The scenario modeling of regional competitiveness risks based on the Chapman-Kolmogorov equations

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Abstract. The paper is devoted to the development of analytical tools for assessing the dynamics of risks to the competitiveness of Russian regions within the conditions of incomplete information. The choice of analysis methods for assessing the risk dynamics was substantiated. A solution based on the implementation of homogeneous Markov models with a discrete set of states and continuous time was proposed, it allowed to assess the probability of risks affecting regional competitiveness. A hierarchical structure of factors that determine the risks of regional competitiveness was formed as a cause-and-effect graph. Corresponding systems of Kolmogorov – Chapman differential equations were obtained and solved. An example for analyzing a 3-element minimal cut set of a cause-effect graph was presented. A set of scenarios for the study of risks and their combinations in various conditions was proposed. The solution was obtained for three leading Russian regions. For a set of scenarios, numerical assessments of risk factors that significantly affect the decline in the competitiveness of regions have been fulfilled. The study results made it possible to rank the effects of critical event occurrence, to identify the most significant risk factors for the loss of sustainable development and competitiveness for the Russian Federation regions.

1. Introduction
The problem of developing and applying mathematical models for assessing social and economic risks at the regional level, including the study of regional competitiveness, remains relevant. A significant place in assessing regional competitiveness is taken by the composite indicator approach. The motivation for using integrated indicators consists in creating an objective tool that allows to compare the competitiveness of different regions. In addition to the Global Competitiveness Index presented annually by the World Economic Forum [1], there are a number of established approaches to region assessment: EU Regional Competitiveness Index [2]; European Innovation Scoreboard [3] and its extension Regional Innovation Scoreboard [4] to assess the competitiveness and innovation of countries and regions. AV RCI rating methodology [5] is proposed for Russian regions within the framework of the competitive environment analysis (assessment of global competitiveness).

A popular approach to regional competitiveness assessment consists of various ratings, various integrated indices that combine sets of indicators that have a direct or indirect impact on the competitiveness level of a region [6–8]. In this case, it is necessary to take into account the multidimensional nature of regional competitiveness [9]. It is noted that competitiveness is not a specific characteristic that can be measured directly. Its assessment is performed using an
indirect set of indicators [10]. Comparative competitiveness indicators are generally useful from an analytical point of view, they allow to interpret the regional relative performance and have visual appeal [11].

The controversial nature of the methodology for assessing regional competitiveness has led to the emergence of various ratings that compare Russian regions in accordance with different sets of indicators. The ratings provide an indication of what is required for an economy to grow sustainably based on the increasing technological complexity. They identify areas requiring additional attention and aim at relevant development programs. Time series compiled of these ratings provide an idea of the overall direction of the economy and predict the trajectory of further changes. The use of integral indices has significant limitations [12]. This approach tends to randomly mix up indicators which are often non-linearly related. The choice of metrics to include in the index is largely determined by the availability of data. The weighing of individual indicators in the integral index is often subjective. Comparative assessments of competitiveness by Gross Regional Product often fail to describe territorial differences and their sources. Regions are usually located within administrative boundaries, there may be inconsistencies between these boundaries and economic realities. In the process of eliminating such problems, an urgent task arises for the further methodology development of competitiveness assessing, as well as mathematical models and methods for its implementation.

The described methods for regional competitiveness assessment are based on the study of indicators at a specific point in time. However, the possibility of assessing indicator changes over a certain period of time is of particular interest. The most common are methods for primary data structuring based on hierarchical structures of a cause-effect graph. Combinatorial, simulation or Markov models can be used to analyze the cause-effect graph. The method of decomposition, factorization, the SDP method of the disjunctive product sum (DNF orthogonalization) are among the most often discussed exact methods in the literature. It is possible to use the fuzzy set theory based on methods of preliminary term ordering in a logical expression (by decreasing Hamming distance, by lexicographic feature, by increasing the term power) [13, 14]. Modern trends in logical-probabilistic analysis are presented in [15,16]. The original development implements dynamic fault tree and algorithms using Markov models. To analyze the indicator dynamics of regional macroeconomic development, the use of Markov models is presented in several studies on the example of the USA and Italy [17,18].

The purpose of this work is to develop and implement a methodology for dynamic assessment of the risk event probabilities that can adversely affect the Russian regions’ competitiveness, using the Kolmogorov – Chapman equations in Markov models.

2. Analytical tool development for modeling the regional competitiveness risk dynamics

For the analysis of indicators and dependencies determined over a certain finite or infinite time interval, the most common dynamic models of system behavior are Markov random processes. This approach determines a set of the system’s possible states based on the information about its performance. Confirmation that the process is carried out by the state values of the event graph can be fulfilled in different ways. In practice, the verification of Markov models is subject to the trade-off between increasing the number of observations to obtain reliable estimations and increasing the probability of the Markov property violating [17]. It is shown that the assumption of the Markov character of the process of probabilities dynamics for macroeconomic indicators is satisfactory during approximately 20–25 years [18]. For time intervals during 70 years, the Markov property is violated [17]. Then a state graph is built, the vertices of which are the states of the system, and the edges are the possible transitions between the states. According to the state graph, the required system of equations is composed, the analytical solution of which allows to obtain mathematical expressions for the estimated indicators. Kolmogorov – Chapman
Equations are often used to calculate the state probabilities of Markov process with continuous time and a discrete set of states. Equation is based on a simple rule: the derivative of any state probability is equal to the sum of the probability flows that transfer the system to this state, minus the sum of all the probability streams that bring the system out of this state. The model is based on the assumption that the probabilities of the parameters are given by the Poisson distribution. The probability flow is the product of probability by the Poisson parameter of the risk realization intensity or functioning restoration.

Let a discrete deterministic universal set of possible events that pose risks to the region competitiveness be used as a model.

To solve the problem of assessing the regional competitiveness risks dynamics, taking into account a complex of social, political and economic factors on the basis of the Kolmogorov–Chapman equations, it is necessary to implement the following stages.

**Stage 1. Regional competitiveness risk factor structure formation.**

Within this stage, it is necessary:

- to select and group competitiveness risk factors;
- to establish causal relationships for the events using Fault Tree Analysis (FTA) models.

Let us consider the following as an event:

- an elementary event, as an indivisible element of the universal set of events;
- any set of elementary events;
- any finite sequence of events;
- the result of applying a logical operation for events.

Based on this understanding of events, they can be considered as elementary events or chains of elementary events, and with the event presentation in a more general form, i.e. sets of elementary events and sequences of elementary event sets. In addition, it is assumed that when considering specific tasks, elementary events and more complex events have a meaningful interpretation [19]. Any event can be presented as a cause in one causal relationship and, as a consequence, in another causal relationship.

Revealing the causal relationship of events and its direction is the main property of events. The use of differential, integral, algebraic equations and other means for determining dependencies is challenging, since it requires the variables in the equations to determine properties on sets of heterogeneous data and indicators. The apparatus of binary relations is a promising mathematical tool that can be used to represent the directional connections of objects when using heterogeneous data in high uncertainty conditions. Organizing these events into chains allows to build an event graph.

As a result of the first stage, the collection and structuring of data on various indicators of the social and economic development of regions should be carried out and, based on the identification of cause-effect relationships, a cause-effect graph with a hierarchical structure should be built.

**Stage 2. Analysis of the causal graph.**

The analysis of cause-effect graphs allows the use of modern discrete mathematics methods for representing complex objects. To represent causal relationships, it is proposed to use Binary Decision Diagram (BDD) [20]. In BDD terms, logical functions are represented as a binary causal graph, in which the inner vertices are function arguments.

On the basis of such relationships, cause-effect structures, in particular, causal graphs, can be formed. The logical tree vertices correspond to elementary events and arcs correspond to cause-effect relationships between events. For the logical trees under consideration, an event at the top of the tree can be represented as a consequence of events combined by a logical operation of conjunction or disjunction.
A complex structure can be analyzed in parts that contain groups of indicators, the combination of which through a logical operation leads to the implementation of the root event of the hierarchical data structure.

Then, for a fragment of the hierarchical structure, it is possible to build a state graph. For all possible values of the vertex parameters and their possible combinations, a system of equations is constructed. Its solution allows to obtain numerical values of the probability fluxes for each of the possible states. This method of studying Markov processes is one of the most common methods for analyzing complex systems represented by a cause-effect graph.

Such mathematical description of Markov process that occurs in a system with discrete states depends on at what moments of time the system can shift from one state to another state. With an exponential distribution of the random residence time of the system in each of its states, Markov process is homogeneous (the intensities of transitions between states do not depend on time). Homogeneous Markov processes with a discrete set of states and continuous time are the main apparatus for studying the dynamics of the intensity of probability flows of parameters of complex systems with recovery. A justified method for analyzing a cause-effect graph is an approach based on the addition theorem for the probabilities of joint events of the minimal paths (sections) implementation.

Let there be a causal relationships graph with the set of vertices \( E = \{E_1, E_2 \ldots E_R\} \). The minimal cut set in a system of an arbitrary structure is the minimal set of risk events, the implementation of which leads to the realization of a root vertex event and the realization of the risk of losing the ability to operate the entire system. Let us define the set \( M \) of minimal sections as the set of basic events that make up critical combinations. Let the dimension of the minimal cut set be equal to \( m \), \(|M| = m\). Thus, one can obtain the set \( S \), \(|S| = 2^m = g\), of possible states of the system under study. The intensities of transitions between states are determined by the Poisson parameters. Then, for each of the states, it is necessary to compose a differential equation describing the influence of causes on the root vertex of the causal graph:

\[
\frac{dP_i(t)}{dt} = -\sum_{k=0}^{g-1} q_{ik} P_i(t) + \sum_{k=0}^{g-1} q_{ki} P_k(t),
\]

where \( P_i(t) \) are the probabilities of the controlled object transition to certain state \( i, i = 0, 1 \ldots g - 1 \). The transition rate matrix \( Q = \{q_{ik}\}_{(g-1)\times(g-1)} \) is constructed based on the state graph adjacency matrix where \( q_{ik} \) is transition rate from state \( i \) to state \( k \). The diagonal elements of transition rate matrix are \( q_{ii} = -\sum_{k,i\neq k} q_{ik} \).

In present study, \( Q \) contains the corresponding parameters of the intensity of actions to restore \( d_j \) and actions to implement the risk of the corresponding vertex \( l_j \) for each vertex in the state graph. In the transition rate matrix \( Q \) will be used as elements \( l_j \), the Poisson parameter of therisk event implementation, and \( d_j \), the Poisson parameter of the risk countering for the basic event of the causal graph.

The system of Kolmogorov – Chapman differential equations in matrix form has the following form:

\[
\begin{pmatrix}
\frac{dP_0(t)}{dt}, \frac{dP_1(t)}{dt}, \ldots, \frac{dP_{g-1}(t)}{dt}
\end{pmatrix} = \begin{pmatrix}
P_0(t), P_1(t), \ldots, P_{g-1}(t)
\end{pmatrix} \cdot Q.
\]

Thus, when analyzing the regional competitiveness risk assessment on the basis of structured data in the form of a causal graph at the second stage, we obtain:

1) sets of minimum sections for the existing structure of a directed graph with event nodes that are functions of causes;
2) event graphs for all minimal sections;
3) Kolmogorov – Chapman equations for event graphs corresponding to the minimum sections.
Stage 3. Numerical simulation for individual regions.

At this stage, a computational experiment and a discussion of the numerical simulation results are carried out. The study of competitiveness involves the inclusion of a large number of different indicators in the model, while complex multi-parameter models will require the use of special techniques and software.

3. Implementation of the model based on Kolmogorov – Chapman equations in the study of the regional competitiveness in the Russian Federation

Stage 1. In the process of constructing a causal graph for assessing the competitiveness risks, a set of indicators of social and economic development is proposed, which are widely used in regional competitiveness studies of [21–24].

To construct the model, an expanded set of indicators of regional statistics was used which provides a systematic multifactorial assessment of the competitiveness risks of Russian regions (cost of fixed assets; the degree of depreciation of fixed assets; railway density; highway density; average per capita monetary income; the population with incomes below the subsistence level; the number of official unemployed; minimum life expectancy; coefficient of natural growth of the population; coefficient of migration growth; availability of dilapidated housing; number of doctors per 10,000 population; number of registered crimes; mining; agricultural land area; forest area; electricity production; amount of pollutant emissions substances; the volume of polluted wastewater discharged into water bodies; the proportion of unprofitable organizations; arrears of taxes and fees; income from entrepreneurial activities; use of the Internet in organizations; number of personal computers; use of electronic document management systems in organizations; the number of personnel engaged in research and development; internal research and development costs; the cost of technological innovation; volume of innovative products).

Effective social and economic development requires reliable, self-enforcing institutions [25]. For a systematic analysis of regional competitiveness, it is necessary to assess the development of the transactional sector, without which the continuous progressive development of the region is difficult. Distinguishing the transactional and transformational indicator category in order to identify competitiveness risk factors is an important aspect of the study.

In the process of modeling competitiveness risks at the regional level, it is proposed to use a set of elementary events $E$ using the following characteristics: region competitiveness ($E_0$); transformational ($E_1$); transactional ($E_2$); technical ($E_3$); social ($E_4$); natural resources ($E_5$); institutional ($E_6$); informational ($E_7$); innovative ($E_8$); use of fixed assets ($E_9$); developed transport infrastructure ($E_{10}$); income level of the population ($E_{11}$); demographic ($E_{12}$); living standards ($E_{13}$); mining ($E_{14}$); agricultural land area ($E_{15}$); forest resources ($E_{16}$); electricity generation ($E_{17}$); ecological ($E_{18}$); the proportion of unprofitable organizations ($E_{19}$); arrears of taxes and duties ($E_{20}$); business income ($E_{21}$); number of personal computers ($E_{22}$); use of the Internet in organizations ($E_{23}$); use of electronic document management systems in organizations ($E_{24}$); number of personnel engaged in research and development ($E_{25}$); internal expenditure on research and development ($E_{26}$); costs of technological innovation ($E_{27}$); volume of innovative products ($E_{28}$); the cost of fixed assets ($E_{29}$); depreciation rate of fixed assets ($E_{30}$); density of railway tracks ($E_{31}$); road density ($E_{32}$); average per capita monetary income ($E_{33}$); population with incomes below the subsistence level ($E_{34}$); the number of officially unemployed ($E_{35}$); life expectancy ($E_{36}$); natural population growth rate ($E_{37}$); migration growth rate ($E_{38}$); dilapidated housing ($E_{39}$); the number of doctors per 10,000 population ($E_{40}$); reported crime rate ($E_{41}$); emissions of polluting products ($E_{42}$); discharge of polluted waste water into water bodies ($E_{42}$).

Figure 1 shows a causal graph for assessing the risks of regional competitiveness for taking into account the mutual influence of indicators.

Stage 2. Let us consider as an example, a 3-element minimum cross-section for analyzing a
critical combination of events consisting of elementary events associated with competitiveness risks: decrease in the volume of innovative goods, works and services $E_{28}$, decrease in the value of fixed assets $E_{29}$, increase in the degree of depreciation of fixed assets $E_{30}$.

The corresponding event graph is a description of the critical combinations of these elementary events. The vertices of the obtained state graph will correspond to the joint occurrence of all possible states of a 3-element system. In total, $2^3 = 8$ states are possible for the intensities of the probability flows $P_i(t)$ $i = 0, 1, \ldots, 7$, for the occurrence of the following events presented on the state graph: $P_0(t)$ – none of the events happened $E_{28}, E_{29}, E_{30}$; $P_1(t) - E_{29}$ event occurred; $P_2(t) - E_{30}$ event occurred; $P_3(t) - E_{28}, E_{30}$ events occurred; $P_4(t) - E_{28}, E_{29}$ events occurred; $P_5(t) - E_{28}, E_{29}, E_{30}$ events occurred; $P_6(t) - E_{28}, E_{29}, E_{30}$ events occurred; $P_7(t) - E_{28}, E_{29}, E_{30}$ events occurred.

Eight equations are compiled for them:

\[
\begin{align*}
\frac{dP_0(t)}{dt} & = -P_0(t)(l_1 + l_2 + l_3) + d_1P_1(t) + d_2P_2(t) + d_3P_3(t), \\
\frac{dP_1(t)}{dt} & = l_1P_0(t) - (l_2 + l_3 + d_1)P_1(t) + d_1P_1(t) + d_3P_5(t), \\
\frac{dP_2(t)}{dt} & = l_2P_0(t) - (l_1 + l_3 + d_2)P_2(t) + d_1P_4(t) + d_3P_6(t), \\
\frac{dP_3(t)}{dt} & = l_3P_0(t) - (l_1 + l_2 + d_3)P_3(t) + d_1P_5(t) + d_2P_6(t), \\
\frac{dP_4(t)}{dt} & = l_2P_1(t) + l_1P_2(t) - (d_1 + d_2 + l_3)P_4(t) + d_3P_7(t), \\
\frac{dP_5(t)}{dt} & = l_3P_1(t) + l_1P_3(t) - (d_1 + d_3 + l_2)P_5(t) + d_2P_7(t), \\
\frac{dP_6(t)}{dt} & = l_3P_2(t) + l_2P_3(t) - (d_2 + d_3 + l_1)P_6(t) + d_1P_7(t), \\
\frac{dP_7(t)}{dt} & = l_3P_3(t) + l_2P_5(t) + l_1P_6(t) - (d_1 + d_2 + d_3)P_7(t).
\end{align*}
\]

Stage 3. Let us apply the model to certain regions that traditionally belong to the most

Figure 1. A graph of causal relationships for assessing the regional competitiveness risks.
competitive ones. In accordance with a large set of social and economic indicators, such regions as Moscow, St. Petersburg, Moscow Region, the Republic of Tatarstan, Krasnodar Territory, Sverdlovsk Region, Krasnoyarsk Territory, Khanty-Mansi Autonomous Area, Rostov Region, Nizhny Novgorod Region are distinguished as the most competitive ones [5]. Within the framework of the scenario approach, it is proposed to study three regions of the first 10 most competitive regions (Moscow, Krasnodar Territory, Nizhny Novgorod Region). Thus, we will analyze the risks of regions belonging to the same category of the most competitive ones while significantly differing according to the rating assessment, which will ensure the comparability of the research results.

The study used a model based on the Kolmogorov – Chapman equations to assess the competitiveness risk dynamics in accordance with a set of 9 scenarios. Different scenarios correspond to significantly different combinations of sets of crisis interventions and associated risk mitigation measures.

Let us define the intervals $l_j \in [0,1], d_j \in [0,1]$ for the values of the model parameters $l_j, d_j, j = 1, \ldots, 3$. For scenario modeling, we define low, medium and high levels of the Poisson parameters values $l_j, d_j$ as follows. For a low level of parameter values, the corresponding parameters belong to the interval $[0, 0.1]$, for the middle level of parameter values, the corresponding parameters belong to the interval $(0.1, 0.5]$, for a low level of parameter values, the corresponding parameters belong to the interval $(0.5, 1]$. 

Table 1 presents general approach of a computational experiment for assessing the regional competitiveness level for a set of different options of unfavorable event occurrence and counteraction to them. Let us consider 9 different scenarios corresponding to the main combinations of model parameters according to low, medium and high intensity of both crisis impacts and the intensity of countering impacts.

| Scenario | $l_1$ | $l_2$ | $l_3$ | $d_1$ | $d_2$ | $d_3$ |
|----------|------|------|------|------|------|------|
| Scenario 1 | low | low | low | low | low | low |
| Scenario 2 | low | low | low | medium | medium | medium |
| Scenario 3 | low | low | low | high | high | high |
| Scenario 4 | medium | medium | medium | low | low | low |
| Scenario 5 | medium | medium | medium | medium | medium | medium |
| Scenario 6 | medium | medium | medium | high | high | high |
| Scenario 7 | high | high | high | low | low | low |
| Scenario 8 | high | high | high | medium | medium | medium |
| Scenario 9 | high | high | high | high | high | high |

All indicators corresponding to the basic events had to be normalized, since they have different dimensions. The normalized values of the regional competitiveness factors are used as the initial values in the system of differential equations, through bringing them to a unified scale. The normalization was carried out in various ways for factors that increase the likelihood of adverse consequences to increase regional competitiveness, and factors that reduce this likelihood. To set the initial value for $P_0(0)$, the normalized numerical scores of the regional competitiveness were used [5]. The normalized indicator values belong to $[0,1]$. In this study, the elementary event initial values correspond to the normalized indicator values in 2018.

The differential equation system for three regions in accordance with 9 scenarios was solved numerically using the Runge-Kutta method with automatic step adjustment. The SciPy Python 3.8.3 module [26] was used. The dynamics of the risk probability values for individual indicators
of regional competitiveness and critical event combinations with the initial conditions – the values of these indicators in 2018 are shown on the time interval [0, 8] years.

The results of individual calculations are presented in graphics. For clarity, the diagrams added a critical value level for the value of the $P_c$ probabilities. In this case, the value $P_c = 0.2$ was used as a critical level for comparative analysis. The dynamics of the simulated variables is presented for scenarios 4 and 5 characterized by the probability of occurrence of adverse consequences associated with risk factors from the considered section.

Comparison of the dynamics of $P_i(t)$ values, $i = 0\ldots7$, for scenario 4 with a medium probability of unfavorable changes for competitiveness factors from the set $M$ ($l_j = 0.45$, $j = 1\ldots3$, $d_j = 0.001$, $j = 1\ldots3$) for Moscow is shown in figure 2. Figure 3 shows $P_i(t)$ values, $i = 0\ldots7$, in accordance with scenario 5 for Moscow with an increase in $l_j$, $j = 1\ldots3$, and with the same commitment in the implementation of measures to counteract the ($l_j = 0.45$, $j = 1\ldots3$, $d_j = 0.45$, $j = 1\ldots3$).

![Figure 2. Dynamics of the values of the probabilities of a critical combination of elementary events for Moscow (scenario 4).](image1)

![Figure 3. Dynamics of the values of the probabilities of a critical combination of elementary events for Moscow (scenario 5).](image2)

Analysis of the diagrams for Moscow allows for the conclusion that the risks associated with an increase in the fixed asset depreciation and a decrease in the volume of innovative goods are most likely.

With an increase in crisis phenomena to a medium level, the probability for all critical combinations of events increases. However, the probabilities corresponding to various combinations of critical events do not exceed the $P_c$ level for $t > 3$. To compare the regions for scenario 4 (figure 4) and scenario 5 (figure 5) $P_i$, $i = 0\ldots7$, for Krasnodar Territory are shown. The parameter values $l_j$, $j = 1\ldots3$, $d_j$, $j = 1\ldots3$ in this case remain the same.

For the Krasnodar Territory, the probabilities corresponding to various combinations of critical events exceed the $P_c$ level at $t > 1$. For the Nizhny Novgorod Region for scenario 4 (figure 6) and scenario 5 (figure 7), $P_i$, $i = 0\ldots7$ are given, and the values of the event occurrence possibility and counteraction are the same as for Moscow and the Krasnodar Territory.

For the Nizhniy Novgorod region, the probabilities corresponding to various combinations of critical events exceed the $P_c$ level for all $t$. In addition, the different variability of risk levels for the regions considered should be noted.

Such results are quite consistent with expert assessments and existing ratings, which confirms the possibility to use the proposed model for assessing regional competitiveness.

For a more detailed analysis, let us consider the probabilities corresponding to individual critical events (figure 8–9) for all 9 scenarios.
The more probable competitiveness risk factors are distinguished based on the example of two regions that differ significantly in terms of competitiveness. For the city of Moscow, under various scenarios, an event associated with the risk of a decrease in the volume of innovative goods is more likely (Figure 8). For the Nizhny Novgorod region, adverse events associated with a decrease in the cost of fixed assets are more likely.

Figure 10 presents descriptive statistics in the form of a Whisker diagram for a fixed set of critical events ($P_0$, $P_1$, $P_2$, $P_3$).

The variability of the probabilities for individual critical events ($P_3$ for Moscow, $P_1$ for the Krasnodar Territory and Nizhny Novgorod Region) allows for the conclusion that the competitiveness factors associated with the corresponding critical events require special attention in the risk management process. The median values for different scenarios indicate the most significant risk factors that preserve the leading invariance under different scenarios for each region.
Figure 8. Values of the probabilities of a critical combination of elementary events for Moscow.

Figure 9. Values of the probabilities of a critical combination of elementary events for the Nizhny Novgorod Region.

Figure 10. Descriptive statistics for $P_0$, $P_1$, $P_2$, $P_3$ for different scenarios for regions.

4. Conclusion

The analysis of the currently existing methods for assessing the regional competitiveness shows that approaches based on the use of integral indices are actively used. These methods have significant limitations, such as the tendency to combine indicators into an integral indicator while in reality they may have complex non-linear relationships. In addition, the choice of indicators included in the integral index is largely determined by the availability of data. The weighing of individual indicators in the integral index is often subjective. Comparative assessments of competitiveness often do not describe territorial characteristics.

The main disadvantage of the described methods for assessing the regional competitiveness is the fixedness of the indices at a specific point in time and the impossibility of constructing predictor estimates.

In the process of eliminating such problems, the further development of methodological and analytical tools for assessing regional competitiveness dynamics taking into account a complex of social, political and economic factors, comes to the agenda. The feasibility of actual mathematical models based on Markov models for analyzing the dynamics of complex social and
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Economic objects have been substantiated. This approach allows to solve the problem of assessing the regional competitiveness risks. Mathematical models were developed to determine the likelihood of risks of regional competitiveness reduction by individual characteristics. The collection and structuring of primary data on the indicators of the competitiveness of the Russian Federation regions were carried out. A hierarchical causal graph has been built to prevent regional competitiveness risks. The study of the resulting graph is carried out on the basis of its fragments that form the minimum graph sections, allowing to analyze individual groups of risk factors. Reducing the problem dimension is carried out by identifying groups of events, the occurrence of which leads to a critical loss of competitiveness. For such combinations of events, a system of Kolmogorov–Chapman differential equations was formed and solved.

The paper considers a model example of the proposed approach implementation for selected regions of the Russian Federation (Moscow, Krasnodar Territory, Nizhny Novgorod Region) for one of the minimal cut set. A specific feature of the considered methodology is the use of a scenario approach that provides an opportunity to study the behavior of regional competitiveness in different conditions, taking into account the different intensity of the onset of crisis events and taken countermeasures. Analysis of the dynamics of the simulated variables corresponding to various critical event combinations allows to draw conclusions about the variability of risks for individual factors of regional competitiveness. In addition, the data analysis for various sets of model parameters presented in the form of scenarios makes it possible to identify region-specific competitiveness factors that may entail the greatest risks. The practical relevance of the work lies in the ability to identify risk factors and their combinations that require special attention when determining countermeasures. Further research is related to the study of an extended cut set list and testing the proposed model for the regions of the Russian Federation.

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