Article

Cognitive analysis of the structural stability for the knowledge-intensive sectors of the regional economy

A. A. Firsova[1]✉, E. L. Makarova[2]

[1]Saratov State University, 83 Astrakhanskaya St., Saratov 410012, Russia

[2]South Federal University, 105/42 Bolshaya Sadovaya St., Rostov-on-Don 344006, Russia

Anna A. Firsova, a.firsova@rambler.ru, https://orcid.org/0000-0002-8906-6326, AuthorID: 462073

Elena L. Makarova, elmakarova@sfedu.ru, https://orcid.org/0000-0003-4100-4879, AuthorID: 513570

Abstract. The paper demonstrates the application of cognitive modeling methods to study the functioning problems of semi-structured complex economic systems. The aim of the research is to study the structural stability of the relationship between knowledge-intensive sectors and regional economy using cognitive analysis. The concepts and factors influencing the studied systems are determined, cognitive maps of the relationship between knowledge-intensive sectors and regional economy are created, a qualitative analysis of the properties and cycles has been carried out. Impulse and scenario modeling made it possible to draw a conclusion about structural stability of the developed cognitive model. Various scenarios of the system's behavior under the influence of impulse modeling are visualized. The research results can be used to support decision-making process due to developing strategies and policies for the balanced development of knowledge-intensive markets and socio-economic systems.

Keywords: cognitive modeling, cognitive map, scenario analysis, impulse modeling, knowledge-intensive sectors

Научная статья

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Когнитивный анализ структурной устойчивости знаниеёмких секторов региональной экономики

А. А. Фирсова[1]✉, Е. Л. Макарова[2]

[1]Саратовский национальный исследовательский государственный университет имени Н. Г. Чернышевского, Россия, 410012, г. Саратов, ул. Астраханская, д. 83

[2]Южный федеральный университет, Россия, 344006, г. Ростов-на-Дону, ул. Большая Садовая, д. 105/42

Фирсова Анна Александровна, доктор экономических наук, доцент, профессор кафедры финансов и кредита, a.firsova@rambler.ru, https://orcid.org/0000-0002-8906-6326, AuthorID: 462073

Макарова Елена Львовна, кандидат педагогических наук, доцент кафедры менеджмента и инновационных технологий, elmakarova@sfedu.ru, https://orcid.org/0000-0003-4100-4879, AuthorID: 513570

Аннотация. В настоящей работе демонстрируется применение методов когнитивного моделирования для изучения проблем функционирования слабоструктурированных сложных экономических систем. Цель исследования — изучение структурной устойчивости взаимосвязи знаниеёмких секторов и региональной экономики с использованием инструментов когнитивного анализа. Определены концепты и факторы, влияющие на изучаемые системы, разработаны когнитивные карты взаимосвязи знаниеёмких секторов и региональной экономики, проведен качественный анализ их свойств и циклов. Импульсное и сценарное моделирование позволили получить выводы о структурной устойчивости разработанной когнитивной модели. Также визуализированы различные сценарии поведения системы под воздействием импульсного моделирования. Результаты исследования могут быть использованы для поддержки процесса принятия решений при разработке стратегий и политики сбалансированного развития знаниеёмких рынков и социально-экономических систем.

Ключевые слова: когнитивное моделирование, когнитивная карта, сценарный анализ, импульсное моделирование, знаниеёмкие секторы

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Introduction

In a modern post-industrial society knowledge-intensive sectors, which are intended to create, accumulate and disseminate knowledge, became one of the most important segments of the economy [1]. The knowledge-intensive markets have the greatest innovative potential and act as drivers of economic development. Effective and balanced development of knowledge-intensive sectors markets determines progressive structural changes in the economy and affects sustainable regional development. The rapid development of these markets in recent years makes it relevant to study the phenomenon of their evolution, the determined factors and their systemic dynamics.

The purpose of this research is to study the structural stability of the relationship between knowledge-intensive sectors and regional economy using mathematical instruments of cognitive analysis. To realise it, the following tasks were successively solved: definition of concepts and factors affecting the studied systems, development of a cognitive map, qualitative analysis of the cognitive model (analysis of properties and cycles), impulse modeling and scenario analysis to determine the structural stability of the socio-economic system.

1. Cognitive model

Cognitive modeling provides opportunities for studying the functioning problems of semi-structured complex systems consisting of separate but interrelated elements and subsystems, which are knowledge-intensive sectors and regional economic systems [2]. A cognitive model is a graphical and formalized representation of relationships between concepts (objects, factors, indicators, connections and interacting systems).

Cognitive structuring is an effective tool for supporting decision-making process in strategy development, allowing to identify objects and connections between them, when the control object and its external environment are a complex of semi-structured processes and factors that significantly affect each other. The use of impulse modeling for scenarios generated under various disturbing influences allows one to determine structural stability, predict behavior and determine possible directions of the development of the system under study [3–7].

It is proposed to carry out a cognitive analysis of the structural stability for the markets of knowledge-intensive services sequentially in the framework of the following stages. At the first stage, it is necessary to develop a cognitive map (Fig. 1) of the system:
$$G = \langle V, E \rangle,$$
where G is a signed directed graph (digraph): V is the set of vertices $V_i \in V$, $i = 1, 2, \ldots, k$, which are elements of the system under study; E is the set of arcs $e_{ij} \in E$, $i, j = 1, 2, \ldots, N$, which reflect the relationship between the vertices V_i and V_j.

To assess the structural stability of markets in knowledge-intensive sectors, 18 indica-
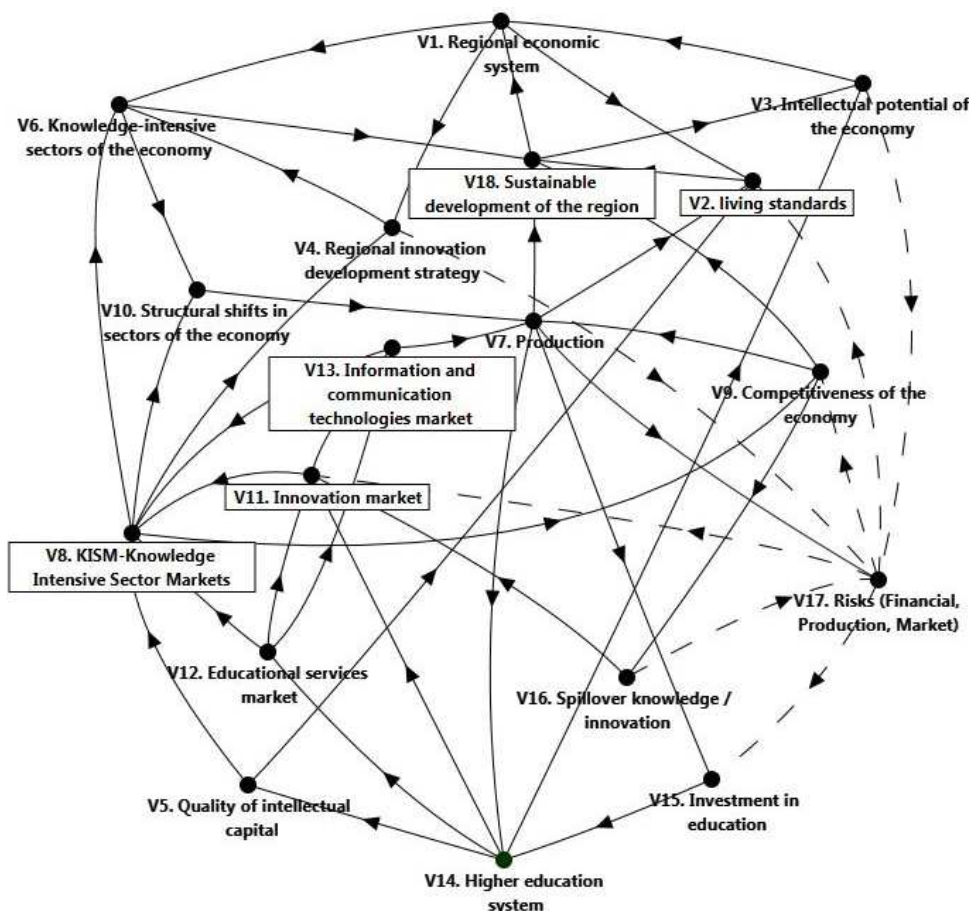

Fig. 1. Cognitive model (G) of the relationship between regional sustainable development and knowledge-intensive markets

tors will be used, including indicators: the socio-economic system of the region, population standard of living, the intellectual potential of the economy, the intellectual potential of society, the strategy of innovative development of the region, quality of intellectual capital, knowledge-intensive sectors of the economy, manufacturing, knowledge-intensive sector markets, economic competitiveness, structural (positive) shifts in economic sectors, innovation market, educational services market, information and communication technologies market, higher education system, investment in education, dissemination of knowledge and innovation, risks, sustainable development of the region. The indicators' system was selected on the basis of theoretical data on socio-economic regional systems, using previous research, analysis of statistical data and expert assessment in the framework of the study [8–10]. After determining the vertices, the facts of the cause-and-effect relationship between them (the arcs of the cognitive map) are established. The cognitive map imitates the structure of a real complex system with structural stability of knowledge-intensive sectors markets.

A cognitive model of the relationship between sustainable development of the region and the markets of knowledge-intensive sectors includes the following vertices.

1. "Regional economic system" vertex V_1, $v_1^i \in V_1$, $i = 1, 2, \ldots k_1$, determined by the microeconomic production function, is the connecting link of regional factors of production, such as labor, enterprises, resources and includes the share of high-tech and knowledge-intensive industries in the gross regional product [11].

2. "Living standards" vertex V_2 is the level of satisfaction of the material and spiritual needs of people with a mass of goods and services in a certain period of time under certain conditions.

3. "Intellectual potential of the economy" vertex V_3, $v_3^i \in V_3$, $i = 1, 2, \ldots k_1$ is a set of human, material and financial resources that are involved in two closely related key areas of the spiritual life of society – science and economy [12].

4. "Regional innovation development strategy" vertex V_4, $v_4^i \in V_4$, $i = 1, 2, \ldots k_1$ is a set of long-term goals due to the objective needs of regional development, as well as the activities of regional authorities to develop priority areas for the innovative development of the region and mechanisms to ensure their implementation [13].

5. "Quality of intellectual capital" vertex V_5, $v_5^i \in V_5$, $i = 1, 2, \ldots k_1$ characterizes the system of its properties, which, firstly, corresponds to the qualitative definiteness of this capital, and secondly, characterizes the involvement in socio-economic relations, the nature of participation and the way of interaction with other elements of the socio-economic system, including the quality of socio-economic relations [14].

6. "Knowledge-intensive sectors of the economy" vertex V_6 describes economic sectors in which the production of goods and services is based on knowledge-intensive activities that contribute to a rapid pace of advancement in technical and scientific innovation.

7. "Production" vertex V_7, $v_7^i \in V_7$, $i = 1, 2, \ldots k_1$ combines indicators of production innovative activity for organizations in the region, including indicators: volume from innovative organizations; the proportion of innovative organizations in the region; the use of specialized software in enterprises.

8. "Knowledge Intensive Sector Markets" vertex V_8 covers markets of the results of intellectual activity, where, unlike ordinary markets, it is not knowledge that is sold, but the conditions for its acquisition, providing access to it, reliable channels, reconstruction, interpretation of meanings, educational texts [15].

9. "Competitiveness of the economy" vertex V_9, $v_9^i \in V_9$, $i = 1, 2, \ldots k_1$ includes indicators: the region ability to achieve high rates of economic growth that would be

sustainable in the medium term; the productivity level in a given region; the ability of companies in a given region to compete successfully in certain markets.

10. "Structural shifts in sectors of the economy" vertex V_{10} reflects in the basic ways a market or economy functions.

11. "Innovation market" vertex V_{11}, $v_{11}^i \in V_{11}$, $i = 1, 2, \ldots k_1$ includes indicators: internal expenditures on research and development in the constituent entities of the region, share of internal costs for research and development, the ratio of internal costs for research and development to gross regional product at current prices, current and capital costs associated with research and development; the number of personnel engaged in research and development, the number of bearers of intellectual capital in explicit and implicit forms; issuance of documents by constituent entities of the Russian Federation, units (number of documents issued on inventions, utility models, industrial designs).

12. "Educational services market" vertex V_{12}, $v_{12}^i \in V_{12}$, $i = 1, 2, \ldots k_1$ is a market where the demand for educational services from the main economic entities (individuals, households, enterprises and organizations, the region) and their supply by various educational institutions interact, and includes the following indicators: funding for educational institutions of higher education, number of bachelors, specialists, master students — labor resources in the knowledge economy [16].

13. "Information and communication technologies market" V_{13}, $v_{13}^i \in V_{13}$, $i = 1, 2, \ldots k_1$ includes the following indicators: the volume of investments in fixed assets aimed at the acquisition of information, computer and telecommunication equipment at actual prices; share of people employed in the ICT sector in the total employed population.

14. "Higher education system" vertex V_{14}, $v_{14}^i \in V_{14}$, $i = 1, 2, \ldots k_1$ includes the following indicators characterizing its economic and innovative components: number of educational institutions of higher education; number of researchers with advanced degrees; number of publications of organizations indexed in the scientific citation systems; number of licensing agreements of an educational organization [17, 18].

15. "Investments in education" vertex V_{15} means tangible or intangible costs, the purpose of which is to profit or achieve the desired results from desired education.

16. "Knowledge/innovation spillover" V_{16} describes the process of innovations' dissemination in society, the regularity of the new products, technologies, ideas dissemination among potential consumers (users) from the moment of their appearance [19].

17. "Risks" vertex V_{17} shows risks arising from adverse changes in the economy of the region and risks due to changes in the political environment (national or global) affecting entrepreneurial activity of the region [2].

18. "Sustainable development of the region" V_{18} is a complex process leading to the solution of population problems at the regional level, to increase improvement of the living conditions of the region's inhabitants by achieving balanced socio-economic development [20].

A cognitive map of the relationship between sustainable development of the region and the markets of knowledge-intensive sectors was developed using the software system CMLS (Cognitve Modeling Large System) [21].

In the cognitive map G, solid lines show the influence sign "+" between the vertices of the model, meaning "an increase/decrease in the signal in V_i leads to an increase/decrease in the signal in V_j"; the dash-dotted lines show the influence sign "−" between the model vertices, meaning "an increase/decrease in the signal in V_i leads to a decrease/increase in the signal in V_j".

2. Model characteristics' calculation

After the development of the cognitive map at the second stage of cognitive modeling, the analysis of the model's properties was performed, such as its resistance to disturbances, structural stability, path and cycle analysis, connectivity analysis, etc.

Fig. 2 shows the cycles' analysis results of the cognitive map G (Fig. 1) and one of the positive cycles is highlighted in green. Fig. 3 shows an example of a negative cycle highlighted in purple.

The cognitive model cycles' analysis of the relationship between the sustainable development of the region and the markets of knowledge-intensive sectors showed that this system contains 682 cycles, including 661 cycles of positive (reinforcing) and 21 cycles of negative (stabilizing) feedback. Positive cycles have an even number of negative arcs or do not have them at all; negative cycles contain an odd number of negative arcs. The system is considered structurally stable if there is an odd number of negative cycles in it. According to this criterion, the analyzed system is structurally stable.
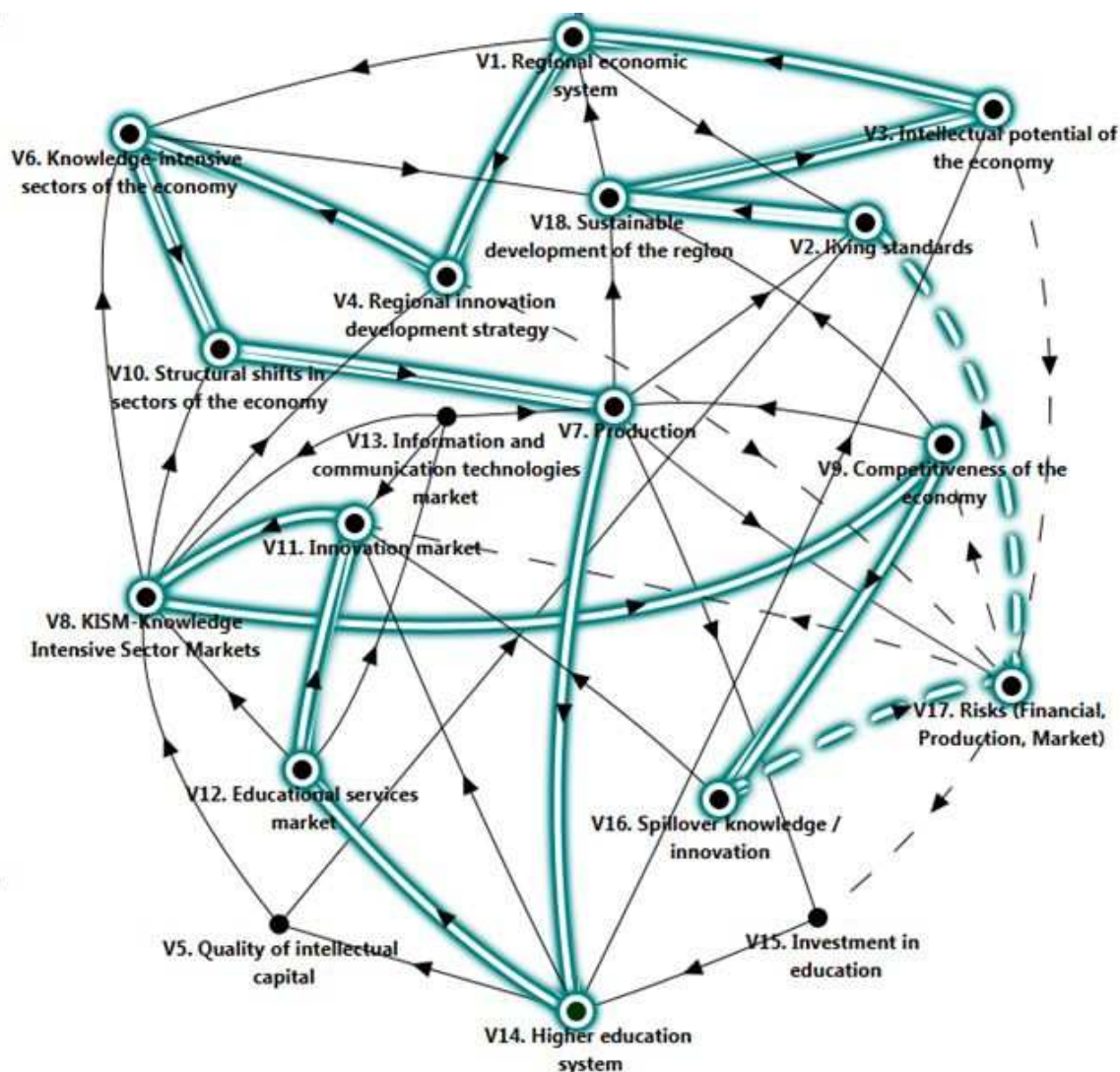

Fig. 2. Highlighting the positive cycle of the vertex V_1 "Socio-economic system of the region" (color online)
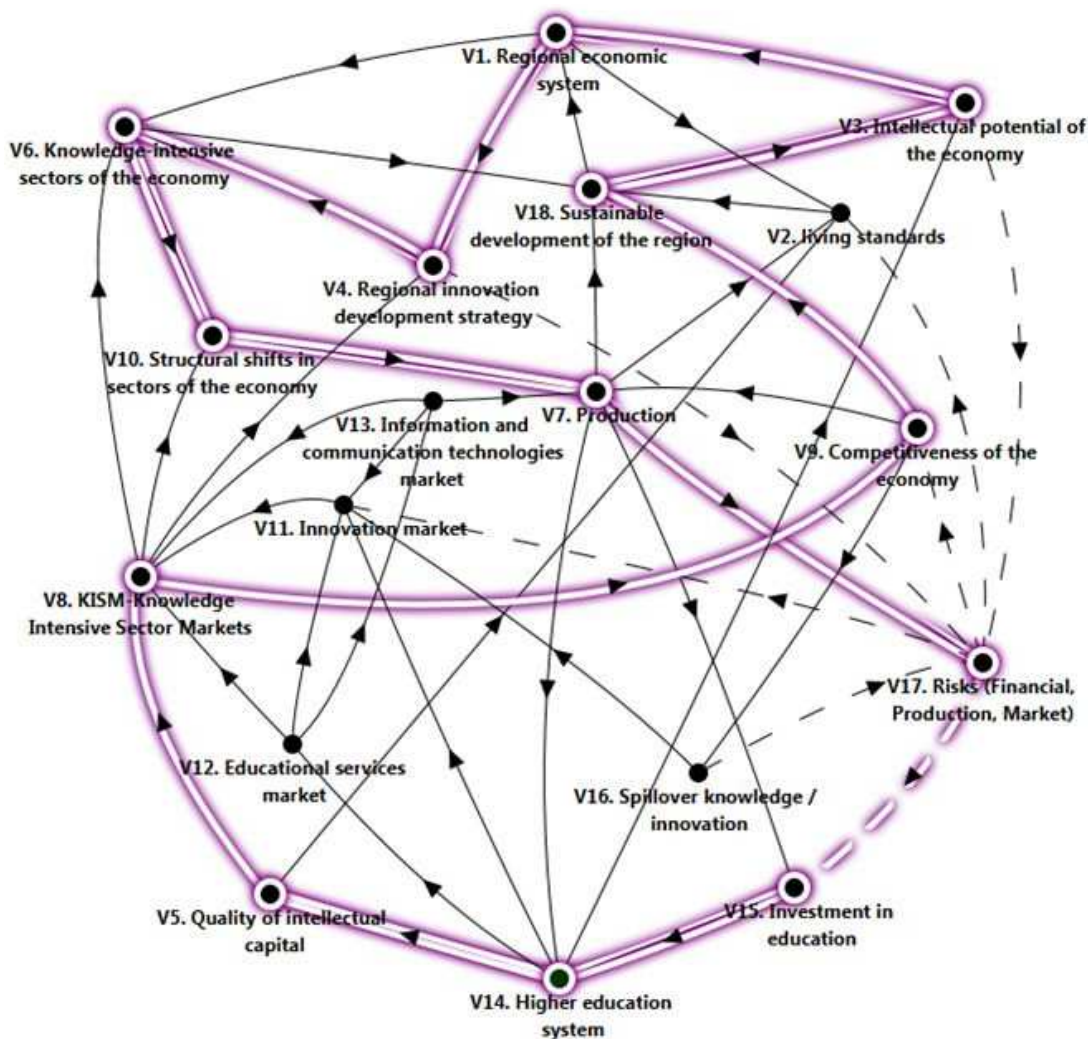
Fig. 3. Highlighting the negative cycle of the vertex V_1 "Socio-economic system of the region" (color online)

3. Scenario modeling

As part of the third stage, we will analyze the results of scenario modeling for the sustainable development of the region and the markets of knowledge-intensive sectors.

The CMSS program allows impulse modeling — an impulse processes' simulation of a cognitive map for the relationship between sustainable development of the region and the markets of knowledge-intensive sectors by introducing impulses, interpreted in accordance with the task at hand, as "disturbing" or "controlling". It is possible to introduce disturbances of different magnitude (normalized) to any of the vertices, as well as to their combination.

Scenario 1. To construct the chosen scenario, let us assume that the state of knowledge-intensive sector markets is improving in the system: disturbing impulse $q_8 = +1$; vector of actions $Q_1 = \{q_1 = 0; 0; q_8 = +1; 0; \ldots; 0\}$. In Fig. 4 and the Table, the results of impulse modeling are visualized according to a scenario that imitates the impact of improving the state of knowledge-intensive sector markets on the processes in the socio-economic system of the region, the impulse enters one peak.

An improvement in the state of knowledge-intensive sector markets after the 4th cycle leads to an increase in all indicators in general and a sharp decrease of Risks (V_{17}), and after $n > 4$, a particularly rapid growth of all factors is observed.

Table

Scenario "Improvement of the knowledge-intensive sector markets state" revolting impulse $q_8 = +1$

| Step/Vertex	0.	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
VI. Regional economic system	0.	0.	0.	0.	2.0	7.0	17.0	31.0	59.0	143.0	369.0
V2. Living standards	0.	0.	0.	0.	3.0	5.0	15.0	34.0	75.0	150.0	361.0
V3. Intellectual potential of the economy	0.	0.	0.	0.	2.0	7.0	16.0	23.0	46.0	121.0	326.0
V4. Regional innovation development strategy	0.	0.	1.0	1.0	1.0	3.0	10.0	25.0	57.0	106.0	223.0
V5. Quality of intellectual capital	0.	0.	0.	0.	0.	2.0	6.0	8.0	10.0	24.0	78.0
V6. Knowledge-intensive sectors of the economy	0.	0.	1.0	2.0	2.0	4.0	13.0	35.0	82.0	163.0	329.0
V7. Production	0.	0.	0.	2.0	3.0	5.0	4.0	13.0	42.0	118.0	225.0
V8. KISM — Knowledge Intensive Sector Markets	0.	1.0	1.0	1.0	1.0	3.0	8.0	26.0	47.0	80.0	155.0
V9. Competitiveness of the economy	0.	0.	1.0	1.0	2.0	1.0	4.0	15.0	49.0	86.0	156.0
V10. Structural shifts in sectors of the economy	0.	0.	1.0	2.0	3.0	3.0	7.0	21.0	61.0	129.0	243.0
V11. Innovation market	0.	0.	0.	0.	2.0	3.0	11.0	24.0	51.0	96.0	237.0
V12. Educational services market	0.	0.	0.	0.	0.	2.0	6.0	8.0	10.0	24.0	78.0
V13. Information and communication technologies market	0.	0.	0.	0.	0.	0.	2.0	6.0	8.0	10.0	24.0
V14. Higher education system	0.	0.	0.	0.	2.0	6.0	8.0	10.0	24.0	78.0	199.0
V15. Investment in education	0.	0.	0.	0.	3.0	3.0	6.0	11.0	36.0	81.0	194.0
V16. Spillover knowledge/innovation	0.	0.	0.	1.0	1.0	2.0	1.0	4.0	15.0	49.0	86.0
V17. Risks (Financial, Production, Market)	0.	0.	0.	−1.0	0.0	−1.0	−7.0	−23.0	−39.0	−76.0	−158.0
V18. Sustainable development of the region	0.	0.	0.	2.0	5.0	10.0	15.0	36.0	97.0	248.0	517.0
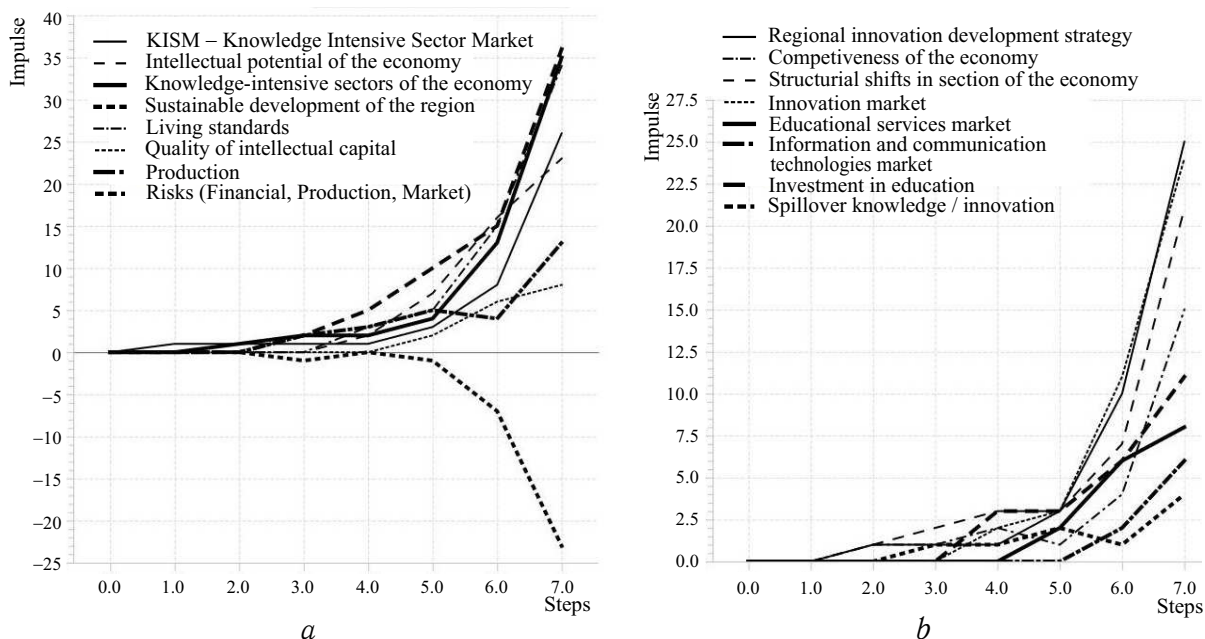
Fig. 4. Graphs of impulse processes at the vertexes V_1-V_{18} of the scenario "Improvement of the knowledge-intensive sector markets state"

Scenario 2. To construct the chosen scenario, let us assume that the system is undergoing a comprehensive improvement in the state of the "Innovation market", "Educational services market", "Information and communication technologies market" subsystems, while "Risks" are increasing: disturbing impulses $q_{11} = +1$; $q_{12} = +1$; $q_{13} = +1$; $q_{17} = +1$; vector of actions $Q_1 = \{q_1 = 0; 0; \ldots q_{11} = +1; q_{12} = +1; q_{13} = +1; 0; \ldots; q_{17} = +1; 0\}$.

In Fig. 5, the results of impulse modeling are visualized according to a scenario that simulates the effect of a complex improvement in the state of subsystems, the impulse enters four vertices.

A complex improvement in the state of the "Innovation market", "Educational services market", "Information and communication technologies market" subsystems, while "Risks" are increasing after the 5th cycle leads to an increase in all indicators in general and a sharp decrease of Risks (V_{17}) and after $n > 6$, a particularly rapid growth of all factors is observed.

Scenario 3. To construct the chosen scenario, let us assume that the system is undergoing a complex improvement in the state of the "Innovation market" and "Educational services market" subsystems, but at the same time the state of "Investment in education" is deteriorating, "Risks"
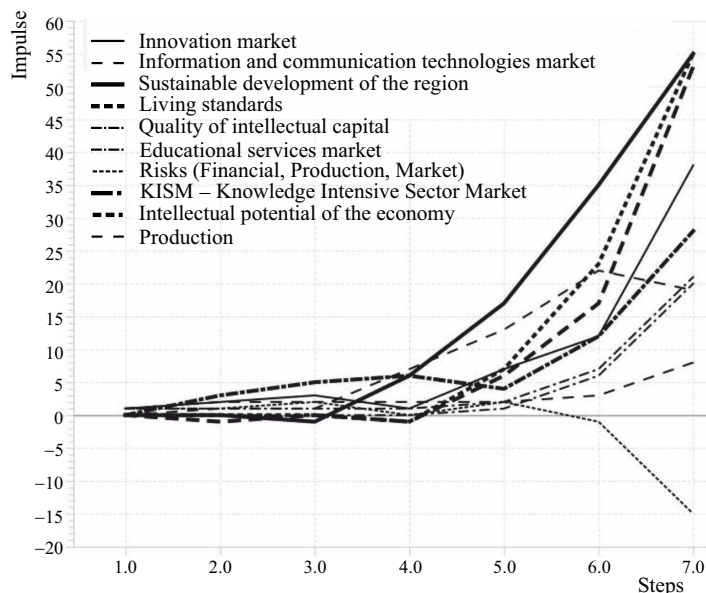

Fig. 5. Graphs of impulse processes at the vertexes V_1-V_{18} of the scenario "Complex improvement in the state of the "Innovation market", "Educational services market", "Information and communication technologies market" subsystems, while "Risks" are increasing
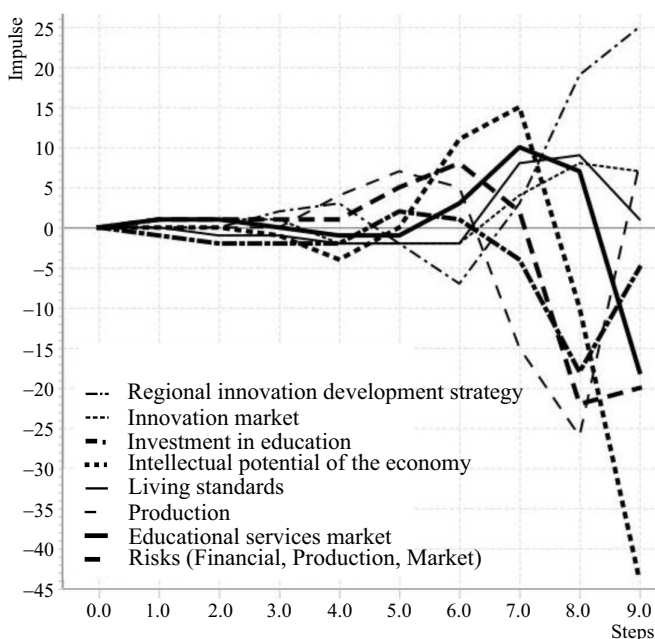
Fig. 6. Graphs of impulse processes at the vertexes V_1–V_{18} of the scenario "Complex improvement in the state of the "Innovation market" and "Educational services market" subsystemswith simultaneous deterioration of "Investment in education"and an increase in "Risks"

are increasing: disturbing impulses $q_{11} = +1$; $q_{12} = +1$; $q_{15} = -1$; $q_{17} = +1$; vector of actions $Q_1 = \{q_1 = 0; 0; \ldots q_{11} = +1; q_{12} = +1; 0; \ldots q_{15} = -1; 0; \ldots q_{17} = +1; 0\}$. The results of impulse modeling according to a scenario that simulates the effect of impulses on the general state of the system is visualized in Fig. 6, the impulse enters four vertices.

The chosen scenario leads to an unsustainable situation at all the vertexes V_1-V_{18} for the region and the knowledge-intensive sectors markets. This situation shows that "Investment in education" is crucial for the whole socio-economic system of the region.

Conclusion

The paper demonstrates the abilities of the software system CMLS (Cognitve Modeling Large System) while using the cognitive analysis methodology for solving management problems and assessing the structural stability of the relationship between knowledge-intensive sectors markets and the regional economy. The structural stability of the semi-structured complex system was established by analyzing the cycles of the cognitive map. Impulse and scenario modelling in this model and analysis of variable scenarios were carried out.

The presented methodological approach makes it possible to model the behaviour of the studied systems in response to disturbing influences and to analyze possible predictive development scenarios. The research results can be used as decision support program tools in substantiating strategies and developing a policy for the balanced development of knowledge-intensive sectors markets and the socio-economic system of regions.

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