recommendations on Climate Adaptation [12]. As a result, 5 linear equations will be obtained with respect to five unknown coefficients ai, where i=1…5.

3. Having solved the resulting closed system of linear equations, we determine the coefficients of the linear functions of the right-hand sides of the fuzzy inference rules corresponding to the given qualitative value Y1*.

The correspondence between the data of the qualitative expression and the type of function is presented in Table 1.

Table 1: *Linear functions for the formation of the right parts of the rules of the Sugeno system*

Qualitative expression, Y_1	Type of linear function
Moderately hazardous	Y_1=0,339*Э+6,983*О+0,145*К+0,029*П+5,510*С
Dangerous	Y_1=0,067*Э+0,485*О+0,202*К+0,186*П+2,078*С
Very dangerous	Y_1= 0,031*Э+0,355*О+0,149*К+0,323*П+2,019*С
Extremely_dangerous	Y_1= 0,007*Э+0,460*О+0,784*К+0,491*П+3,886*С

Further, similarly to the Mamdani system, we will introduce into the system 5 input variables Erosion, Landslide, Karst, Flooding, Retreat, and one output variable General_Hazard_Rating (see Fig. 3). Thus, we obtain linear dependencies for a comprehensive assessment of exposure to hazardous natural processes with a climatic factor that most threaten cultural heritage sites.

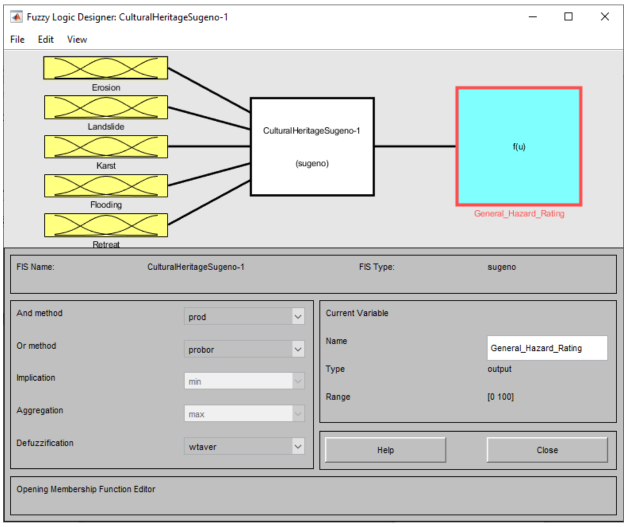

Figure 3: *View of the shell of the Sugeno system in the visualizer of the FIS package.*

IV. Conclusion

The proposed approach allows us to give a complex comprehensive assessment of the sustainability of the cultural heritage object and allows us to determine qualitatively and quantitatively the condition of the object, determine the weight of each negative factor of hazardous natural processes, including the climatic factor in the formation of the sustainability indicator in general. At the same time, the technical condition of the object and its category of significance of cultural heritage objects are taken into account. These indicators are important in determining the assessment of the sustainability of several cultural heritage objects on the territory of one municipal district or region as a whole to justify the implementation of measures to protect cultural heritage objects.

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