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N.D. Pankratova, <https://orcid.org/0000-0002-6372-5813>

V.A. Pankratov, <https://orcid.org/0000-0002-8264-5835>

Institute for Applied System Analysis NTU of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”

E-mail: natalidmp@gmail.com, pankratov.volodya@gmail.com

Modeling of scenarios for the underground construction planning based on the foresight and cognitive modeling methodologies

Presented by Corresponding Member of the NAS of Ukraine N.D. Pankratova

The modeling of scenarios for the underground construction planning is based on the mathematical support of foresight methodology aimed at the creation of alternative scenarios and the cognitive modeling to build scenarios for the development of a desired future and ways of their implementation. We propose to use these methodologies together: the results obtained at the stage of the foresight methodology should be used as initial data for the cognitive modeling. Using the foresight process at the first stage of modeling allows us, with the help of expert assessment procedures, to identify critical technologies and to construct the alternatives of scenarios with quantitative characteristics. For the justified implementation of a particular scenario, the cognitive modeling allows one to build causal relationships with the consideration of a large number of interconnections and interdependences. The developed strategy is applied to the study of underground construction objects in order to select reasonable scenarios for their future development.

Keywords: *foresight, cognitive modeling, urban underground construction, geological environment, decision-making.*

Regulation of the urban development with the purpose to increase the ecological standards and life safety in constantly growing metropolises is one of the most urgent, though insufficiently researched and difficult, world problems [1-3]. It leads to the seeking of new places for the production facilities and social and other objects of the human activity. The space of megacities created in the process of underground construction becomes a new, underground habitat, which should be comfortable and safe for humans.

Strategy of modeling of the scenarios for the underground construction planning. The proposed strategy is based on a mathematical support of the foresight methodology aimed at the creation of alternative scenarios and the cognitive modeling of scenarios for the planning of a desired future for underground constructions and ways of their implementation. The metho-

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dological and mathematical support of a strategy in the form of a two-stage model based on a combination of the foresight and cognitive modeling methodologies is developed [4]. The involvement of scanning methods, STEEP analysis, brainstorming, and SWOT analysis at the first level of the stage allows the expert assessment to identify critical technologies in the field of economic, social, environmental, technical, technological, information and other directions [5]. 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 the analysis and processing are the initial ones for the solution of foresight tasks. In this paper identifying the 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 (Technique for Order Preference by Similarity to an Ideal Solution) method is applied [6]. 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 alternative proximity to the ideal solution, a multicriterial measure is used [7]. As soon as the critical technologies are identified we cross to the second level, using the qualitative methods for the creation of alternatives to the scenarios of socio-economic systems [4].

When the output information for the cognitive modeling is given in the statistical form, the method of constructing an integrated indicator data is proposed [8]. It allows one, at the construction of a cognitive map, to reasonably add or remove its vertex to break a sequence of interconnected nodes.

The proposed strategy for the development of a socio-economic system allows us to construct a science-based procedure to implement a priority alternative scenario of different nature complex systems, by using the cognitive modeling. In the framework of the foregoing, let us call the studied complex system “Natural-technical geosystem”. According to the developed methodology of cognitive modeling of complex systems [4], the modeling is carried out in some stages. At the first stage, using theoretical and practical data on the underground urban planning obtained with the methodology of foresight, a cognitive model is developed. In this case, a two-level cognitive model was obtained, since the conditions and factors that determine this complex system belong to different levels of the hierarchy. For example, “Environmental risks” can be attributed to the upper, more general level of the hierarchy, while “Engineering and geological processes” to the lower one.

At the first stage, we used cognitive models such as a cognitive map – a sign oriented graph (1) and a functional graph in the form of a weighted sign digraph [4, 9].

$$G = \langle V, E \rangle, \tag{1}$$

where G is a cognitive map in which V are concepts, a finite set of vertices of the cognitive map $V_i \in V, i = 1, 2, \dots, k; E = \{e_{ij}\}$ – the set of arcs e_{ij} of the graph, $i, j = 1, 2, \dots, m$, 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 one, negative (–1), when an increase (decrease) in one factor leads to a decrease (increase) in another one, 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 the variables (interaction of factors) is a quantitative or qualitative description of the effect of changes in one variable on others at the corresponding vertices.

The 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, and $F(X, E)$ is the arc transformation functional.

At the second stage of the cognitive modeling, to study the properties of the cognitive model, we used methods of structural stability and perturbation resistance analysis, methods for analyzing the model connectivity (simplicial analysis), and graph theory methods [4, 9–11].

At the third stage of the cognitive modeling, to determine the possible development of processes in a complex system and to construct the development scenarios, we used the impulse process model (modeling the propagation of disturbances in cognitive models) [11]:

$$x_{v_i}(n+1) = x_{v_i}(n) + \sum_{v_j: e=e_{ij} \in E}^{k-1} f(x_i, x_j, e_{ij}) P_j(n) + Q_{v_i}(n), \quad (2)$$

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

Modeling of Underground Construction. *The first stage.* Cognitive Model Development. Table presents data on the vertices (concepts) of the hierarchical cognitive model without reference to a specific territory, in a generalized form. We used 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. In Table, the vertices of the upper (first level) are denoted as $I - V_i, i = 5, 11, 13, 15, 16$.

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 one to justify the management decisions in a given situation.

The second stage. Before using the cognitive model to determine its possible behavior, the various properties of the model are realized. In this case, the structural stability, perturbation resistance analysis, and connectivity of the model must be considered. The results of the analysis are compared with the available information on the underground construction.

Resistance to perturbations. The cognitive model I_G was not resistant to perturbations according to the accepted criterion [10, 11]: the maximum modulo M root of the characteristic equation of the matrix of relations of the graph I_G is $|M| = 1.82 > 1$.

Structural stability. The 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 [11].

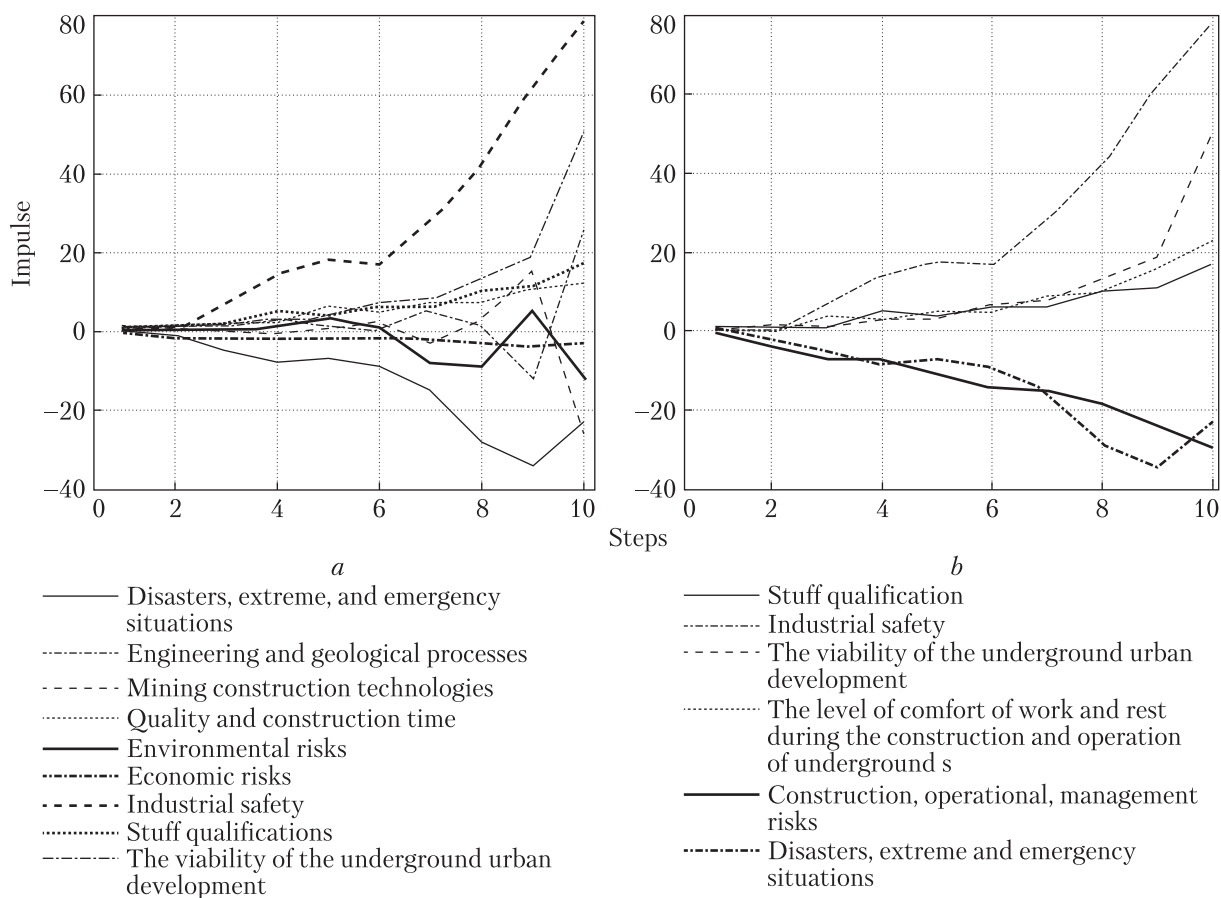
The given example of the analysis of the cycles of the cognitive model showed the variety of cycles of the cause and effect relationships that exist in complex systems. There are 68 of them in the analyzed system. Without an appropriate theoretical analysis, there is a great risk of the human factor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

The third stage of modeling. The scenario analysis is designed to forecast possible trends in the development of situations on the model. To generate scenarios of the development of the system, the 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 (2).

Let us 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 expedient to develop a plan for a computational experiment before excluding pulse simulation, eliminating at least almost impossible variants. Introducing disturbances to the vertices, the decision-maker is looking for the answer to the question: “What will happen if ...?” The software system gives possibility, in the process of pulse modeling and

**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 |
| $I - V_6$ | Genetic type and lithological composition of soils | Basic |
| V_1 | Mountain and hydrostatic pressure, seismic impact | Basic |
| V_2 | Surface 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 | Estimated soil resistance | Basic |
| V_7 | Aquifers and High Water | Disturbing |
| V_8 | Relief Type and Morphometry | Basic |
| V_9 | Engineering and geological processes | Disturbing |
| V_{10} | Mining construction technologies | Regulating |
| V_{12} | The level of comfort of the work and rest during the construction and operation of underground structures | Indicative |
| V_{14} | Construction, operational, management risks | Disturbing |
| V_{17} | Staff qualifications | Regulating |
| V_{18} | Industrial Safety | Basic |
| V_{19} | Quality and construction time | Regulating |



The process of pulse modeling

analysis of the obtained results, to introduce the controlling or disturbing influences at any modeling step. This allows us to change (correct) scenarios in the model dynamics and to determine the effects that bring the processes closer to the desired ones.

Here, we present the results of a pulse modeling of one of the best scenarios. 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 ($I-V_{13}$).

Control actions of scenario:

$q_9 = +1, q_{10} = +1, q_{17} = +1, q_{19} = +1, q_{13} = +1$, the perturbation vector $Q = \{q_1 = 0, \dots, q_9 = +1, q_{10} = +1, \dots, q_{13} = +1, \dots, q_{17} = +1, \dots, q_{19} = +1\}$.

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

The analysis of the results of a pulse modeling according to this scenario shows that the introduction of control actions to the indicated vertices can counteract the negative impact of possible disasters and extreme situations, reducing the impact of economic, environmental, and technological risks. Thus, the scenario can be considered favorable, since the industrial safety is increasing.

Conclusion. It is planned to use the proposed strategy for creating the scenarios for real geotechnological objects of underground construction. This material is an important formalized part and shows the possibility of making a decision under conditions of the geological uncertainty and multifactorial risks. It should be noted the importance of the proposed strategy to planning the development of the underground space of Kiev and underwater tunnels under the Dnieper river. If we approach the construction of such structures as a joint complex (car and subway tunnels, underground culverts near the Dnieper river, a tunnel on the ring highway, etc.), the combination of geoinformation, experience, panel tunneling units and equipment, production and supply of construction materials can dramatically reduce costs for the underground construction of these facilities and improve the quality and efficiency of tunneling. Most importantly, the use of underground constructions will increase the quality and safety of people's lives.

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Н.Д. Панкратова, <https://orcid.org/0000-0002-6372-5813>

В.А. Панкратов, <https://orcid.org/0000-0002-8264-5835>

Інститут прикладного системного аналізу

НТУ України «Київський політехнічний інститут ім. Ігоря Сікорського»

E-mail: natalidmp@gmail.com, pankratov.volodya@gmail.com

МОДЕЛЮВАННЯ СЦЕНАРІЇВ ПЛАНУВАННЯ ПІДЗЕМНОГО БУДІВНИЦТВА НА ОСНОВІ МЕТОДОЛОГІЙ ПЕРЕДБАЧЕННЯ ТА КОГНІТИВНОГО МОДЕЛЮВАННЯ

Моделювання сценаріїв для планування розвитку підземного будівництва базується на математичному забезпеченні методології передбачення з метою створення альтернатив сценаріїв та когнітивного моделювання для побудови сценаріїв розвитку бажаного майбутнього та шляхів їх реалізації. Ці методології пропонується використовувати разом: отримані результати на етапі методології передбачення використовують як вихідні дані для когнітивного моделювання. Використання процесу передбачення на першому етапі моделювання дозволяє за допомогою процедур експертної оцінки виявити критичні технології та побудувати альтернативні сценарії з кількісними характеристиками. Для обґрунтованої реалізації певного сценарію використовується когнітивне моделювання, яке дозволяє будувати причинно-наслідкові зв'язки з урахуванням великої кількості взаємозв'язків та взаємозалежностей. Розроблена стратегія застосовується для вивчення об'єктів підземного будівництва з метою вибору обґрунтованих сценаріїв їх подальшого розвитку.

Ключові слова: *передбачення, когнітивне моделювання, міське підземне будівництво, геологічне середовище, прийняття рішень*