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Cognitive and Simulation Modeling of Socioeconomic Systems*

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***Abstract*—The article describes the cognitive and simulation metamodel and modern cognitive tools developed for modeling socioeconomic systems. The tools are presented by crisp and fuzzy cognitive maps, parametrical vector functional graph, the solution of a problem of definition of sustainability of model is proposed and simulation example. The metamodel can be used to solve problems of modelling the structure and behavior analysis socioeconomic systems, forecasting of ways and development strategies. The fragment of a computing experiment is given**

Keywords*— *socioeconomic systems; cognitive modeling; crisp; fuzzy; hierarchical cognitive models; simulation

I. INTRODUCTION

The relevance of the presented work is based on increasing attention to research of social and economic (further socioeconomic) systems for the purpose of scientific-reasonable decision on their stable development under uncertainty conditions [1, 2]. Methods of cognitive-simulation for the study of socioeconomic systems are actively used [3, 4]. But features of the socioeconomic systems (SES) demand the adaptation of the existing cognitive tools for the solution of structure and behavior modeling problems, foresight of methods and management for their development. Therefore it is suggested to use the developed tools of cognitive modeling SES [5-7] which allow to reflect the main feature SES, the fact that they include the interaction of a technical subsystem with a social and economic subsystem, and the external environment in the conditions of uncertainty. The results in the new direction of fuzzy cognitive modeling and simulation on hierarchical cognitive maps allow to consider these features SES. Cognitive tools can be used both for design and for scientific foresight of development of intellectual systems for decision support in SES.

II. PROBLEMS AND TASKS OF COGNITIVE AND SIMULATION MODELING OF THE SOCIOECONOMIC SYSTEMS

Nowadays the application of methods and techniques of cognitive and simulation modeling to subject focused socioeconomic systems allows to solve the problems of description and explanation of a socioeconomic system, anticipation of the ways of its development, the analysis of structure, the analysis of sustainability, the scenario analysis and some other system tasks. All this requires the complex solution of different problems in a unified system of cognitive and simulation modeling that implements the cross-disciplinary approach.

Let us note that the cognitive and simulation approach to research of socioeconomic systems, and the cognitive modeling need to be considered as a thinking method in relation to these systems and not just as a tool kit or instructions intended for perception of an object. In the flow of knowledge in a system there is «an uncertainty disclosure». To ensure the success of this process, the researcher needs the respective instrument, which is high professionalism and understanding of his own knowledge processing. Tools of cognitive modeling are necessary to provide the researcher an opportunity «to manage» the knowledge processing and structuring. The expert's process of cognitive knowledge structurization can be understood as «uncertainty disclosure» of a socioeconomic system. But at the same time it is also necessary to note one more feature of socioeconomic systems concerning the fact that in real systems decisions are made by many people at the same time and the subjective preferences of decision makers can have a multi-vector focus. Coordination of decisions can be reached in the course of cognitive modeling and assessment of its results before different insufficiently reasoned management decisions are implemented in the real system; the computing experiment can find the existing inconsistency in intellectual models of either one or a group of experts, to reduce the «risk of a human factor».

Considering the mentioned above features of socioeconomic systems, it is possible to substantiate the different purposes and tasks of their cognitive research. Thus we can attribute the following to the main objectives of the research: understanding, explanation, description of SES, forecasting (scientific prediction), adaptation or scientific-reasonable control of development of socioeconomic systems, their enhancement. In

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case of decision making in the implementation process of the given purposes, carrying out imitation modeling of properties, structures, behavior is previously necessary, as the natural experiment with a «live» system (economic, social, ecological, political, etc.) for achievement of such purposes is either inadmissible, impossible, expensive, dangerous, or all this together. So far the field of imitation modeling is wide and variously developed, however no special attention is directly paid to processing the knowledge of researchers (experts, the decision makers) and its influence on result of modeling and the subsequent conclusions and recommendations. By this issue the essential risk of "a human factor" is covered.

The developed cognitive and simulation modeling of socioeconomic systems is essentially one more direction of imitation modeling, although having the property to include and reflect the fact of influence of knowledge processing on the end result. It occurs, particularly, by structurization and stage-by-stage restructurization of the expert's knowledge in the course of the solution of a complex of problems of cognitive modeling. The following problems are suggested in this complex: tasks of identification of an object; analysis of ways and cycles of cognitive model; analysis of observability and controllability; sustainability; sensitivity; adaptability; composition-decomposition; analysis of various aspects of complexity and analysis of connectivity; self-organization of system; forecasting and scientific prediction; solution of optimization problems; decision making under conditions of different uncertainty. At the same time the decision making happens both in relation to the most studied object, and in relation to the research process. The problem of unification of various tasks and approaches, methods, techniques of their decision in a single system, is actually a knowledge processing formalization problem for different aspects of SES and its decision, possibly by means of special and cross-disciplinary tools. Regarding the above mentioned tasks, this can be a combination of technologies and tools of cognitive sciences; expert, statistical and other methods for identification and description (model development) of an object, the theory of sets and the graphs theory methods, the control theory, the theory of catastrophic crashes, system theories, theories of hierarchical systems, complexity theories, the simplicial analysis of connectivity, optimization theory, decision making theory and many others.

III. Technique

It goes without saying that it is problematic to build a unified formal system of research for socioeconomic systems of different nature from the existing methodologies, approaches, methods, technologies, etc. But in our research related to cognitive modeling of socioeconomic systems we have gone in such way – to work at a joint of sciences, implementing the cross-disciplinary principle.

A. Base of Cognitive Methodology of Socioeconomic Systems

To build a basis of research system of cognitive modeling for SES, it is suggested to use a backbone set-theoretic - cognitive simulation metamodel of a research M [6]:

$$M=\{M_O, M_E, M_{OE}, M_D, M_{MO}, M_{ME}, Q, M_{DM}, M_U, M_H, A\}, \quad (1)$$

where: M_O – identification of the system model (object model), M_E – model of the environment, M_{OE} – model of interaction of the object and the environment, M_D – model of the system behavior, M_{MO} and M_{ME} – measurement models for the state of the system and the environment, Q –perturbation/operation influences, M_{DM} – decision making model, M_U – model management system, M_H – model of an «observer» (engineers, cognitivists, experts, researchers), A – model unification and object change process selection rules. The mathematical models M_O, M_E, M_{OE} are cognitive models both jointly and separately; let us note that the interactions between vertices (concepts) of cognitive model can be presented by systems of equations, and also in the language of probability theory and fuzzy sets. M_D is the model of the system behavior, particularly, in the form of pulse processing. Q are the perturbation and operation influences that are implemented during modeling on cognitive model; M_{MO} and M_{ME} are sets of rules, procedures, measuring means.

Development of all the mentioned above models, their research, modification according to the information about real system are included into the process of cognitive structurization of the expert knowledge. Introduction in the M_H metaset of an «observer», «expert» allows to form the research and decision making methodology taking into account the development of the knowledge processing regarding an object in researcher's mind. The observer model is shown in the flow of knowledge regarding an object and the decisions made by him; ultimately the model of his perception, knowledge and understanding of an object is the cognitive model of a socioeconomic system. Creation of a metamodel (1) for a specific system settles the purposes, research problems and decision making, allowing to organize the process of research. In the course of the research and consecutive decision making by an expert the objects of a metamodel can change.

B. The Types of Cognitive Models

Let us introduce a definition. The cognitive methodology of a research of socioeconomic systems is the logical organization of activities of the researcher implementing a metamodel (1), implying the determination of the purpose, subject and object of research, methods and information technologies of cognitive modeling that allow to understand and explain the mechanism of the phenomena and processes in an object, to develop the possible scenarios of its development, to choose the effective solutions on management of an object and/or its adaptation to the environment. Distinctive feature of cognitive modeling is its multistaging.

Development of a cognitive model of SES is suggested to start with the development of a crisp (G) or fuzzy cognitive map (FCM) depending on properties of the system and information about it at the moment. It is known that mathematically the cognitive map is a signed directed graph [8]:

$$G = \langle V, E \rangle \tag{2}$$

The cognitive map reflects the relationships of cause and effect in the system between vertices (concepts) V, $v_i \in V$, $i = 1,2,\ldots,k$, which are elements of the studied system; E – a set of arcs, arcs $e_{ij} \in E$, $i,j = 1,2,\ldots,n$ reflect interrelation between vertices of v_i and v_j. An opportunity to consider not only quantitative, but also qualitative factors is one of the benefits of a cognitive map; a cognitive map allows to see "the whole picture in general, without losing details".

The cognitive map G can be defined by a square matrix of the relations $E_G = (e_{ij})_{h\times h}$, with an element e_{ij} of the matrix E_G on the intersection of line i and column j able to assume values «1» if influence of vertices is unidirectional, «–1» if influence is multidirectional, or «0» – influence is absent. G_0 (starting, initial model) is constructed on the basis of visualization of initial ideas of the system structure, its external environment, the nature of interaction between vertices. Verification of the G_0 model can be carried out by an expert or by formalized methods.

For introduction of the fuzzy cognitive map we will adhere to the idea proposed by B. Kosko [9] and suggest the development of a construction technique for cognitive maps in the form of a fuzzy directed graph of the 1st and 2nd kind. Let us introduce the concept of FCMs (fuzzy cognitive map) as a fuzzy directed graph of the first and/or second kind (it is known that a fuzzy directed graph of the 2nd kind can be unambiguously transformed, if necessary, into a fuzzy directed graph of the 1st kind). Then we will designate a pair of sets as a FCM.

$$\tilde{G} = \left(V, \tilde{U}\right) \tag{3}$$

where $V = \{v_i\}$, $i \in I = \{1, 2, ..., n\}$ is a crisp set of vertices (or concepts), and $\tilde{U} = \{< \mu_u < v_i, v_k > / < v_i, v_k >>\}$ is a fuzzy set of edges (or arcs), where $< v_i, v_k > \in V^2$, and $\mu_u < v_{i,i} v_k >$ is a membership degree of the oriented edge $< v_{i,i} v_k >$ to the fuzzy set of directed edges $\tilde{U}$.

Let us note that at this stage of modeling the transition to the second stage of cognitive technology – the comprehensive analysis of the cognitive map for a solution of a complex of system tasks is already possible. Definition of sustainability of the developed model is one of important tasks. In particular, for definition of structural sustainability of FCMs the following approach is offered [7].

To do this, take an arbitrary vertex $v_i \in V$ from FCMs and find for it fuzzy transitive closure and fuzzy reciprocal transitive closure, which are fuzzy sets on the vertex set V. Then we find their intersection:

$\tilde{C}(v_i) = \tilde{\Gamma}(v_i) \cap \tilde{\Gamma}^{-}(v_i) = \{<\alpha_1/v_1>, <\alpha_2/v_2>, \ldots, <\alpha_i/v_i>, \ldots, <\alpha_n/v_n>\}$, where $\alpha_j \in [0,1]$.

If the carrier of fuzzy set $\tilde{C}(v_i)$ coincides with the set of vertex V, then the fuzzy graph $\tilde{G} = \left(V, \tilde{U}\right)$ describing FCMs is strong connection, and the degree of its structural sustainability will be defined as $S(\tilde{G}) = \min\{\alpha_1, \alpha_2, ..., \alpha_n\}$. Otherwise the degree of its structural sustainability $S = 0$.

The initial model of a system in the form of a cognitive map can be transformed consistently into a mathematically (and substantially) more complex cognitive model with such main types as vector functional graph, parametrical vector functional graph, modified graph. The parametrical vector functional graph for crisp cognitive models has the form:

$$\Phi = \langle G, X, F, \Theta \rangle \tag{4}$$

where Φ – vector having: G – a signed directed graph, X – set of vertex parameters of this graph, Θ – space of vertex parameters; $F=(X,E)=f(x_i,x_j,e_{ij})$ – function of transformation of the arcs. We have a special case of model (4) if the function F accepts values of weight coefficient w_{ij} defined by the statistical data or an expert in the form of some number, or accepts values from an interval $w_{ij} \in [w_{ij1}, w_{ij2}]$. Such model can be referred to as quasi fuzzy type.

For imitation modeling it is expedient to adjust interval borders to «–1» and «+1» values. Operations of normalization of communication values between vertices [6]. For normalization of link values, the following method of interval conversion is proposed: $w_{ij}^{nor} = \left[\dfrac{w_{ij1}}{w^{\max}}, \dfrac{w_{ij2}}{w^{\max}}\right]$, $w^{\max} = \max\limits_{\substack{1\le i\le h,\\ 1\le j\le h}} \{w_{ij2}\}$, where w_{ij}^{nor} normalized interval values of links between vertices v_i and v_j, $w_{ij}^{nor} \in [-1, 1]$; $w^{\max}$ – maximum values among the maximum values of the links represented as intervals. As a result of normalization, values of links between vertices are obtained in the form of intervals with normalized values $w_{ij}^{nor} = [w_{ij1}^{nor}, w_{ij2}^{nor}]$. In order to obtain one normalized odd value from the interval, the following action is recommended: $w_{ij}^{*nor} = \dfrac{w_{ij1}^{nor} + w_{ij2}^{nor}}{2}$.

Therefore we have $-1 \le w_{ij} \le 1$, with $w_{ij} = 0$ if influence of v_i on v_j is absent; $0 < w_{ij} \le 1$ at positive influence of v_i on v_j, i.e.

when increase/decrease of influence of vertices v_i leads to increase/decrease of a signal in v_j vertices; at negative influence of v_i on v_j $-1 \leq w_{ij} < 0$ the increase/decrease of value of vertices v_i leads to decrease/increase in value of vertices v_j. The introduced interval allows to carry out the estimates of qualitative analysis taking into account the various nature of factors and distinction in force of communications between the objects in a system. In case we state the relation as a membership function F, we deal with a fuzzy cognitive model:

$$\tilde{\Phi} = \left\langle \tilde{G}, \tilde{X}, \tilde{F}, \Theta \right\rangle \quad (5)$$

where $\tilde{G} = \left(V, \tilde{U}\right)$ is a fuzzy weighed directed graph whose vertices are characterized by fuzzy parameters $\tilde{X}$, and edges are fuzzy relationships of cause and effect between parameters $\tilde{F}$.

Cognitive maps can be formed in hierarchy, so the hierarchical cognitive map has the following form:

$$I_G = \left\langle G_k, G_{k+1}, E_k \right\rangle, \; k \geq 2 \quad (6)$$

where G_k and G_{k+1} – cognitive maps for k and $k+1$ level respectively, with some vertices connected by E_k arcs. If the functions of arc transformation are defined, then a hierarchical cognitive model takes place. Let us note that levels of hierarchy of system management can be represented by a model of the hierarchical cognitive map, and also the subordinate level can represent the cognitive map that "expands" a vertex (vertices) of the cognitive map of the top level. Interaction by certain rules of systems can be also presented by the general model of interaction by K hierarchy:

$$IGG = \{I_{G1}, I_{G2}, ..., I_{GK}, R\} \quad (7)$$

where R – rules of interaction. In works [5] the interaction described by game theory language is considered, and in [10] the device of fuzzy logic and fuzzy sets is used for the description of multilevel complex systems, and the method of finding the transitions between reference situations based on comparison of fuzzy intervals is proposed.

It is offered to use pulse modeling for scenarios definition of the development socioeconomic system. If distribution of the increasing pulse influences is considered, i.e. pulse influence increases upon transition from one system element to another, to do this:

$$w_i(t+1) = w_i(t) \prod_{j=1}^{\deg v_i} \varepsilon_{ji} imp_j(t), \quad (8)$$

where $imp_j(t)$, $j \in \{1,2,...,n\}$ – external pulse influence; ε_{ij} – weight of edge (or arc); w_i – an indicator of condition vertex (concept). To do this:

$$w_i(t+1) = w_i(t) \prod_{j=1}^{\deg v_i} \varepsilon_{ji} imp_j(t), \quad (9)$$

If distribution of the fading pulse influences is considered, i.e. pulse influence weakens upon transition from one system element to another.

C. Example

The cognitive map (CM) of Stavropol Krai regional social and economic system is constructed, CM contains 15 vertices: V1 – final consumption, V2 –production, V3 – employment, V4 – income, V5 –gross accumulation, V6 – federal regulators, V7 – interregional and external economic exchange, V8 – environment, V9 – population, V10 – political and economic risks, V11 – industry, V12 – agriculture, V13 – human capital, V14 – education, V15 – migration. Pulse modeling is carried out for the analysis of possible development of situations in system. For this purpose the impulse is entered into certain timepoints in the corresponding vertices of CM. The plan of a computing experiment (CE) is developed, the fragment is presented (Table I).

TABLE I. FRAGMENT OF THE PLAN OF CE

Sce- nario	Im- pulse								
		V1	*...*	*V10*	*V11*	*V12*	*V13*	*V14*	*V15*
1	q_{10}=+1			+1					
2	q_{10}=+1 q_{14}=+1			+1				+1	
3	q_{10}=+1 q_{11}=+1 q_{13}=+1			+1	+1		+1		

The result of a computing experiment has shown that the scenario 1 is pessimistic, increase of political and economic risks leads to deterioration of condition in all vertices of CM. The analysis of a change possibility of this tendency is carried out. We will consider scenario 2, in the Fig. 1 and Fig. 2 the schedules examples of pulse processes corresponding to the scenario 2 are represented.

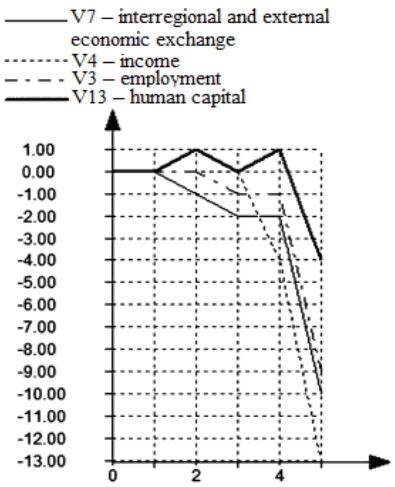

Fig. 1. Scenario “2a”

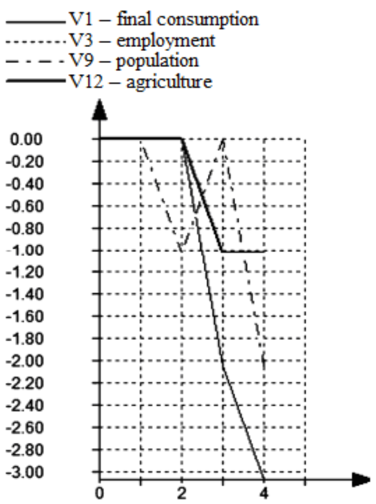

Fig. 2. Scenario “2b”

Modeling begins with zero value of vertices parameters. On abscissa axis modeling steps, on ordinate axis – the sizes of impulses generated in vertices as a result of the analyzed revolting influences are noted. The analysis of schedules shows that the scenario 2 is also not successful. On the first two steps improvement is observed, but already to the 4th step falling of indicators in the analyzed CM vertices is visible. Application of the scenario 3 allows to draw a conclusion that development of the industry and investment into the human capital can resist to political and economic risks.

Above-mentioned models (1)-(9) are the tools presented cognitive simulation metamodel of socioeconomic systems.

IV. Conclusion

Socioeconomic systems belong to the class of complex systems, and it demands application of system approach to their research, the use of principle interdisciplinary and development of complex methods and models. For implementation of these requirements the backbone set-theoretic metamodel as a basis of research system of cognitive and simulation modeling socioeconomic systems is presented in the article. The metamodel describes interaction of the object and the environment, the system behavior, the perturbation/operation influences, the rules of association models etc., including in conditions of uncertainty. On the basis of a metamodel tools of cognitive modeling are developed: crisp cognitive map, fuzzy cognitive map, hierarchical cognitive map, parametrical vector functional graph, approaches to the analysis of cognitive maps are offered and model of pulse process. Pulse modeling is used for the purpose definition of perspective scenarios development system. The use of mathematical apparatus crisp and fuzzy directed graph for the description of cognitive models allows to solve system problems of analysis complexity and connectivity, sustainability, sensitivity, scientific-reasonable decision-making and some others. Tools have been approved and shown working capacity.

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