Development of a Mathematical Model for Decision Support Systems in Social Structures Based on the Formation of Assessments of the Competitiveness of the Regions of the Russian Federation

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Abstract The problem of constructing a mathematical model for assessing the competitiveness of the regions of the Russian Federation has been formulated and solved. For this, a structuring method based on hierarchical trees is proposed. Their leaves are statistical indicators of socio-economic activity according to official data. These indicators are combined using integral characteristics. An example of the analysis of networks of socio-economic indicators based on the construction of minimum sections of the Kolmogorov-Chapman equations for the "Innovation" indicator is given. To describe the leaf vertices of the indicator trees, it is proposed to use status functions that represent complex-valued functions. The proposed mathematical model represents a system of integrodifferential equations, including the status function for the integral indicator of the competitiveness of the region, functions for each of the integral indicators, polynomials that are obtained as a result of interpolation of statistical data, and management influences. The analysis of the obtained graphs of the normalized values of several static indicators, the assessment of trends is given. The possibility of using numerical methods of nonlinear dynamics based on status functions to take into account the cross-section and mutual influence of the parameters of the risks of competitiveness of the regions of the Russian Federation for use in decision support systems in cyber-physical systems is shown.

Keywords Kolmogorov-Chapman equations · Decision support system · The competitiveness of regions · Graph of causal relationships · Status functions · Cyber-physical systems

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1 Introduction

Ensuring an adequate level of competitiveness of the Russian economy is associated with significant structural changes of a technological and organizational nature, both at the international and regional levels [1–5]. In this regard, the formation of a modern mathematical model of the competitiveness of regions is in demand [6–8]. Note that mathematical modeling, well developed in physics, hydrodynamics, quantum mechanics, chemistry, biology, nanotechnology, medicine, and other sciences, allows one to synthesize processes, materials, and new material structures, which cannot be created and controlled without predictive mathematical models.

At the same time, modeling in socio-economic systems "lags" behind the natural sciences. Moreover, to understand the processes in society and manage them using artificial intelligence, appropriate mathematical models are needed. However, the required mathematical models are difficult to create and even more difficult to test. Consider, for example, a laser. For the components of its structure, many mathematical models can be assembled, folded like constructor cubes. Then write a program, test the dependence on parameters, getting, for example, millions of data on 100 by 100-point grid structures. Then you need to check them with the experiment, get the result and data sets for further research based on them.

However, if we consider the structure of the socio-economic system (SES) as a cyber-physical system (CPS), then it will be necessary to synthesize and collect thousands of indicators into the structure [9]. The next task is to collect the real values of these indicators. This process is laborious and time-consuming. Analysis of changes over time is an even more difficult task since the social network changes during data collection and the structure of SES economic indicators is also not invariant and changes over time. Therefore, the problem arises of creating such structures so that it is possible to create reproducible algorithms for the dynamics of these processes in time for use in the FSC of the studied socio-economic processes.

2 Statement of the Problem of Developing a Mathematical Model for Intelligent Decision Support Systems

The construction of a mathematical model for intelligent decision support systems seems to be an urgent task in the process of overcoming imbalances in the socio-economic development of Russian regions [6, 7].

Let us consider in more detail the direction of research from the point of view of developing methodological and analytical tools for assessing the dynamics of risks [10, 11] to the competitiveness of Russian regions using artificial intelligence and methods of cyber-physical systems.

The aim is to assess the dynamics of competitiveness using artificial intelligence. This requires, based on an understanding of the doctrine of the organization of theoretical and practical human activity, to develop a methodology for solving the tasks following the set goal. The main idea is to implement a method for structuring a large number of indicators of socio-economic activity of the regions of the Russian Federation available for analysis in the corresponding cyber-physical system. Let this structuring be based on hierarchical structures. In them, the leaves of the tree will be the statistical indicators of socio-economic activity from the official statistics [12, 13]. Further, we will combine using specially developed integral indicators [14, 15].

The development of the proposed mathematical model is based on analogies of quantum-electric wave functions and membership functions of the theory of fuzzy sets. For individual social processes, the new method of status functions (SF) [16] was well demonstrated, which allows one to take into account the intersection and mutual influence of individual indicators.

3 Characteristics of Methods for Analyzing Networks of Socio-Economic Indicators

Thus, a causal graph of indicators can be obtained. The analysis of this graph can be carried out by methods of constructing minimal sections of the Kolmogorov-Chapman equations [15]. Based on such graphs, networks of socio-economic indicators can be built. Let's define them as a set of relevant nodes connected by one or more relations [17]. The relations of connections of leaf vertices will be determined based on specially synthesized indicators. For example, if statistical data is available on indicators in the constituent entities of the Russian Federation:

- the number of researchers with a scientific degree;
- internal costs for research and development;
- the level of innovative activity of organizations;
- the volume of innovative goods, works, services,
- Let's combine them into an indicator:
- indicator of innovation.

Then we will form a set of indicators. The significance of these indicators is different; accordingly, their connections in the system are also different. Let us construct the links between the indicators of the competitiveness of the region for the CFS by analogy with computer networks. Then topologies such as star, bus, mesh, fully connected mesh, tree, combined topologies will be possible. In addition, the graph may not be connected, it may contain isolated vertices and networks of vertices of different topologies.

First, you need to analyze the interaction of indicators. Such an analysis is possible based on four main approaches [18–20]:

1. Structural approach (or formal-mathematical). Based on the analysis of the geometric shape of the network and the intensity of interactions between nodes. In our case, the analysis of the competitiveness of the region is initially lacking. Therefore, for the formed network, it is not advisable to focus on such methods

of analysis, in which special attention is paid to the mutual arrangement of vertices, centrality, and transitivity of interactions.

2. The resource-based approach considers the possibilities of interaction participants, as network nodes, to attract network resources to achieve certain goals. At the same time, the nodes located in identical structural positions of the social network are differentiated according to their resources (influence, status, information, capital).
3. The normative approach studies the norms and rules that affect the processes of interactions between network nodes.
4. The dynamic approach focuses on changes in the structure of the network over time.

If we focus on a dynamic approach, then it is possible to create a network of parameters based on the opinions of experts, and then conduct a study of its transformation. The resource-based approach will allow you to create complex structures based on status functions. However, you first need to build a network prototype for use in a cyber-physical system.

4 Description of the Network Preimage

Let's try to rebuild the causal graph into a network structure. We will be based on the indicators of the leaf vertices of the causal graph presented in [15]. For them and their groups, we used the notation Ei from [15]. For the groups created for the network graph, in this work, we use the notation Qi.

Group–1 (q1): the use of fixed assets (E9) includes:
the cost of fixed assets q11 (E29); depreciation rate of fixed assets q12 (E30).
Group–2 (q2): the development of transport infrastructure (E10) includes:
the density of railway tracks q13 (E31); road density q14 (E32).
Group–3 (q3): the income level of the population (E11) includes:
per capita money income q15 (E33); population with incomes below the subsistence level q16 (E34); the number of officially unemployed people q17 (E35).
Group–4 (q4): demographic (E12) includes:
life expectancy q18 (E36); population growth rate q19 (E37); the coefficient of migration growth q20 (E38).
Group–5 (q5): quality of life q21 (E13) includes:
dilapidated and dilapidated housing q22 (E39); the number of doctors per 10,000 population q23 (E40); the number of registered crimes q24 (E41).
Group–6 (q6): natural resources (E5) includes:
mining q25 (E14); agricultural land area q26 (E15); availability of forest resources q27 (E16); electricity production q28 (E17); emissions of polluting products q29 (E42); discharge into water bodies of polluted wastewater q30 (E43).
Group–7 (q7): institutional (E6) includes:

share of unprofitable organizations q31 (E19); arrears of taxes and duties q32 (E20); business income q33 (E21).
Group–8 (q8): informational (E7) includes:
the number of personal computers q34 (E22); Internet use in organizations q35 (E23); use of electronic document management systems in organizations q36 (E24).
Group–9 (q9): innovative (E8) includes: personnel engaged in research and development q37 (E25); internal expenditure on research and development q38 (E26); costs of technological innovation q39 (E27); the volume of innovative goods q40 (E28).

At the initial stage, we will assume that the listed groups of exponents q1 $\div$ q9 have the same mutual influence, respectively, have the topology of a fully connected mesh.

In addition, we introduce the vertex q10—representing the competitiveness of the region and assume that it is connected with all vertices q1 $\div$ q9. Each of the vertices q1 $\div$ q9 is associated with the vertices, which are "leaf" and described by controlled indicators, the data of the values of which are obtained from the statistics [21]. Each of the vertices q1 $\div$ q9 forms a star topology for the associated "leaf" indicators.

Figure 1 shows the result of the transformation of the causal graph obtained for the analysis of the competitiveness of the regions of the Russian Federation by the methods of solving the Kolmogorov-Chapman system of differential equations for use in the CFS.

5 Interpretation of Status Functions in Graph Nodes

We will interpret the status functions (SF) in leaf vertices for the following reasons.

1. For "leaf" tops. Here SF is a complex-valued function. The SF amplitude is determined based on official statistics [12, 13]. The following assessment levels are possible:
    (a) low–medium–high;
    (b) bad–satisfactory–good–excellent;
    (c) low–below average–average–above average–high.

An orthonormal function is assigned to them. These functions are similar to the "pure states" functions in quantum mechanics. However, in our case, these functions will initially be mixed, since, depending on the numerical range of measurement of the indicator of the socio-economic activity of the region, one of three possible levels of assessment can be selected. Therefore, the result based on the orthonormal functions will immediately be mixed.

Let's say the probabilities of their changes can be interpreted as membership functions. Let us normalize the membership functions using the Gram-Schmidt methods

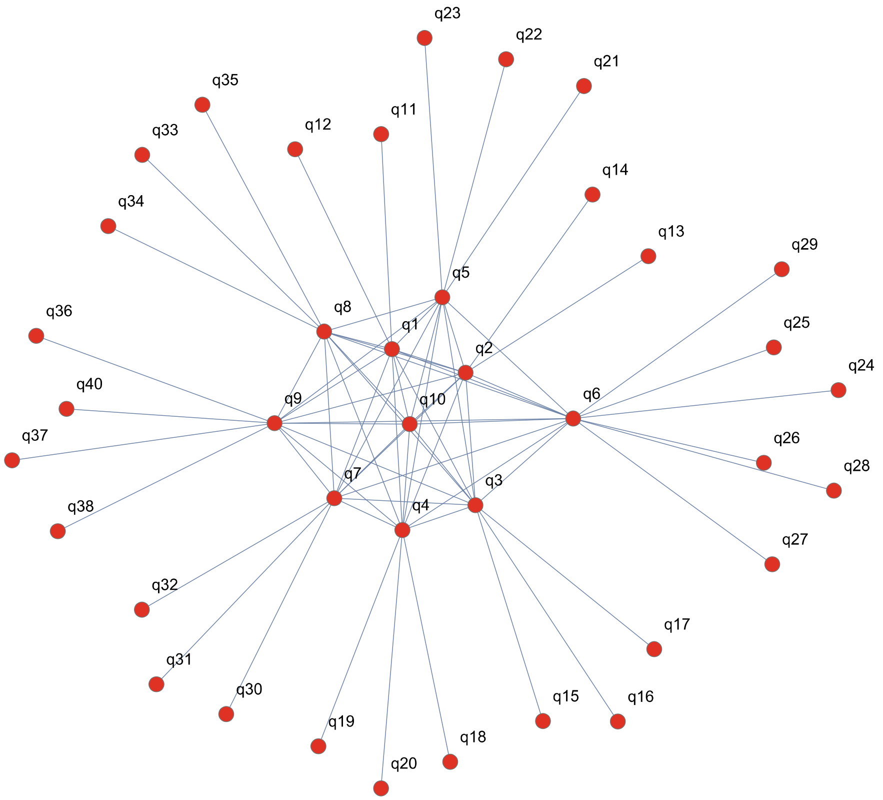

Fig. 1 Transformation of the causal graph of the competitiveness of the region [15] into a network graph that is not a state graph

and obtain sets of orthonormal alternating functions. These alternating functions can represent an analog of the probability of realizing the observed value. They can be assigned to the corresponding state by analogy with membership functions. In addition, they are orthonormal and can be used as an analog of quantum mechanical functions of pure states.

The complex part $e^{2\pi ikr}$ is formed from a comparison of the trend over the last 3 years. A steady tendency towards a deterioration in the indicator k = −1, a slight deterioration in k = −0.33, no change in k = 0, a slight deterioration in k = 0.33, a steady tendency toward an improvement in the indicator k = 1.

Let's say that when evaluating states, 3 possible values are used: low–medium–high.

$$\psi_{low} = 3.37619(e^{-50.(\mathrm{r}+0.14)^2} - 0.580252e^{-22.2222r^2}; \tag{1}$$

$$\psi_{average} = 1.9394e^{-22.2222r^2}; \tag{2}$$

$$\psi_{high} = 1.37668e^{-(14.-50.r)r} + 1.87105e^{(14.-50.r)r} - 5.02117e^{-22.2222r^2}. \quad (3)$$

The complex part sets the direction of displacement of the mean value in r. The basic variable r introduced by analogy with the theory of fuzzy sets characterizes the space of mixing or mutual influence of exponents.

Let's introduce time dependence. Let's say it is similar to the time dependence of the Cobb–Douglas production function [22, 23]. However, the task is to form an oscillatory function similar to a quantum mechanical function. Then it is logical to expect a time dependence somewhat different from the Cobb–Douglas model. We represent it in the form $e^{-i\varepsilon t}$, where ε is some constant.

Thus, let us assume that a certain parameter of the system of parameters of the competitiveness of a region can be represented by a status function, which is measured when collecting statistical data. Moreover, SF is in a sense analogous to the wave function of "pure states" of a quantum mechanical particle. This function for a free quantum mechanical particle can be represented as:

$$f(r,t) = C(t)\psi(r)e^{-(i\varepsilon t - 2\pi kr)}, \quad (4)$$

where r is a coordinate in a certain space, t is time, $C(t)$ is the dependence of the amplitude on time, $\psi(r)$ is the characteristic of the maximum of the SF in the space of mixing parameters, ε is some constant, k is the characteristic associated with the "momentum" of the investigated object. The particle energy is proportional to $k2$. Thus, its approximate form can be obtained from the equation of flows.

2. For integral indicators q1 ÷ q10. Each of the vertices q1 ÷ q9 is associated with vertices that are "leaf" and described by controlled indicators, the values of which are obtained from the statistics [21]. Therefore, the variables q1 ÷ q9 must be obtained from the indicators included in them. The value of the q10 exponent should be obtained from the set of q1 ÷ q9 exponents. Let's start forming them based on a mathematical model.

6 Development of a Mathematical Model for Assessing the Competitiveness of Regions

We design equations for integral indicators based on optical-electrical analogy. We proceed from the put forward assumption that each controlled indicator changes according to some complex harmonic law. This idea is fully consistent with modern ideas of cyclical oscillatory processes in the economy [24].

Let the competitiveness of the region be a complex value and depend on itself according to the law of Malthus. The limitation is associated with its complex part. The competitiveness is positively influenced by managerial influence. This can also be considered a hypothesis since it can be proved that it is the managerial influence that positively affects the growth of competitiveness. A negative impact is also possible. Let us assume that the managerial influence has a positive effect.

Let instead of competitiveness in the right side of the equation be used its dependence on the sum of its 9 intermediate indicators. Each of these indicators is represented by an integrodifferential equation for the integral indicator itself, which on the right side of the equation will be used as the sum of an unknown indicator and its particular value, represented by a polynomial. The polynomial is obtained as a result of interpolation of real statistical data describing the leaf indicators of the graph in Fig. 1. At the same time, for each of the intermediate indicators included in the structure of the causal graph, indicators have been used that form its branch. For example, for the intermediate integral indicator "Innovative", the sheet indicators "The number of researchers with a scientific degree in the constituent entities of the Russian Federation", "Internal expenditures on research and development by the constituent entities of the Russian Federation", "The level of innovative activity of organizations", "The volume of innovative goods, works, services"(see Fig. 2).

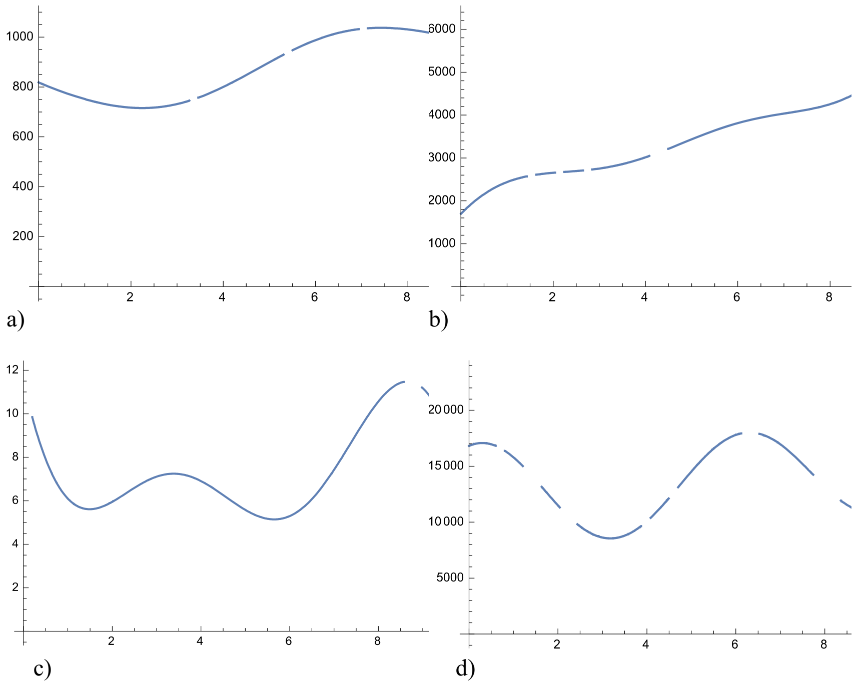

Fig. 2 The dots represent the normalized values of the indicators **a** the number of personnel engaged in research and development q_{37}; **b** internal costs for research and development q_{38}; **c** costs of technological innovations q_{39}; **d** the volume of innovative goods q_{40} obtained from the data [13] for the Saratov region for the period 2010 $\div$ 2019, the solid line—the results of interpolation of statistical data

Thus, we will begin to form a system of equations for assessing the competitiveness of the region.

For root node q10:

$$\frac{df(t)}{dt} = \alpha\left(i\beta\sum_{j=1}^{9} q_j(t) - \sum_{j=1}^{9} q_j(t) + p(t)\right). \tag{5}$$

For intermediate nodes of the first level, which are the consequences of causes $q_1 \div q_9$:

$$\frac{dq_k(t)}{dt} = \alpha\left(i\beta\left(q_k(t) + \int_{-1}^{1}\left(\sum_{i=1}^{k} q_i(t)\psi_j(r)\right)dr + polimom_k(t)\right) - q_k(t)\right.$$
$$\left. - \int_{-1}^{1}\left(\sum_{i=1}^{k} q_j(t)\psi_j(r)\right)dr - polimom_k(t) + p(t)\right). \tag{6}$$

Let's add managerial impact:

$$\frac{dp(t)}{dt} = \gamma(i\delta p(t) - p(t) + w(t)f(t)), \tag{7}$$

Let's introduce a description of the socio-economic environment:

$$\frac{dw(t)}{dt} = \chi(A - w(t) - \frac{1}{2}\big(f^*(t)p(t) + f(t)p^*(t)\big), \tag{8}$$

where $f(t)$ is the SF for the integral indicator of the region's competitiveness q10, qk are the functions for each of the integral indicators q1 ÷ q9, $polimom_k$ is the polynomial obtained as a result of the interpolation of statistical data for the period 2009 ÷ 2019, $p(t)$—F, characterizing the management impact, $w(t)$—SF, describing the environment in which the region operates, α—the rate of relaxation of the student to the initial state, β—the coefficient of the interaction of control with the controlled system, γ—the rate of reflection and recovery of the management system for the possibility take managerial influences, δ is the coefficient of the interaction of the control system with the controlled, χ is the rate of recovery (relaxation) of the environment, A is the characteristic of the threshold state of the socio-economic environment, *—denotes the symbol of complex conjugation.

7 Analysis of Numerical Simulation Results for Leaf Vertices

Consider an example of the formation of an SF for leaf vertices for one of the groups of parameters innovative (q9). Let us assume SF in the form (4). Here are the normalized values of statistical data for the Saratov region. Based on statistical data (Table 1), we construct $polimom_k(t)$ (Fig. 2). The characteristic of mixing indicators has three possible values (1) ÷ (3) and the corresponding form of the function is shown in Fig. 3. The direction of the bias trend is set by possible values that are obtained from comparison with data from other regions of the corresponding cluster and may have the following values: "High values of the indicator, it has been growing for the last 3 years, more than 10% higher than the same indicator for neighboring regions", "High values, changes within 3 years within the margin of error", "High values of the indicator, growing for the last 3 years." For them, k = −1, k = 0, k = +1.

Let's interpolate the data in Table 1 and get the following expressions:

Table 1 Values of indicators of the group of parameters "Innovations"

Indicator/year	Number of personnel engaged in research and development q37	Internal expenditures on research and development q38	Expenditures on technological innovations q39	The volume of innovative goods q40
2010	729	2365,275	6,4	17,222,125
2011	753	2693,1602	5,5	7713,7124
2012	741	3020,6738	7	10,617,418
2013	823	2843,242	6,4	13,180,746
2014	778	3298,273	6,8	8484,9
2015	1055	3577,7	6,3	23,177,377
2016	1067	4387,7	4,8	16,065,337
2017	994	4464	11,794,872	10,348,813
2018	1014	4484,3	11,157,718	12,833,643
2019	939	6209,6	6,1	13,457,747

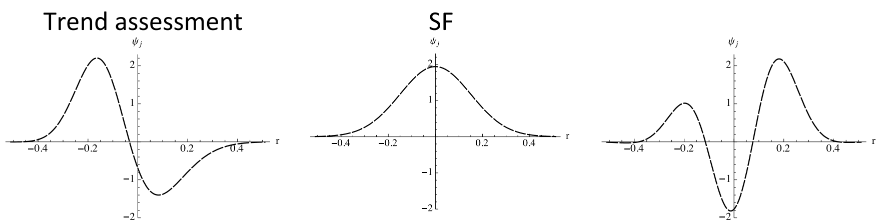

Fig. 3 Type ψ (r) for low, medium and high values of the linguistic term of assessment

For q_{37}
$$polimom_{37} = 655.127e^{-0.1t} + 32.1817e^{-it} + 32.1817e^{it} - i\,274196e^{-0.1it} + i\,274196e^{0.1it} + i\,139778e^{-0.2it}i - 139778e^{0.2it}. \tag{9}$$

For q_{38}
$$polimom_{38} = -46479.8e^{-0.1t} + 169.581e^{-it} + 169.581e^{it} + i\,1.0824410^{7}e^{-0.1it} - i\,1.0824410^{7}e^{0.1it} - i\,5.5018510^{6}e^{-0.2it}i - i\,5.5018510^{6}e^{0.2it} + 47838.5e^{-0.001t}. \tag{10}$$

For q_{39}
$$polimom_{39} = 4899e^{-0.1t} - 537.115e^{-it} - 537.115e^{it} - i\,3.3794310^{6}e^{-0.1it} + i\,3.3794310^{6}e^{0.1it} + i\,1.7132210^{6}e^{-0.02it} - i\,1.7132210^{6}e^{0.02it}. \tag{11}$$

For q_{40}
$$polimom_{40} = 1436.1e^{-0.1t} + 2226.6e^{-it} + 2226.6e^{it} + i4.2903510^{6}e^{-0.1it} - i\,4.2903510^{6}e^{0.1it} - i\,2.1268810^{6}e^{-0.02i} + i\,2.1268810^{6}e^{0.02it}. \tag{12}$$

8 Conclusions

Thus, it is possible to put forward a hypothesis about the possibility of adding a factor in the form of e^{-it} to SF [16]. This dependence can be traced from the interpolation results. The function is dependent on the total energy of the system, which cannot be obtained from a single parameter. At a minimum, it is necessary to form a complete system of monitored indicators, but this is not enough. It cannot be guaranteed that the list of monitored indicators fully describes the system of competitiveness of the region of the Russian Federation. Or, for a complete system of all regions, this system will also be approximate, since in reality the system is open and exchanges, like a cyber-physical system, energy with the environment. Thus, at the present stage of modeling the competitiveness of Russian regions, it is necessary to agree with the approximate representation of energy. The undoubted advantage of the model is the assumption that the system has energy.

Secondly, you need to decide: what data is available for analysis? Data collection was carried out based on databases such as the Russian Statistical Yearbook, Socio-economic indicators [21], and IAS "FIRA PRO". As a result, information and analytical base for further research have been developed, which is characterized by the use of data structures with the systematization of indicators in a chain of cause-and-effect events and combining them into integral indicators of CPS, which made it possible to use this information in the developed methods of algorithmic data analysis with a focus on creating an intelligent information system. identifying risks associated with maintaining and developing regional competitiveness.

Third, a complex system has been obtained; therefore, it is advisable to use it for fragmentary analysis. In this regard, a methodology, algorithms, and mathematical models have been developed based on the Kolmogorov-Chapman, Cobb–Douglas equations, equations of the dynamics of quantum generators, and optical-electrical analogy.

Such a complex transformation, based on preliminary assessments of competitiveness based on the Kolmogorov-Chapmen equations, proceeds from the understanding that Markov processes are considered in the systems of Kolmogorov-Chapman equations. In practice, the evaluation of Markov chains is a trade-off between increasing the number of observations to obtain reliable estimates and increasing the probability of violation of the Markov property. When we strive to improve accuracy, we are forced to abandon the used model. However, without the initial model, it is impossible to develop mathematical models intended for the development of methodological and analytical tools for assessing the dynamics of the risks of competitiveness of Russian regions using artificial intelligence for CPS. The development of the model is based on analogies of quantum-electric wave functions and membership functions of the theory of fuzzy sets. For individual social processes, the new method of status functions was well demonstrated, which allows one to take into account the cross-section and mutual influence of individual indicators. Modification of the Kolmogorov-Chapman equations is carried out to use status functions to assess individual indicators.

Thus, the possibility of using numerical methods of nonlinear dynamics for analyzing the competitiveness of regions of the Russian Federation is shown, which is distinguished by the use of the method of status functions, which made it possible to take into account the intersection and mutual influence of parameters of competitiveness risks for use in cyber-physical systems. Original methods have no analogs in modern literature. The results of the work are intended for use in the development of mathematical models of advising systems for monitoring and countering the disruption of the stable functioning and development of regions of the Russian Federation using modern mathematical models and information technologies in the CFS [25–27].

As a result, a description of the temporal and logical structure of tools for assessing the dynamics of competitiveness risks were obtained, statistical data were collected and structured, mathematical models were tested, which served as the basis for programs for the further development of methodological and analytical tools for assessing the dynamics of competitiveness risks using artificial intelligence for the corresponding CPS.

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