Methodological basis of simulation and cognitive modelling technology of socio-economic systems

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Abstract. The results of the study are presented in the article, the purpose of which is to provide a methodology for modeling studies and forecasting the development of social and economic systems (SES) based on fuzzy hierarchical cognitive approach. The task of developing methods of SES formalization is being solved. Basic methods: system analysis, hierarchical multilevel system theory, control and decision-making theory, graph theory, fuzzy set and fuzzy logic theory, simulation modeling. The subject of the study is a generalized model of the socio-economic system. The paper describes the theoretical foundations of the original simulation-cognitive modeling technology developed to model socio-economic systems. The technology combines crisp and fuzzy cognitive models. The theoretical-multiple metamodel of the complex system under study is disclosed, the identification model of which is based on the metamatrix developed by the author. There is presented an integrated diagram of the methodology of application simulation-cognitive methodologies of SES, its stages are indicated. The practical application of the methodology will make it possible to develop science-based management solutions to ensure the safe and sustainable development of SES and to take into account the human risk factor.

1. Introduction

In the modern economy and socio-economic systems (SES) there are changes that entail the setting of current tasks and the need to develop reasonable management solutions to solve them and manage the paths of sustainable development of SES [1]. For the production of such solutions, it is necessary to build an adequate model with which it is possible to evaluate the consequences of decisions and would select the most optimal.

The complexity property is present at social and economic systems on micro and at the macro levels therefore SES is the typical representative complex, the difficult formalized system. Modelling issues in such systems are raised in modern research carried out both in Russia and around the world [2-4].

The second property of such systems studied [5] and the requirement for modelling is consideration of uncertainties and accidents in the system. In SES is always something we are not yet known or not understood until the end. As a result of such accounting, the following issues and characteristics of SES, which need to be solved: a system with an unknown or unstable structure, accident - a situation that may or may not occur, probability of failures in operation of system elements etc. The presence of "heterarchies" type in the organization structure of SEA [6] also gives a sign of complexity. In addition the construction of the formalized model of a difficult formalized system requires taking into account a
large list of elements and components expressed in both quantitative and qualitative forms, provided that the full depth of the study of the system is adequately displayed.

The current promising direction of applied research in the field of modeling complex systems, an integral part of which is the presence of uncertainty, is cognitive approach. The uncertainty that exists due to the nature of the complex system makes it difficult, and often excludes the use of accurate quantitative methods and approaches. Cognitive approach allows identifying complex system, to use theoretical-multiple description on the basis of fuzzy logic, to refine model according to data of expert estimates, to combine quantitative and qualitative data for modeling and study of behavior of complex multi-factor systems. The distinctive feature is that the tools used allow modeling any complex system for the purpose of forecasting, planning and management, to use different input information flows and scenarios, to analyze the complete dynamics of system and object development.

2. Research problem

In order to implement the above-mentioned features to generate reasonable management decisions on the sustainable development of SES and the possibility of building intelligent information and management systems with poorly structured situations, it is proposed to use an approach based on fuzzy cognitive modelling methodology. The work is devoted to the description of methodological foundations of simulation and cognitive technology of modelling of socio-economic systems.

It is proposed for development reasonable management decisions explore management as a process independent of the specific characteristics of the object and subject, such an approach in some way simplifies our task, but allows it being solved without losing adequacy. In this case, management as a process is reduced to defining parameters, investigating structural features, and determining the sequence of steps within it. With this interpretation, control part of a system and managed part of the system are usually allocated, Fig. 1.

![General control diagram SES](image)

**Figure 1.** General control diagram SES

The X₁, ..., Xₙ elements are called system inputs (input variables); Y₁, ..., Yₘ - system outputs (output variables), input and output variables communicate the system with the external environment; V₁, ..., Vₖ - uncontrolled effects on the system; G₁, ..., Gₗ - control inputs, designed to change the purpose of system operation, which may occur from the external environment α₁, ..., α₉ - system parameters; Z₁, ..., Zₚ.
elements - characterize the system state, record all changes in the system state due to input signals and internal processes in it.

Management in such systems is carried out as an information process: receiving, processing and transmitting information. The change in the state of the system as a result of the control takes place on the basis of the acquisition of information (arrival of input signals) and is a reaction to the command that is generated in the system after the analysis of the information contained in the input signal.

Management activities have pronounced systemic properties: hierarchy, cyclicity, upward and downward information flows, availability of reverse links. This understanding gives us reason to consider management activities also as a complex system.

The cognitive approach makes it possible to manage without knowing the object of control completely. This is a so-called functional management approach. It is a merit that the criteria of optimality for a decision in this case are not the subject of a decision. The criterion may be predetermined.

The cognitive approach in pure form is not engaged in the development of goals for economic objects, the approach allows determining the best ways to manage the system, that is, we have the task of managing processes.

3. Technique

3.1 Set-theoretic metamodel

So, cognitive set-theoretic metamodel of researched complex system, its foundations were laid in the work [7] also it is developed in [8-9], proposed to be described as follows:

\[ M = \{ M_O, M_E, M_{OE}, M_D, M_{GIS}, Q, M_{DM}, M_U, M_H, A \} \]  

where: \( M_O \) – the identifying system model (object model); \( M_E \) – environment model; \( M_{OE} \) – object-environment interaction model; \( M_D \) – model of system behavior, including in the form of scenario space \{Opt, Neitr, Pessim\}, implemented in simulation of perturbation and control effects on cognitive model; \( M_{GIS} \) – geographic information system model (GIS); \( Q \) – perturbation/operation influences, \( Q \subseteq \{Imp\} \) – subset of impulses; \( M_{DM} \) - decision making model; \( M_U \) – control model system; \( M_H \) – model of an «observer» (engineers, experts, operators); \( A \) – rules of associations of models and rules for selecting object change processes.

All elements (set) of the metamodel (1) can, for the most part, be formalized as simple cognitive models, and as higher-level metamodels, this can lead to a formalized description of the hierarchical structure of a real complex system. Note that the interactions between concepts of a hierarchical cognitive model can be represented by systems of equations described in the language of probability theory and fuzzy sets, the use of fuzzy logic and metaveristics to find the optimal solution (the path between concepts) is allowed.

Let us dwell on the description of \( M_O \) – the identifying system model (object model), which in turn is described by the tuple:

\[ M_O = <T, Matr, M_{MA}, U> \]  

where \( T \) – set-theoretic description of hierarchical model SES; \( Matr \) – metamatrix of model, Fig. 2; \( M_{MA} \) – decision models and algorithms; \( U \) – algorithms for checking models for stability and sensitivity.
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Figure 2. Model metamatrix

Note that $V_1, ..., V_j, ..., V_k$ concepts can be concepts at the same hierarchy level or at different levels. $G$ – crisp cognitive model (CCM), where $G = \langle V,E \rangle$ directed graph; $\tilde{G}$ – fuzzy cognitive model (FCM); $\Phi$ – this is a parametric function graph for distinct models; $\tilde{S}$ - cognitive model of a situation.

To study the effect of changing concepts parameters, as well as taking into account the influence of feedback loops, a pulse process rule is used, which establishes how deviations of one or more variables propagate over a period of time across the system, and according to [10] is distinguished.

Propagation of increasing impulse impacts when the impulse impact is increased in the transition from one system element to another:

$$ w_i(t+1) = w_i(t) \prod_{j=1}^{\deg v_i} \varepsilon_{ij} \text{imp}_j(t) $$

(3)

Propagation of decaying impulse impacts when the impulse impact is reduced in the transition from one system element to another:

$$ w_i(t+1) = w_i(t) \prod_{j=1}^{\deg v_i} (1 - \varepsilon_{ij} \text{imp}_j(t)) $$

(4)

where $\text{imp}_j(t), j \in \{1, 2, ..., n\}$ – external pulse influence; $\varepsilon_{ij}$ – arc weight; $w_i$ – indicator of a concept condition.

Thus, the mathematical apparatus of cognitive models allows formally constructing forecasts of the development or trajectory of the simulated system.

3.2 Methodology stages

In the study described, the fundamental assumption in the development of a complex system modeling methodology is: to systems whose problems are poorly structured, the cognitive approach is most applicable, and the description of a complex system taking into account its uncertainty is possible by means of a set of harmonized models reflecting different aspects of the functioning of a complex system.

The proposed simulation-cognitive methodology of SES modelling based on multilayer fuzzy cognitive models allows developing management solutions for sustainable development of both individual subsystems and the whole SES at macro- and micro- levels.

At different stages of the methodology, the basic input information is a large array of heterogeneous statistics, but expert estimates are used as a complement. Due to this fact the methodology is based on the principle of combining formalized modeling methods and expert procedures in order to improve the validity and collegiality of management decisions. This principle will also solve the problem of the
fundamental impossibility of fully formalizing systems of human preferences and values in decision-making procedures. It is believed that this approach creates the possibility of taking into account historical values and local cultures, as opposed to ignoring these components in existing models of socio-economic systems. As a result of all stages, the decision-maker will receive a set of sustainable SES strategies at the macro and micro levels. Let us present the main stages of the methodology in the form of a diagram, Fig. 3.

Figure 3. Model metamatrix
4. Conclusion

Cognitive modeling makes it possible to build models that take into account such features as the condition of incomplete information, availability of qualitative information, influence of human factor, stability of development in conditions of bifurcations, such approach to modeling will allow determining possible and rational ways of situation management with the aim of transition from negative initial states to positive ones.

Thus, the application of simulation and cognitive modeling methodology, unlike, for example, traditional dynamic models, allows acting ahead of and not to bring potentially dangerous situations to threatening and conflict situations, to build models in the interests of analysis and forecasting of the development of technical, socio-economic and political systems.

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