ТЕОРЕТИЧНІ ТА ПРИКЛАДНІ ПРОБЛЕМИ
І МЕТОДИ СИСТЕМНОГО АНАЛІЗУ

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SYSTEM APPROACH TO THE UNDERGROUND CONSTRUCTION OBJECTS PLANNING BASED ON FORESIGHT AND COGNITIVE MODELLING METHODOLOGIES[1]

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Abstract. The system approach to the underground construction objects planning based on foresight and cognitive modeling methodologies is proposed. Using the foresight methodology allows with the help of expert estimation procedures to identify critical technologies and build alternatives of scenarios with quantitative characteristics. For the justified implementation of a particular scenario the cognitive modelling is used, which allows to build causal relationships based on knowledge and experience, understand and analyze the behaviour of a complex system for a strategic perspective with a large number of interconnections and interdependencies. The suggested system approach allows planning of underground objects on the basis of reasonable scenarios selection and justification of their creation priority.

Keywords: foresight, cognitive, impulse modelling, planning, scenarios, underground construction.

INTRODUCTION

The growth of megalopolises, their populations, expansion of infrastructure are of the characteristic features of the modern world. Regulation of urban planning in order to improve environmental standards and safety of life in constantly growing megacities is one of the most pressing, but insufficiently studied and complex world problems [1]. It is leads to the search of new places to production facilities, social and other objects of human activity [2–4]. The space of megacities created by man in the process of underground construction becomes a new, underground habitat, which should be comfortable and safe for humans. Risks in underground space development which is characterized by space-temporal variability are considered in [5–8].

Various directions of implementing system approach for planning urban surface construction in megacities are known [9, 10]. Analyzing the trends of the future development of the underground space of megacities are considered the individual projects of underground urban studies that characterize the directions

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of urban underground construction in the near and medium perspective [11]. So, In Chicago, the second largest economic center in the United States, it is planned to build an underground city with a vertical layout, which will have 100 underground floors. As for the underground development, the studies went no further than general task setting and analysis of research methods [12].

Underground urban planning is a complex system in many aspects. Firstly, this system consists of many interconnected subsystems and objects. Secondly, the processes occurring in this system during construction and during operation are also complex and in some cases poorly predictable, because they are largely associated with various geological processes. The problems that accompany underground urban development can be attributed to poorly structured problems.

A system approach to the planning of underground urban studies, based on the methodology of foresight, as a tool for the concept of sustainable development of megacities was proposed in [13].

The goal of the system approach presented in this paper is to study some problems of the underground object's viability in extreme and emergency situations.

SYSTEM APPROACH TO THE UNDERGROUND CONSTRUCTION OBJECTS PLANNING BASED ON FORESIGHT AND COGNITIVE MODELLING METHODOLOGIES

In this paper the system approach to the underground construction objects planning based on the mathematical support of foresight methodology with the aim of scenarios alternatives creating and cognitive modeling to build scenarios for the development of the desired future and ways of their implementation is proposed. For realization of this system approach the totality of the properties and characteristics of the studied objects, as well as the features of the methods and procedures used to create them taking into account. Based on a comparison of the characteristics of the qualitative analysis methods, the requirements for their application, the disadvantages and advantages of each of them, researchers of foresight problems should choose the rational combination of methods, establish the correct sequence for their use, account the totality of requirements for systems and the features of the tasks to be solved.

The system approach in the form of a two-stage model based on a combination of foresight and cognitive modelling methodologies is developed and its scheme presented in Fig. 1 [14]. The involvement of scanning methods, STEEP analysis, brainstorming, SWOT analysis, TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method and VIKOR method at the initial level of the first stage allows using expert assessment to identify critical technologies in economic, social, environmental, technical, technological, information and other directions [15–18]. The basis of this level is the analysis subsystems, which are connected by direct and feedback links to the monitoring system and field tests. The quantitative data obtained after analysis and processing are the initial ones for solving of foresight tasks. The construction of rational alternatives of scenarios for the development of strategically important underground objects are expedient to be performed on the basis of a collection of foresight activities. For this goal, in the process of creating alternatives of scenarios it becomes necessary to involve expert assessment methods, among which are the most commonly used methods of analytic hierarchy, Delphi methods and morphological analysis [19–22].

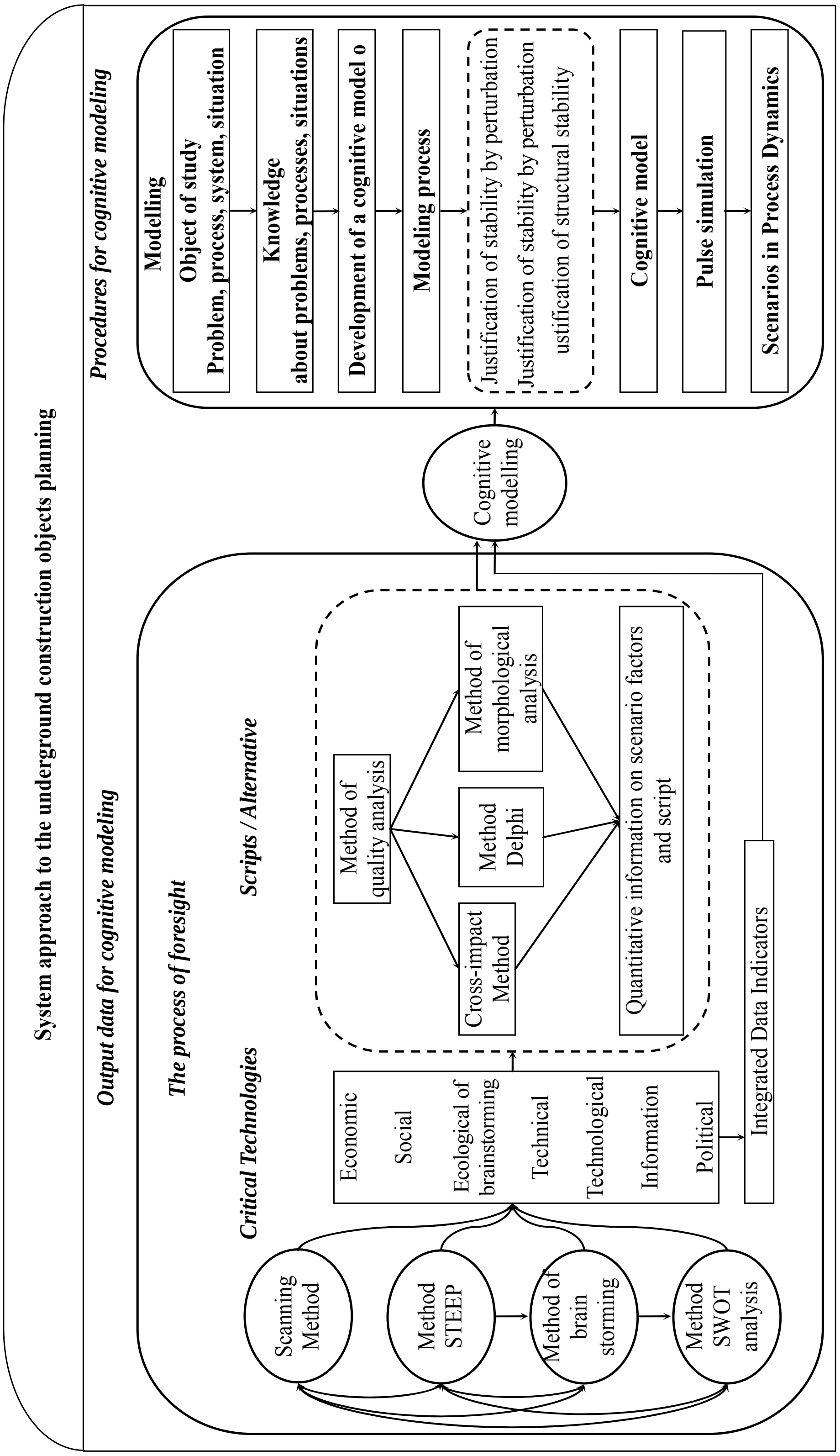


Fig. 1. Scheme of the system approach to the underground construction objects planning

In this paper to identify critical technologies the SWOT analysis method is used. For the purpose of ranking the obtained critical technologies and identifying the most topical ones, the TOPSIS method is applied [16,17]. The method TOPSIS of multicriterial analysis (ranking) of alternatives in addition to estimating the distance from the considered alternative to the ideal solution allows to take into account the distance to the worst solution. The trade-off in choosing the best alternative is based on the fact that the chosen solution must be at the same time as close to the ideal as possible and most remote from the worst solution. The obtained rating makes it possible to take into account the weight characteristics of critical technologies that are the vertices of the cognitive map when constructing a cognitive model. According to the VIKOR method, a compromise solution to the problem should be an alternative that is closest to the ideal solution. Moreover, to assess the degree of the alternative proximity to the ideal solution, a multicriteria measure is used [18]. As soon as the critical technologies are identified we cross to the system approach second level, using the qualitative methods for creation alternatives of socio-economic systems scenarios [21].

In some cases, when the output information for cognitive modeling is given in statistical form as separate logical groups, the method of constructing an integrated indicator data is proposed [23]. This enables all groups to aggregate in integrated indicator data used the proposed method of recovery of functional dependences for discrete preset samples or carry out decomposition integrated indicator to individual subject groups, followed by decomposition of the logical sequence characteristics. That is the construction of cognitive maps reasonably add or remove her vertex, vertex to break a sequence of interconnected nodes.

Formalization the method of constructing an integrated indicator data implies the use of this sequence of procedures:

- the selection of indicator which will characterize the specific area of one of the directions of sustainable development (economic, environmental, social);
- grouping by specific characteristics of the data sets, which influence the dynamics, selected at the stage 1 of the indicator formation;
- forming a database for a specific period on the basis of the discrete samples;
- recovery of functional dependencies by the discrete samples;
- analysis of the results based on the recovered dependence.

At the second stage of system approach for the construction of scenarios correspond to selected alternatives, cognitive modelling is involved [24]. which makes it possible to obtain a valid scenario for decision making. According to the developed methodology of cognitive modeling for complex systems [24–27], modeling is carried out in some steps. At the first step of the cognitive modelling, using the results of foresight methodology, theoretical and practical data on underground urban planning, the cognitive model as cognitive map is developed. The cognitive map in the form of a sign oriented graph and a functional graph in the form of a weighted sign digraph are created. At the second step of cognitive modeling the investigation of the cognitive model properties, methods of analysis of structural stability and resistance to disturbances, methods of analysis of model connectivity (simplicial analysis), and graph theory methods are used. The proofs of numerical stability of cognitive maps based on the representation of values and perturbations at the vertices of the graph in matrix form are presented [14]. At the third step of cognitive modeling, to determine the possible development of processes in a complex system and to create the scenario development, an impulse process model (simulation of disturbance propagation on cognitive models) is used, which allows to create the scenarios of development in the process of dynamics and to propose a scientifically based strategy for implementing the priority scenario [28].

So, at the first step of cognitive modelling the cognitive models such as a cognitive map – a sign oriented graph (1) and a functional graph in the form of a weighted sign digraph is created [24–29]

$$G = \langle V, E \rangle,$$

where G is a cognitive map in which V are concepts, a finite set of vertices of the cognitive map $V_i \in V,\ i = 1,2,...,k;\ E = \{e_{ij}\}$ is the set of arcs e_{ij} of the graph, $i, j = 1,2,...,m$, reflect the relationship between the vertices V_i and V_j; the influence of V_i on V_j in the situation under study can be positive (+1) when an increase (decrease) in one factor leads to an increase (decrease) in another, negative (–1) when an increase (decrease) in one factor leads to a decrease (increase) in another , or absent (0). The cognitive map G corresponds to the square matrix of relations A_G:

$$A_G = \{a_{ij}\} = \begin{cases} 1, & \text{if } V_i \text{ is connected with } V_j, \\ 0, & \text{otherwise.} \end{cases}$$

The ratio a_{ij} can take the value “+1” or “–1”. The relation between variables (interaction of factors) is a quantitative or qualitative description of the effect of changes in one variable on others at the corresponding vertices.

Vector Functional Graph

$$\Phi = \langle G, X, F(X, E), \theta \rangle,$$

where G is a cognitive map; X is the set of vertex parameters,, is the space of vertex parameters; $F(X,E)$ is the arc transformation functional.

At the second step of cognitive modeling, to study the properties of the cognitive model, is used methods of structural stability and perturbation resistance analysis [24–26], methods for analyzing model connectivity (simplicial analysis [27, 28]), and graph theory methods [29]. The results of the analysis were compared with the available information on underground construction.

At the third step of cognitive modeling, to determine the possible development of processes in a complex system and develop development scenarios, is using the impulse process model (modeling the propagation of disturbances in cognitive models) [25, 29]:

$$x_{v_i}(n+1) = x_{v_i}(n) + \sum_{v_j : e = e_{ij} \in E}^{k-1} f(x_i, x_j, e_{ij}) P_j(n) + Q_{vi}(n), \tag{1}$$

where $x(n),\ x(n+1)$ are the values of the indicator at the vertex V_i at the simulation steps at time $t = n$ and the next $t = n+1$; $P_j(n)$ is the momentum that existed at the vertex V_j at the moment $t = n$; $Q_{V_i}(n) = \{q_1, q_2, ..., q_k\}$ is the vector of external pulses (disturbing or controlling actions) introduced to the vertices V_i at time moment *n*. It allows to consider of modeling process in dynamic.

MODELLING OF UNDERGROUND CONSTRACTION

In the framework of the foregoing, let us call the studied complex system “Natural-technical geosystem”.

The first step. Cognitive Model Development. Table 1 presents data on the vertices (concepts) of the hierarchical cognitive model without reference to a specific territory, in a generalized form. The generalizing concepts (indicators, factors), independent of the specifics, which can be disclosed and taken into account in the future when developing the lower levels of the hierarchical model, are using. Fig. 2 shows a hierarchical cognitive map I_G: “Natural-technical geosystem”. In Table 1 and Fig. 2, the vertices of the upper (first level) are denoted as $I - V_i$, $i = 5, 11, 13, 15, 16$.

Table 1. The vertices of the hierarchical cognitive map “Natural-technical geosystem”

Code	Vertex explanation	Vertex assignment
$I - V_{11}$	The viability of the underground urban development	Indicative
$I - V_{13}$	Disasters, extreme and emergency situations	Perturbing
$I - V_{15}$	Environmental risks	Perturbing
$I - V_{16}$	Economic risks	Perturbing
$I - V_5$	Genetic type and lithological composition of soils	Basic
V_1	Mountain and hydrostatic pressure, seismic impact	Basic
V_2	Surface Load Static Load Index	Basic
V_3	The indicator of the static load of the surrounding soil massif	Basic
V_4	Existing underground facilities	Disturbing
V_6	Estimatedsoilresistance	Basic
V_7	Aquifers and High Water	Disturbing
V_8	ReliefTypeandMorphometry	Basic
V_9	Engineering and geological processes	Disturbing
V_{10}	Mining construction technologies	Regulating
V_{12}	The level of comfort of work and rest during the construction and operation of underground structures	Indicative
V_{14}	Construction, operational, managementrisks	Disturbing
V_{17}	Staffqualifications	Regulating
V_{18}	Industrial Safety	Basic
V_{19}	Quality and construction time	Regulating

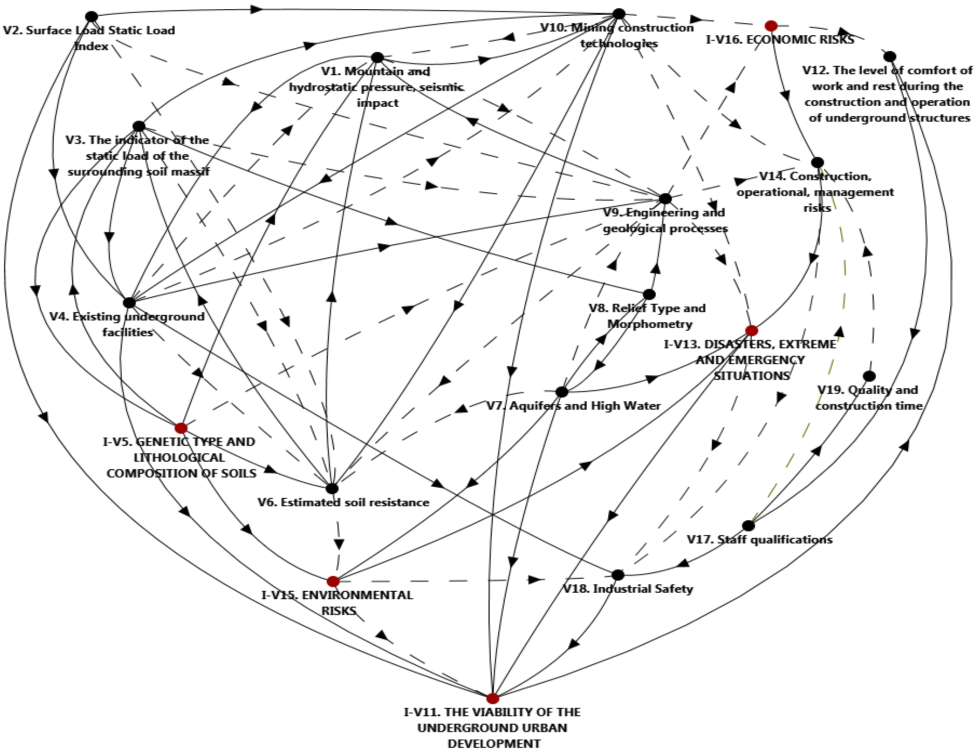


Fig. 2. Hierarchical cognitive map I_G “Natural-technical geosystem”

The cognitive model is a simulation model that makes it possible not to conduct an experiment on a “living” system, but to simulate its behavior and possible future development under the influence of various factors, generating new knowledge about the system. This allows to justify management decisions in a given situation.

The second step of modeling. Before using the cognitive model to determine its possible behavior, the second step of modeling analyzes the various properties of the model are fulfiled. In this case, the stability properties of the model must be analyzed.

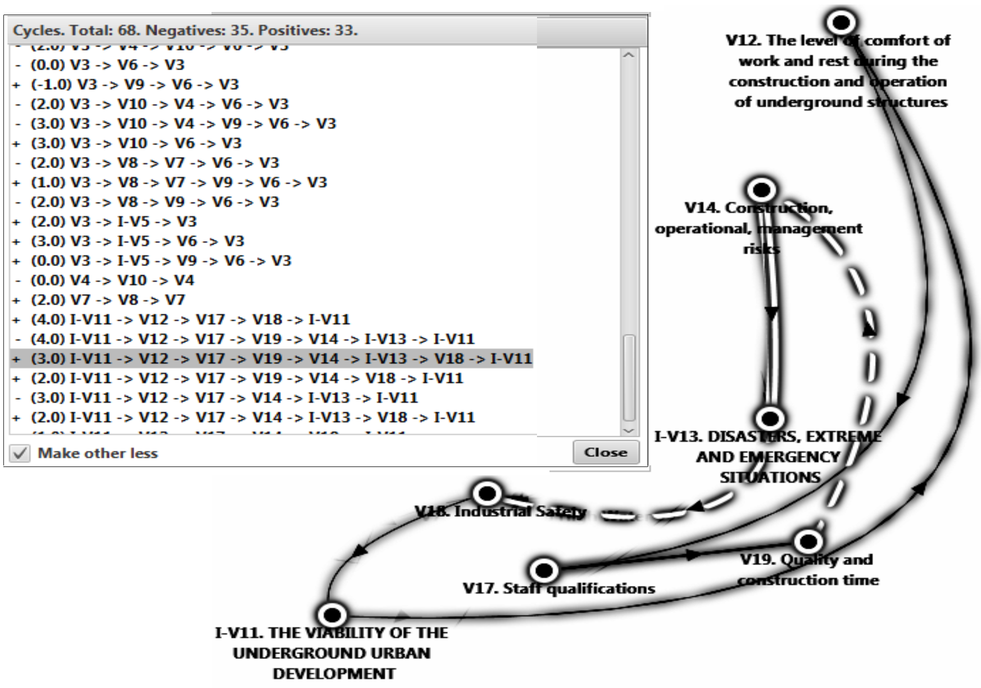
The results of the analysis of the model properties obtained using the CMLS software system [30]. Figs 3 and 4 shows an example of determining the cycles of the cognitive model I_G .

The fig. 3 shows one of the positive feedback cycles, a sign of which is an even number of negative arcs in it. Fig. 4 one of the negative cycles

Impulse sustainability. The cognitive model I_G was not resistant to perturbations according to the accepted criterion [24]: the maximum modulo M root of the characteristic equation of the matrix of relations of the graph I_G is $|M| = 1,82 > 1$ (must be less than 1).

Structural stability. An analysis of the ratio of the number of stabilizing cycles (35 negative feedbacks) and process accelerator cycles (33 positive feedbacks) indicates the structural stability of such a system [24].

The given example of the analysis of the cycles of the cognitive model showed the variety of cycles of cause and effect relationships that exist in complex systems. There are 68 of them in the analyzed system. Without an appropriate theoretical analysis, there is a great risk of the human factor in making managerial decisions, because its consequences may not be obvious due to the complexity of interactions in the system.



```
-  (0.0) V3 -> V6 -> V3
+  (-1.0) V3 -> V9 -> V6 -> V3
-  (2.0) V3 -> V10 -> V4 -> V6 -> V3
-  (3.0) V3 -> V10 -> V4 -> V9 -> V6 -> V3
+  (3.0) V3 -> V10 -> V6 -> V3
-  (2.0) V3 -> V8 -> V7 -> V6 -> V3
+  (1.0) V3 -> V8 -> V7 -> V9 -> V6 -> V3
-  (2.0) V3 -> V8 -> V9 -> V6 -> V3
+  (2.0) V3 -> I-V5 -> V3
+  (3.0) V3 -> I-V5 -> V6 -> V3
+  (0.0) V3 -> I-V5 -> V9 -> V6 -> V3
-  (0.0) V4 -> V10 -> V4
+  (2.0) V7 -> V8 -> V7
+  (4.0) I-V11 -> V12 -> V17 -> V18 -> I-V11
-  (4.0) I-V11 -> V12 -> V17 -> V19 -> V14 -> I-V13 -> I-V11
+  (3.0) I-V11 -> V12 -> V17 -> V19 -> V14 -> I-V13 -> V18 -> I-V11
+  (2.0) I-V11 -> V12 -> V17 -> V19 -> V14 -> V18 -> I-V11
-  (3.0) I-V11 -> V12 -> V17 -> V14 -> I-V13 -> I-V11
+  (2.0) I-V11 -> V12 -> V17 -> V14 -> I-V13 -> V18 -> I-V11
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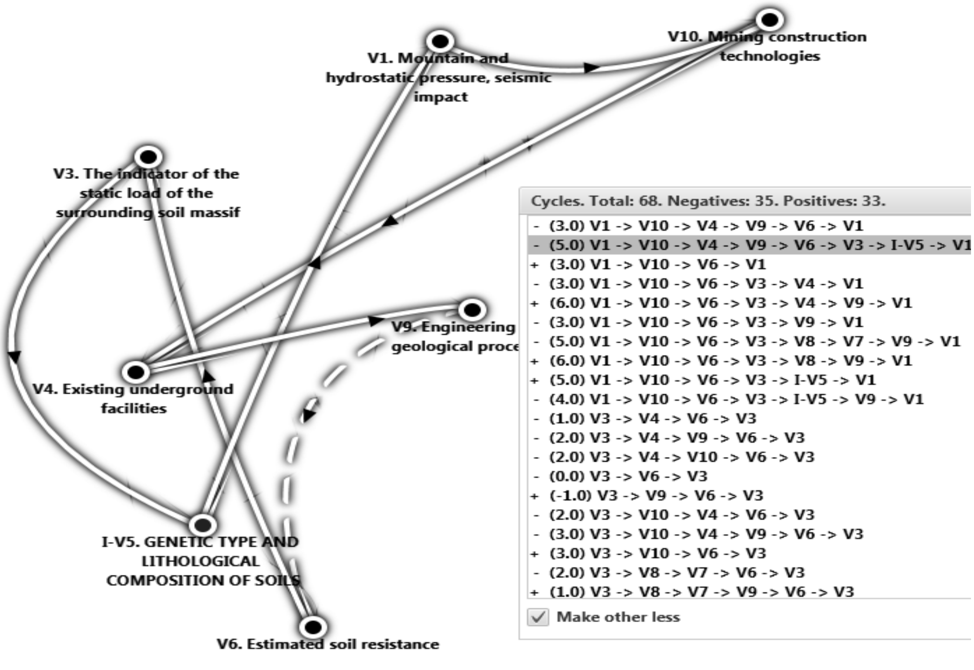
Fig. 3. Cognitive map cycles, one of the positive cycles is highlighted



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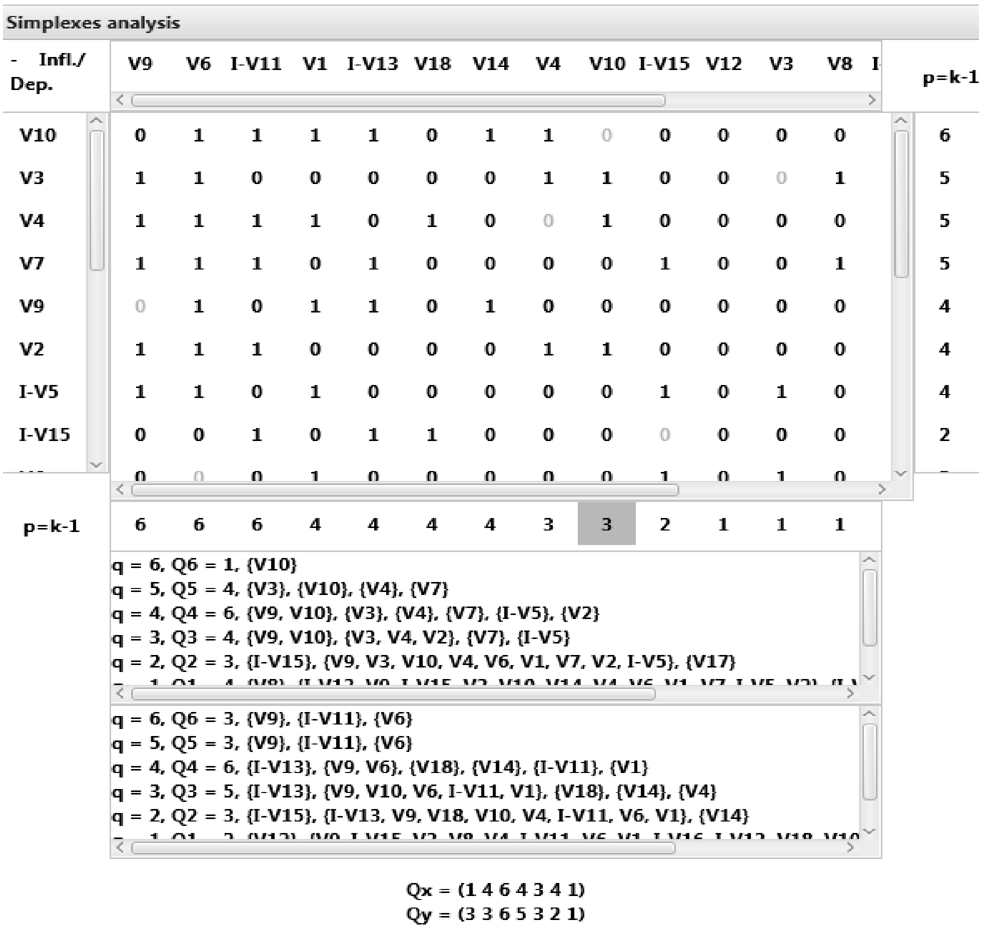
-  (3.0) V1 -> V10 -> V4 -> V9 -> V6 -> V1
-  (5.0) V1 -> V10 -> V4 -> V9 -> V6 -> V3 -> I-V5 -> V1
+  (3.0) V1 -> V10 -> V6 -> V1
-  (3.0) V1 -> V10 -> V6 -> V3 -> V4 -> V1
+  (6.0) V1 -> V10 -> V6 -> V3 -> V4 -> V9 -> V1
-  (3.0) V1 -> V10 -> V6 -> V3 -> V9 -> V1
-  (5.0) V1 -> V10 -> V6 -> V3 -> V8 -> V7 -> V9 -> V1
+  (6.0) V1 -> V10 -> V6 -> V3 -> V8 -> V9 -> V1
+  (5.0) V1 -> V10 -> V6 -> V3 -> I-V5 -> V1
-  (4.0) V1 -> V10 -> V6 -> V3 -> I-V5 -> V9 -> V1
-  (1.0) V3 -> V4 -> V6 -> V3
-  (2.0) V3 -> V4 -> V9 -> V6 -> V3
-  (2.0) V3 -> V4 -> V10 -> V6 -> V3
-  (0.0) V3 -> V6 -> V3
+  (-1.0) V3 -> V9 -> V6 -> V3
-  (2.0) V3 -> V10 -> V4 -> V6 -> V3
-  (3.0) V3 -> V10 -> V4 -> V9 -> V6 -> V3
+  (3.0) V3 -> V10 -> V6 -> V3
-  (2.0) V3 -> V8 -> V7 -> V6 -> V3
+  (1.0) V3 -> V8 -> V7 -> V9 -> V6 -> V3
```

Fig. 4. Cognitive map cycles, one of the negative cycles is highlighted

Analysis of system connectivity, simplicial analysis. Immersed in the study of the structure of the cognitive model, it is desirable to conduct a simplicial analysis of the properties of its connectivity. Such an analysis is carried out in order to study and understand the topological properties of the model and, accordingly, other connectivity faces of the complex system under study that are not detected in the above algebraic analysis. According to R.H. Atkin and J. Casti, connectedness is the essence of the concept of a large system [27, 28].

The connectivity properties of blocks (simplexes) characterize the "deep" connections of the cognitive model, the connections of its simplexes, and not just the vertices, as in the cognitive map. A simplex is formed by each vertex, which is the reason that some other vertices interact with each other. Figs 5, 6 and 7 show the results of a simplicial analysis of the I_G model. Figure 5 shows the transformed matrix of relations of the graph I_G with the dimensions ρ of simplexes $\sigma_{\rho}^{V_i}$ of rows (x) and columns (y) indicated in it in the decreasing order; $\rho = k-1$, k is the number of elements in the corresponding row / column, the dimension of the simplex shows the number of edges connecting the vertices. In Fig. 6, the simplices $\sigma_{\rho=3}^{(V_{10})}$ ($\rho = 3$ means that three edges go out from each vertex) of the simplex are highlighted for one vertex V_{10}. This vertex V_{10} is the reason for the connection of the vertices V_1, V_2, V_3, V_4.Those, vertex Mining



Simplexes analysis

- Infl./ Dep.	V9	V6	I-V11	V1	I-V13	V18	V14	V4	V10	I-V15	V12	V3	V8	p=k-1
V10	0	1	1	1	1	0	1	1	0	0	0	0	0	6
V3	1	1	0	0	0	0	0	1	1	0	0	0	1	5
V4	1	1	1	1	0	1	0	0	1	0	0	0	0	5
V7	1	1	1	0	1	0	0	0	0	1	0	0	1	5
V9	0	1	0	1	1	0	1	0	0	0	0	0	0	4
V2	1	1	1	0	0	0	0	1	1	0	0	0	0	4
I-V5	1	1	0	1	0	0	0	0	0	1	0	1	0	4
I-V15	0	0	1	0	1	1	0	0	0	0	0	0	0	2
p=k-1	6	6	6	4	4	4	4	3	3	2	1	1	1	

```
q = 6, Q6 = 1, {V10}
q = 5, Q5 = 4, {V3}, {V10}, {V4}, {V7}
q = 4, Q4 = 6, {V9, V10}, {V3}, {V4}, {V7}, {I-V5}, {V2}
q = 3, Q3 = 4, {V9, V10}, {V3, V4, V2}, {V7}, {I-V5}
q = 2, Q2 = 3, {I-V15}, {V9, V3, V10, V4, V6, V1, V7, V2, I-V5}, {V17}
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q = 6, Q6 = 3, {V9}, {I-V11}, {V6}
q = 5, Q5 = 3, {V9}, {I-V11}, {V6}
q = 4, Q4 = 6, {I-V13}, {V9, V6}, {V18}, {V14}, {I-V11}, {V1}
q = 3, Q3 = 5, {I-V13}, {V9, V10, V6, I-V11, V1}, {V18}, {V14}, {V4}
q = 2, Q2 = 3, {I-V15}, {I-V13, V9, V18, V10, V4, I-V11, V6, V1}, {V14}
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```
Qx = (1 4 6 4 3 4 1)
Qy = (3 3 6 5 3 2 1)
```

Fig. 5. Results of simplicial analysis (calculation)

construction technologies (V_{10}) is the reason that vertices Mountain and hydrostatic pressure, seismic impact (V_1), Surface Load Static Load Index (V_2), The indicator of the static load of the surrounding soil massif (V_3), Existing underground facilities (V_4) forming one block are interconnected.

Thus, these vertices are the cause of the simplex in the form of a tetrahedron.

Note that simplexes of higher dimension are not depicted on the plane; only their “projection” can be conditionally drawn – Fig. 7.

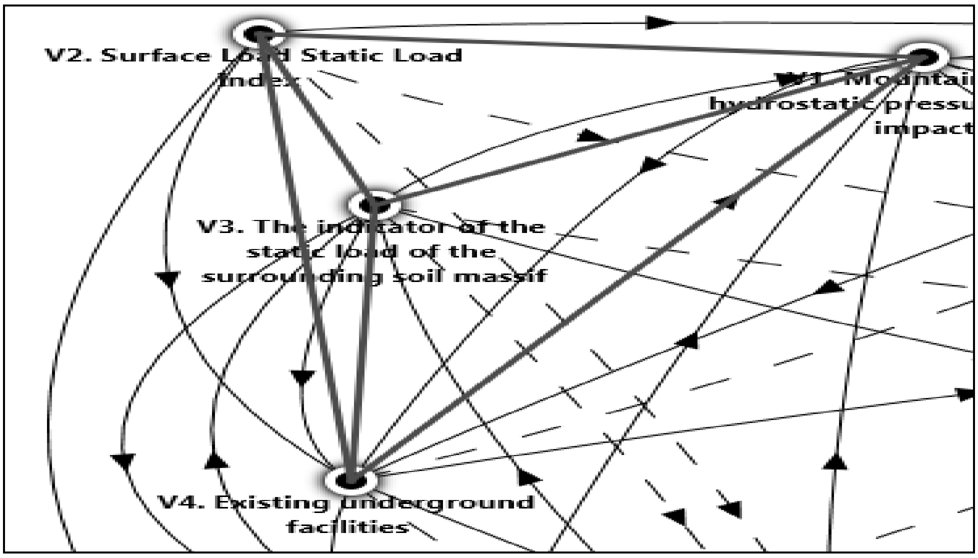
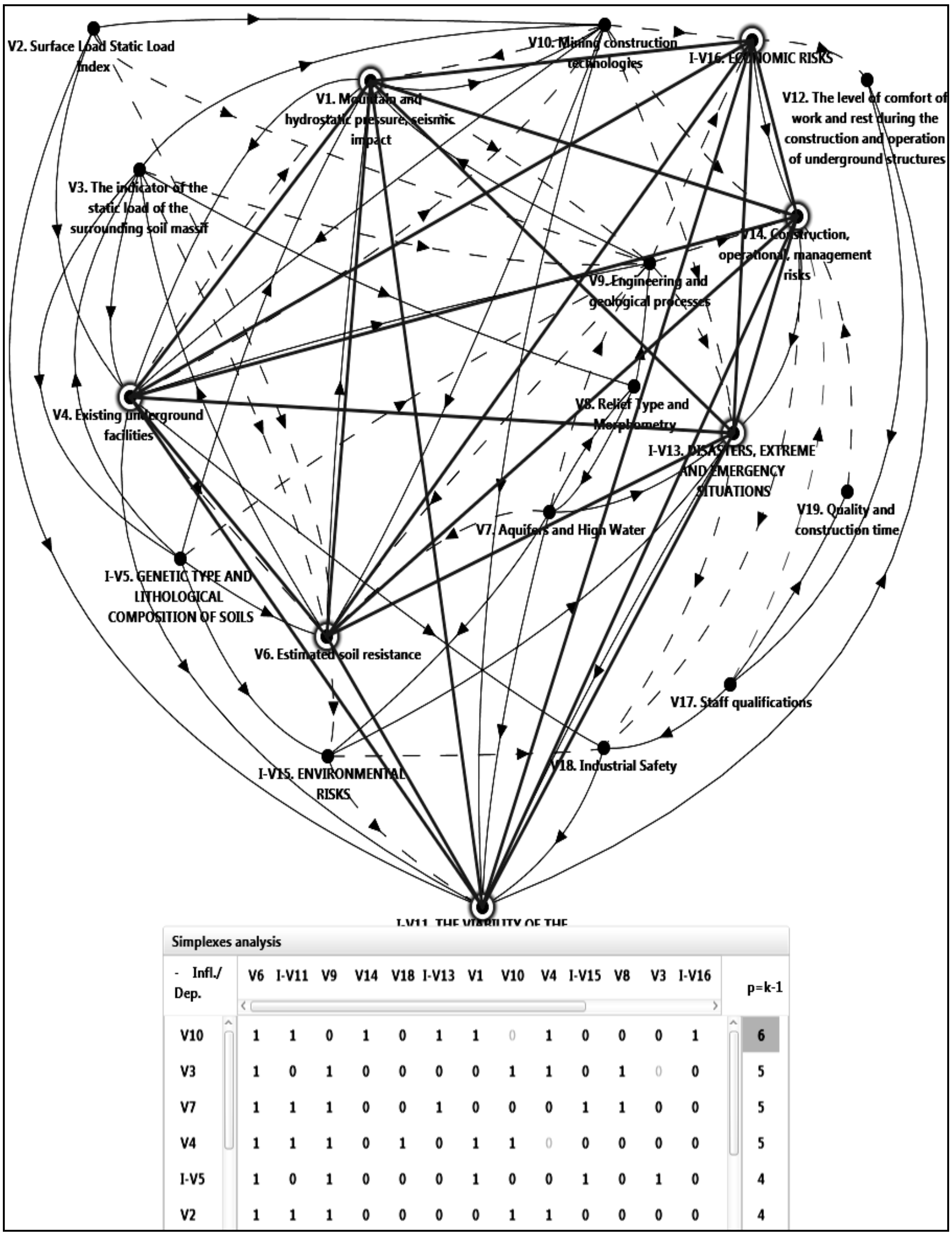


Fig. 6. Image of one of the simplices of dimension $\rho = 3$

Simplexes form q-connected chains $q = 1$ (connection through a vertex), $q = 2$ (connection through an edge), $q = 3$ (connection through a plane), etc., thus uniting into simplicial complexes K_x (along the lines – “inputs”) and K_y (columns –“outputs”). Simplexes are q-connected or not in simplexes (they lack or have connections of simplexes along vertices, edges, planes, m-dimensional volumes). Simplicial complexes are characterized by the structural vectors Q_x and Q_y formed by vertex groups common to different simplexes.

The third stage of modeling. Scenario analysis is designed to anticipate possible trends in the development of situations on the model.To generate scenarios of the development of the system, impacts are introduced into the vertices of the cognitive map in the form of a set of impulses. The impulse process formula has the form (1).

It is possible to introduce perturbations Q of different sizes (normalized) to any of the vertices, as well as to their combination. In connection with a large number of theoretically possible variants of introduced disturbances, it is necessary to develop a plan for a computational experiment before excluding pulse simulation, eliminating at least almost impossible variants.



Simplexes analysis

- Infl./ Dep.	V6	I-V11	V9	V14	V18	I-V13	V1	V10	V4	I-V15	V8	V3	I-V16	p=k-1
V10	1	1	0	1	0	1	1	0	1	0	0	0	1	6
V3	1	0	1	0	0	0	0	1	1	0	1	0	0	5
V7	1	1	1	0	0	1	0	0	0	1	1	0	0	5
V4	1	1	1	0	1	0	1	1	0	0	0	0	0	5
I-V5	1	0	1	0	0	0	1	0	0	1	0	1	0	4
V2	1	1	1	0	0	0	0	1	1	0	0	0	0	4

Fig. 7. Image of the projection of one of the simplexes of dimension $\rho = 6$

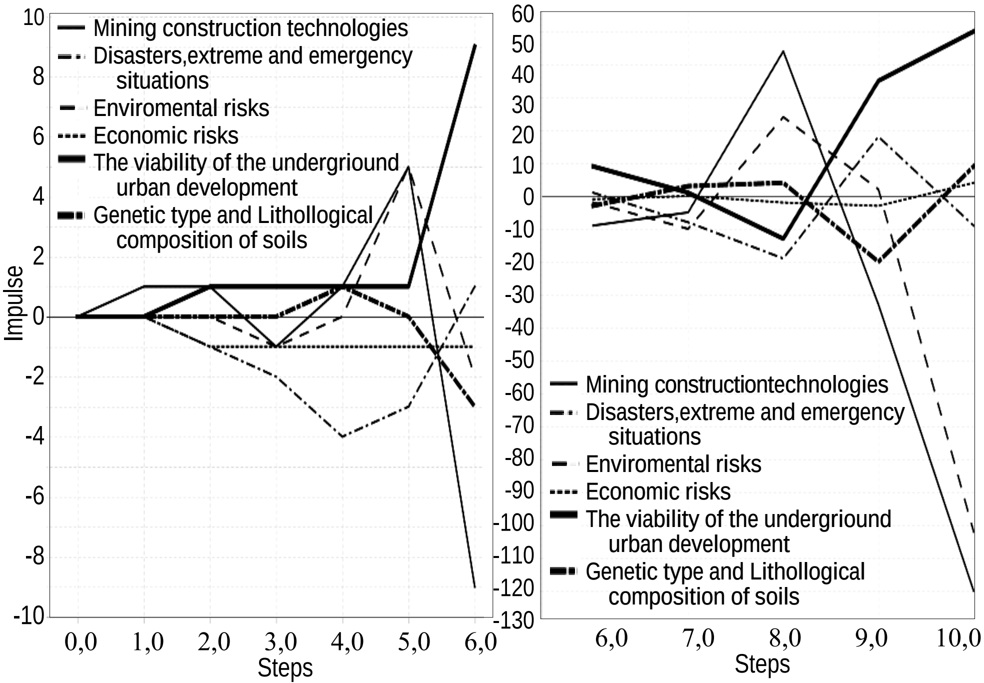
Introducing disturbances to the vertices, the decision-maker is looking for the answer to the question: “What will happen if ...?”

The CMLS software system [30] allows, in the process of pulse modeling and analysis of the obtained results, to introduce control or disturbing influences at any modeling step. This allows to change (correct) scenarios in model dynamics, to determine the effects that bring the processes closer to the desired.

The results of pulse modeling in four scenarios are presented.

Scenario No. 1. Assume good technology is used in underground construction. To the vertex V_{10}, the control action is introduced $q_{10} = +1$, the perturbation vector $Q = \{q_1 = 0, \dots q_{10} = +1, \dots q_{19} = 0\}$.

Fig. 8 shows graphs of pulsed processes. For the convenience of visual analysis of the image, the graphs of pulsed processes in the vertices V_{10}, $I - V_{13}$, $I - V_{15}$, $I - V_{16}$, $I - V_{11}$, $I - V_5$ are represented by two figures: Fig. 8,*a* from the first to the sixth step of modeling and Fig. 8,*b* from the sixth to tenth step of modelling. The image of pulsed processes at a larger number of simulation steps is not necessary, because system behavior trends under these conditions are already evident.



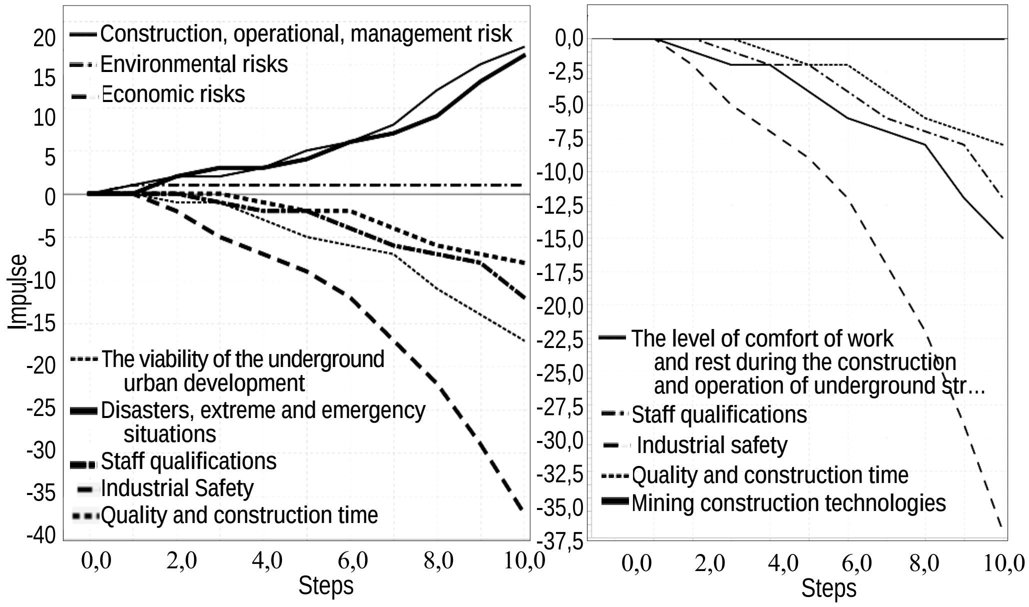
a *b*

Fig. 8. Graphs of pulsed processes, from the first to the sixth step of modeling (*a*) (scenario No. 1); from the first to the sixth step of modeling (*b*) (scenario No. 1)

Modeling scenario No. 1, it is advisable to analyze whether changes in Mining construction technologies (V_{10}) can and in what way affect other vertices of the cognitive model. As can be seen from the graphs in Fig. 8, positive changes in V_{10} can contribute to positive trends in the development of vertices at the top hierarchical level: up to the 5th and 6th steps of the modeling, the declining trends of Disasters, extreme and emergency situations ($I - V_{13}$), Environmental risks ($I - V_{15}$), Economic risks ($I - V_{16}$), Genetic type and lithological composition of soils ($I - V_5$), The viability of the underground urban development ($I - V_{11}$) is growing.

All this may indicate that a single positive change in one of the vertices of the system model may not be enough to exclude the negative impact of risks and other negative influences.

Scenario No. 2. Suppose that the possibility of the simultaneous occurrence of all risks is increasing in the system. Disturbing effects are appearing $q_{14} = +1, q_{15} = +1, q_{16} = +1$, there is perturbation vector $Q = \{q_1 = 0,.., q_{14} =$ $= +1, q_{15} = +1, q_{16} = +1,..., q_{19} = 0\}$.



a *b*

Fig. 9. Graphs of pulsed processes: 9,*a* and 9,*b* are scenarios No. 2

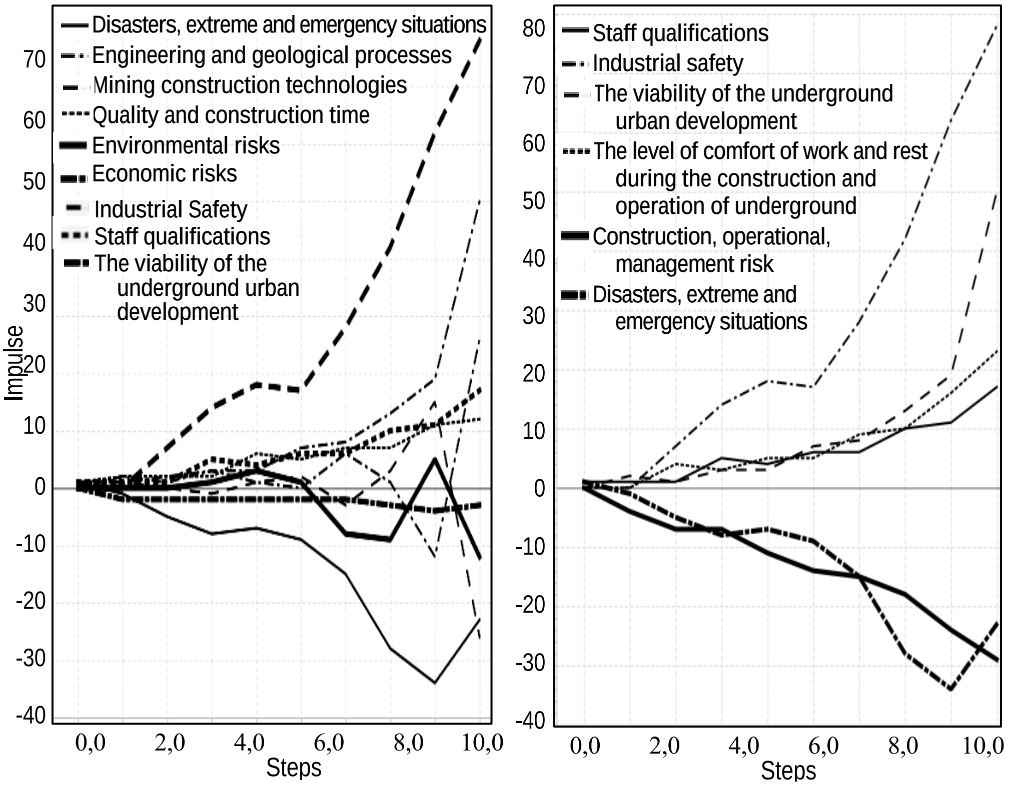
Pulse simulation results are presented in Fig. 9,*a* for vertices V_{14}, $I - V_{15}$, $I - V_{16}$,$I - V_{11}$, $I - V_{13}$, V_{17}, V_{18}, V_{19} and Fig. 9,*b* for vertices $V_{12}, V_{17}, V_{18}, V_{19}, V_{10}$.

The simulation results of the second scenario show an extremely unfavorable option for the development of situations in the system. With increasing risks all indicators of the system fall at both the first and second levels of the hierarchy. This observation forces one to make a decision on the search for the necessary counteraction to the situations that have arisen.

Consider the third scenario. Suppose improving Engineering and geological processes (V_9), Mining construction technologies (V_{10}), Staff qualifications (V_{17}), Quality and construction time (V_{19}), but there are Disasters, extreme and emergency situations ($I - V_{13}$).

Scenario No. 3. Control actions $q_9 = +1$, $q_{10} = +1$, $q_{17} = +1$, $q_{19} = +1$, $q_{13} = +1$, the perturbation vector $Q = \{q_1 = 0, \ldots, q_9 = +1, q_{10} = +1, \ldots, q_{13} =$ $= +1, \ldots, q_{17} = +1, \ldots, q_{19} = +1\}$.

The results of pulse modeling are presented in Fig. 10,*a* for vertices $I - V_{13}$, V_9, V_{10}, V_{19}, $I - V_{15}$, $I - V_{16}$, V_{18}, V_{17}, $I - V_{11}$ and Fig. 10,*b* for vertices V_{17}, V_{18}, V_{19}, $I - V_{11}$, V_{12}, V_{14}, $I - V_{13}$.



a *b*

Fig. 10. Graphs of pulsed processes: 10,*a* and 10,*b* are scenarios No. 3

An analysis of the results of impulse modeling according to scenario No. 3 shows that the introduction of control actions to the vertices of Engineering and geological processes (V_9), Mining construction technologies (V_{10}), Staff qualifications (V_{17}), Quality and construction time (V_{19}), but there are Disasters, extreme and emergency situations ($I - V_{13}$) can counteract the negative impact of possible disasters and extreme situations, reducing the impact of economic, environmental and technological risks. Thus, scenario No. 3 can be considered favorable: industrial safety is increasing.

The simulation results in one more scenario No. 4 is presented. Assume that Construction, operational, management risks can be reduced. In this case, the impulse actions initiate 6 vertices of the model and the synergistic effect of their joint action is investigated. The modeling of this scenario of the situations development on the model is carried out in order to determine whether it is necessary or not to strengthen the impact on the system to achieve good indicators.

Scenario No. 4. Control actions $q_9 = +1$, $q_{10} = +1$, $q_{17} = +1$, $q_{19} = +1$, $q_{13} = +1$, $q_{14} = -1$, the perturbation vector $Q = \{q_1 = 0, \ldots, q_9 = +1, q_{10} = = +1, \ldots, q_{13} == +1,\ q_{14} = -1, \ldots,\ q_{17} = +1, \ldots,\ q_{19} = +1\}$.

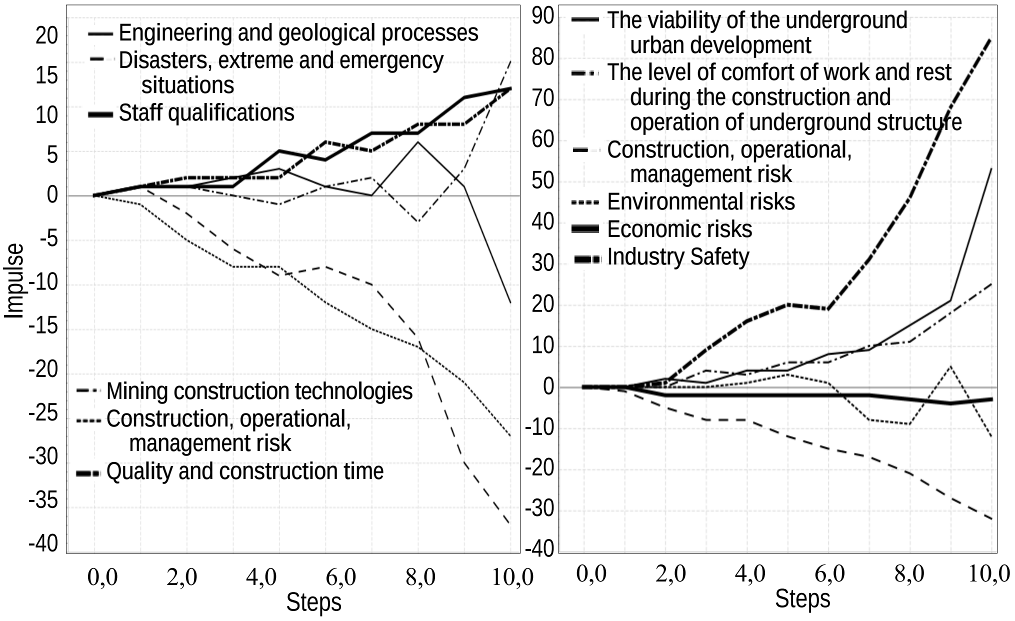
The results of pulse modeling are presented in Fig. 11,*a* for vertices $I - V_{13}$, V_9, V_{10}, V_{14}, V_{17}, V_{19}, and Fig. 11,*b* for vertices V_{12}, V_{14}, V_{15}, V_{16}, V_{18}, $I - V_{11}$.

Analysis of the simulation results of Scenario No. 4, which differs from scenario No. 3 by the addition of an impulse $q_{14} = -1$, simulating the possibility of reducing Construction, operational, management risks showed the following. The combined positive impact of six factors on the system leads to the possibility of the appearance of desirable trends in situations throughout the system. So, there are tendencies of improvement (growth) of the underground urban development viability, the level of comfort, work and rest during the construction and operation of underground structures, Industrial Safety while reducing all types of risk and reducing Disasters, extreme and emergency situations

Let us compare the simulation results of Scenarios No. 1, No. 2, No. 3 and No. 4, using the capabilities of the CMLS software system. The results of pulse modeling at the 10th step of modeling are selected and presented them in the form of histograms in Fig. 12.

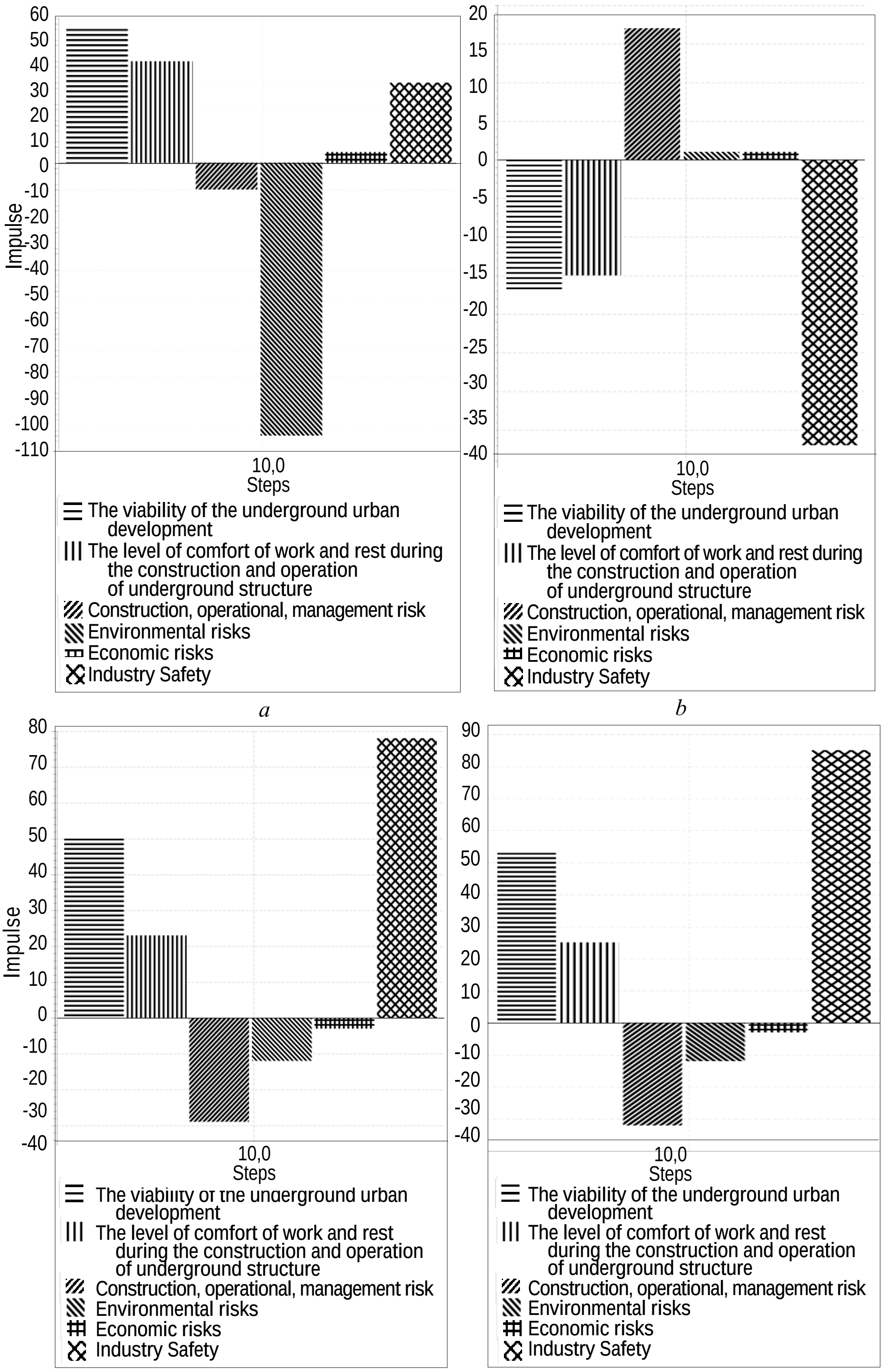
As can be seen from Fig. 12, scenario No. 4 can be considered the best of those considered, although its results are not too different from the results of scenario No. 3. If you set the task of minimizing the cost of resources for the particular scenario implementation, then perhaps scenario No. 3 will be the best, with fewer control actions in the system.

A comparison of the results of scenarios No. 3 and No. 4 with the results of scenario No. 1, in which the control action is applied to only one vertex, shows that it is inferior to scenarios No. 3 and No. 4. So, for example, the pulse value at the vertices of Industrial safety (V10) reaches 30, and according to scenario No. 3, the pulse value at this vertex is 78, and according to scenario No. 4 pulse value is 85. If we compare the simulation results of scenario No. 2 with the results of other scenarios, it is obvious that without countering possible risks, the development scenarios of the Natural-technical geosystem system will be extremely pessimistic.



a *b*

Fig. 11. Graphs of pulsed processes: 11,*a* and 11,*b* are scenarios No. 4



a *b* *c* *d*

Fig. 12. Histograms of pulse values at the 10th step of modeling according to scenario No. 1(*a*), scenario No. 2(*b*), scenario No. 3(*c*), scenario No. 4(*d*)

CONCLUSION

The modelling of scenarios for possible processes of the events development in the analyzed complex system is carried out under the influence of various internal and external disturbances and control impulse effects. The results of the conducted cognitive modeling make it possible to judge that the cognitive models, which systematize and structure various information about the underground construction system, correspond to the real system and can be used to anticipate the possible processes of situations in the system under the influence of various disturbing and controlling factors. The developed author's software system CMLS allows in the process of pulse modeling and analysis of the obtained results to introduce control or exciting actions at any stage of modeling. This allows to change (correct) scenarios in the dynamics of creating a model, to determine the effects that bring the processes closer to the desired. The developed methodology and tools made it possible to combine the assessment of the impacts and relationships of geological factors, technogenic and structural-functional types for the study of the underground objects construction.

The proposed system approach to the study of the of underground objects development based on a synthesis of cognitive modeling and foresight methodologies can become the scientific and methodological basis for the development of the “Construction Geotechnology” science and its practical application to study the problems of underground construction in order to ensure the safety and quality of human life. The developed system approach is applied to the study of underground construction objects in order to select reasonable scenarios for their future development.

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СИСТЕМНИЙ ПІДХІД ДО ПЛАНУВАННЯ ОБ’ЄКТІВ ПІДЗЕМНОГО БУДІВНИЦТВА ЗА МЕТОДОЛОГІЯМИ ПЕРЕДБАЧЕННЯ ТА КОГНІТИВНОГО МОДЕЛЮВАННЯ / Н.Д. Панкратова, В.А. Панкратов

Анотація. Запропоновано системний підхід до планування об’єктів підземного будівництва на основі методологій передбачення та когнітивного моделювання. Використання методології передбачення дає змогу за допомогою процедур експертного оцінювання визначити критичні технології та побудувати альтернативи сценаріїв із кількісними характеристиками. Для обгрунтованої реалізації конкретного сценарію використовується імпульсне когнітивне моделювання, що дозволяє будувати причинно-наслідкові зв’язки на основі знань і досвіду, розуміти та аналізувати поведінку складної системи на стратегічну перспективу з великою кількістю взаємозв’язків і взаємозалежностей. Запропонований системний підхід дозволяє планувати підземні об’єкти на основі вибору обгрунтованих сценаріїв та обгрунтування пріоритетності їх створення.

Ключові слова: передбачення, імпульсне когнітивне моделювання, планування, сценарії, підземне будівництво.

СИСТЕМНЫЙ ПОДХОД К ПЛАНИРОВАНИЮ ОБЪЕКТОВ ПОДЗЕМНОГО СТРОИТЕЛЬСТВА НА ОСНОВЕ МЕТОДОЛОГИЙ ПРЕДВИДЕНИЯ И КОГНИТИВНОГО МОДЕЛИРОВАНИЯ / Н.Д. Панкратова, В.А. Панкратов

Аннотация. Предложен системный подход к планированию объектов подземного строительства на основе методологий предвидения и когнитивного моделирования. Использование методологии предвидения позволяет с помощью процедур экспертного оценивания выявить критические технологии и построить альтернативы сценариев с количественными характеристиками. Для обоснованной реализации того или иного сценария используется импульсное когнитивное моделирование, позволяющее построить причинно-следственные связи на основе знаний и опыта, понять и проанализировать поведение сложной системы на стратегическую перспективу с большим количеством взаимосвязей и взаимозависимостей. Предлагаемый системный подход позволяет планировать подземные объекты на основе выбора обоснованных сценариев и обоснования приоритетности их создания.

Ключевые слова: предвидение, импульсное когнитивное моделирование, планирование, сценарии, подземное строительство.