Economic-mathematical Models for Analyzing the Potential for Self-Development of Territorial Systems

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Abstract. The article is devoted to the construction of tools to support decision-making for the analysis and formation of conditions for self-development of administrative-territorial entities, which contributes to the creation of a competitive environment in them. The Toolkit is based on the use of methods of economic and mathematical modeling in the selection of methods of inter-budgetary regulation in the aspect of activation of functions: stimulating and leveling. The incentive function is aimed at increasing the motivation of the authorities in building up the territorial tax potential and is implemented through the distribution of tax revenues among the budgets vertically according to established standards. The leveling function is performed through financial assistance methods. In order to support decision-making regarding the application of forms of financial policy, the article offers a mathematical model for analyzing territorial units from the point of view of identifying the potential for self-development of territories. The model is based on the application of nonlinear dynamics methods that allow us to get an idea of the qualitative picture of the trend in the dynamics of indicators of development of the territorial system. The presence of an attractor in the dynamics of indicators allows us to judge the potential ability of the territory to self-organization and determines the feasibility of using the stimulating function of inter-budgetary regulation as a prerequisite for the sustainable development of the socio-economic system at the expense of its own revenue sources.

1. Introduction

The Russian economy, which was previously in a difficult situation, is currently characterized by an unstable state caused by the pandemic. Before the epidemic, Western countries applied sanctions against Russia, variations in oil and energy prices, and previously posed a problem of national security of the economy due to its raw material orientation. At the same time, the sanctions have accelerated the process of intensifying the transformation of the Russian economy, which consists in refocusing on improving its competitiveness and moving to a new, innovative model. But the outbreak of the global economic crisis, caused by a viral epidemic, negatively affected the Russian economy and led to its significant decline. Changes in the macroeconomic situation around the world, a decline in demand on world markets and the associated collapse in oil prices threaten a recession of the Russian economy. In this situation, the conduct of budgetary policy requires a radical rethink. The country’s leadership faces an even more acute problem of stimulating economic development and supporting the real sector of the economy in all its territories, which provides protection from the coming series of crises. A necessary condition for solving this problem is to create conditions for self-development of administrative-territorial entities. In this regard, there was a need for regular analysis of regions and municipalities in...
terms of their ability to self-development, which actualized the problem of searching for tools for studying territories in terms of their ability to self-development, as well as creating mechanisms based on it to ensure the necessary conditions for transition to a qualitatively new evolutionary level. A large number of scientists' works are devoted to the problem of studying the processes of self-development of territories. Thus, the results of the study of the potential of socio-economic development of the region, as a fundamental factor in their long-term development, are presented in the article Lavrinenko, Y., Tinyakova, V., Kalashnikov, A., Novikov, A. [1]. The authors put an emphasis on reducing the level of subsidies by increasing investment activity and developing the digital economy. The author’s approach to determining the indicators of regional development for their further development in the framework of assessing the effectiveness of the economy is proposed. The article Kazakov, M., Tinyakova, V. [2] is devoted to the issues of complex diagnostics of peripheral territories of the South of Russia, where a methodological approach to assessing local immunity as part of the complex diagnostics of self-sufficiency and economic development of peripheral territories is developed. The problem of making effective decisions to create conditions for socio-economic development of territories is revealed in the work of Simone C., Barile S., Calabrese M. [3]. The authors propose a new model of ConsulCubo VSA decision support based on research of individual characteristics of territories. Among the numerous works on territorial economic development, we should note the article Morén-Alegrét R. [4], where the author offers qualitative research methods for the sustainable development of peripheral areas of southern Europe, in particular small cities in Alentejo-Litoral (South-West of Portugal) and Alt-Emporda (Catalonia, North-East of Spain). Actual problems of economic development of territorial systems in the conditions of technological transformation are highlighted in the research of Bacior S., Prus B. [5], in which among the factors that drive the economic growth of cities, the authors highlight the construction of motorways. The article summarizes the theoretical and methodological basis for analyzing the impact of the highway on agricultural land and regional sustainable development. The article Yogeswari K., Keerthana R. B. is devoted to the choice of indicators for forming optimal economic corridors between major cities, in particular Chennai and Salem [6]. The qualitative indicators proposed by the authors aim to ensure the industrial growth of territories. Currently, scientists are increasingly attracted to factors that affect the sub-regional determinants of development within emerging economies. In this aspect, we should highlight the work of McDonald C. [7], which improved the "core-periphery" model for analyzing the impact of foreign direct investment on the pace of economic development of peripheral cities. In the context of economic globalization, there is a significant increase in the differentiation of territories by the level of economic development. In this regard, there is an increase in research related to solving problems of territorial inequality. In [8], the authors Aharon-Gutman M., Schaal M., and Lederman I. proposed an immersion model and tools based on it for decision-making aimed at minimizing the growing regional inequality. Generalization of concepts, methods and spatial characteristics of regional stability is given in Peng C. [9,10,11]. The author defines the empirical facts that determine the direction of actions in the planning of territorial development. The article Breinlich H., Ottaviano G. I. P., Temple J. R. W. is devoted to the development of formal approaches to the integrated solution of problems of agglomeration and economic development of the regional economy [12]. The research methods proposed by the authors are based on constructed models that allow conducting experiments. In terms of research on spatial territorial development, the work of Pablo D Fajgelbaum and Cecile Gaubert is known [13]. Based on the processing of data collected during the development of American cities and the assessment of their elasticity, the authors conclude that the redistribution of highly skilled workers to cities with low wages will lead to significant economic growth of the US economy. At the present stage of research in the field of territorial economic development, special attention is paid to mathematical modeling. The research of Streltsova, E. D., Yakovenko, I. V. is devoted to the creation of economic and mathematical tools to support decision-making in managing inter-budgetary relations as a factor of economic growth [14,15]. The authors constructed economic and mathematical models to support decision-making in the process of inter-budgetary regulation, as a significant factor of economic growth. The models are based on the application of the mathematical apparatus of stochastic automata theory and game theory. The priority
directions of the current stage of scientific research is the construction of mathematical models that allow us to study the mechanisms of the evolution of dynamic systems based on mathematical models of the evolution of dynamic systems based on the prediction of time series generated by them. By L. A. Laboissiere, R. A. S. Fernandes, and G. G. Lage [16], proposed a methodology that allows predicting the behavior of stock prices in Brazilian companies. Artificial neural networks are used as a mathematical tool. Linear and nonlinear time series forecasting algorithms using machine learning are proposed by Bouktif S. [17]. A method for predicting time series using a two-level multi-criteria genetic algorithm was developed by Al-Douri Y., Hamodi H. and Lundberg J. [18]. The article Manakov V. and is devoted to solving problems of forecasting financial markets based on the use of artificial intelligence tools. Zhang H. [19]. One of the promising areas of research of evolutionary processes occurring in economic systems is the application of methods of nonlinear dynamics. The concept of chaos, fractals and self-organization in the study of dynamic systems based on nonlinear dynamics methods is developed in the works of Baas A. C. W. [20], Zhiying C., Yong L. and Ping Z. [21].

In this article, the study of the ability of the territorial system to self-organization focuses on the mechanisms of inter-budgetary regulation. As part of these mechanisms, the leading role is played by the processes of shared distribution of tax revenues between budgets vertically. At the same time, an increase in the tax component in the revenues of territorial budgets leads to the interest of their authorities in searching for internal reserves to increase tax potential, which activate the processes of socio-economic development. As a result of the transformation processes taking place in the country against the background of the development of the digital economy, there is a need to build research tools and activate self-organization potentials based on economic and mathematical modeling methods.

2. Problem statement
The economy of the administrative-territorial education is considered as a complex dynamic system consisting of many interrelated and constantly interact with each other and with the external environment economic subsystems of production, consumption and distribution. These subsystems consist of a variety of organizations that belong to the class of producers, consumers, distributors, or a combination of them. Under the influence of internal interactions between these subsystems, the territorial economy evolves over time with ongoing processes of disordering (chaoticization) and ordering (complication) of the structure. The ability of complex systems to make organizational changes that consist in ordering their structure is expressed in a property called self-organization. As a result of self-organization processes, dissipative structures independent of the influence of the external environment arise and the system, evolving, passes into a new quality. These dissipative structures are generated in the process of a complex composition of interactions between organizations—producers, consumers, distributors. But the evolutionary dynamics of the state of the territorial system is determined not only by the factors inherent in its natural internal socio-economic processes. Regulated effects of environmental factors, which include administrative decisions taken at the highest level of the administrative-territorial structure, undoubtedly have a significant impact on the processes of transformation of the territorial system. Under the influence of these influences, in turn, the vector of territorial self-organization and self-development is formed. External influences affecting the evolutionary processes include decisions on inter-budgetary regulation that can adjust the self-organization potential of administrative-territorial units. Such a correction can occur both in the direction of stimulating the interest of local authorities to increase their tax potential, and in the direction of weakening it. The stimulating function of inter-budgetary regulation is performed by granting the right to territories to use part of the collected Federal and regional taxes. It is implemented using regulations that establish the proportions of tax revenue distribution between budgets. The leveling function is implemented by various subsidized methods. This article offers a tool for solving the strategic task of creating conditions for self-development of territories by methods of inter-budgetary regulation: to put emphasis on the implementation of a stimulating or leveling function. If preference is given to the implementation of the incentive function, the authors propose a tool for decision support to determine the norms for the vertical distribution of tax revenues between budgets.
There is no doubt that the use of mechanisms to increase the potential for self-development by strengthening the incentive function of inter-budgetary regulation is appropriate for economically active territories. The problem of achieving financial independence of territories, as one of the determining factors of their self-development, can be successfully solved by sharing taxes only for financially stable or self-developing regions and municipalities that contain "growth points". For underdeveloped territories, the solution of the problem of equalizing the financial capabilities of administrative-territorial entities by activating the stimulating function of inter-budgetary regulation is an ineffective method. In this case, it is advisable to use various methods of financial support in the form of grants to equalize financial opportunities, allowing you to create a springboard for further economic development. But the disadvantage of subsidized methods is the weakening of the motivation of the territorial authorities to increase the tax base. Thus, when creating tools for decision-making on the use of methods to stimulate economic development of the territory, the problem of adequate identification of the state of the territorial economic system, which is under the influence of various factors of the external and internal environment, arose. In this article, the structure of a complex of economic and mathematical models, (see Fig.1), is proposed to solve this problem. The initial data of the complex of economic and mathematical models are the temporary realizations of the values "Income" and "Expenses" of the budget of an administrative-territorial entity, indicated respectively by variables $REV(t)$ и $EXP(t)$. 

![Figure 1. Architecture of the complex of economic and mathematical models of territorial system analysis.](image-url)
One of the most significant indicators of the self-development potential of an administrative-territorial entity is its budget revenues. In consequence, the identification of a territorial system from the point of view of its ability to self-organize is carried out on the basis of time series \( REV(t) \) analysis using nonlinear dynamics methods. As a result of the analysis, the question is solved: what class can the time series under study belong to? In accordance with figure 1, a phase portrait is restored from the time series \( REV(t) \) that reflects the qualitative behavior of the territorial system in terms of its ability to self-development. In this case, an important characteristic of the behavior of a territorial system is the detection of an attractor. The presence of an attractor indicates that the territorial system has the ability to self-organize and tends to some state of internal equilibrium. However, if a dynamic territorial system is chaotic, then its attractor has a fractional fractal dimension and belongs to the class of strange attractors. Thus, the behavior characteristic of the reconstructed attractor is used as a criterion for evaluating the potential for self-development of the territory. In accordance with figure 1, if there is a time series \( REV(t) \) attractor, the system recommends making a decision to activate the incentive function of inter-budget regulation and puts into operation a model for determining the norms for deductions to the territory's budgets from Federal and regional taxes. In the absence of a time series \( REV(t) \) attractor, the system suggests making a decision on providing financial assistance to territories.

3. A model for estimating the dimension of a reconstructed attractor

The behavior of a territorial dynamic system is studied on the basis of a time series \( REV(t) = [R_i(t)]^N_{i=1} \), describing the receipt of financial resources to the budget of a given territorial entity in equal steps \( \tau : t_i = t_0 + (i-1)\tau, i = 1, N \). The time series \( REV(t) = [R_i(t)]^N_{i=1} \) is considered as a nonlinear projection of the phase trajectory generated by a dynamical system on the coordinate of income in a phase space of a certain dimension. It is hypothesized that the system operates in a stationary mode and the phase trajectory passes through the attractor. The theoretical basis for the fact that the characteristics of the phase portrait of a territorial dynamical system can be restored by studying the time series \( REV(t) = [R_i(t)]^N_{i=1} \) is the Takens theorem [20]. In accordance with the Takens method, the scalar time series \( REV(t) = [R_i(t)]^N_{i=1} \) is considered

with some delay in order to determine the state vector (phase space) of the dynamical system. The trajectory matrix constructed as a result of using the delay method for the reconstructed phase space has the form:

\[
REV = \begin{bmatrix}
R(1) & R(2) & \ldots & R(k) \\
R(1+\tau) & R(2+\tau) & \ldots & R(k+\tau) \\
R(1+2\tau) & R(2+2\tau) & \ldots & R(k+2\tau) \\
\vdots & \vdots & \ddots & \vdots \\
R(1+(m-1)\tau) & R(2+(m-1)\tau) & \ldots & R(k+(m-1)\tau)
\end{bmatrix}
\]

The matrix columns are \( m \)-dimensional delay vectors \( (R(t), R(t+\tau), R(t+2\tau), \ldots, R(t+(m-1)\tau)) \) obtained from a time series \( REV(t) = [R_i(t)]^N_{i=1} \) and describe the state of the system at the moment. The geometric image of this state is a point in a-dimensional phase space. Thus, the embedding of a one-dimensional series \( REV(t) = [R_i(t)]^N_{i=1} \), as a projection of a nonlinear trajectory on the income coordinate, is represented by a sequence of points \( S = (S(1), S(2), S(3), \ldots, S(k)) \) with coordinates:

\[
S(1) = (R(1), R(1+\tau), R(1+2\tau), \ldots, R(1+(m-1)\tau)) \\
S(2) = (R(2), R(2+\tau), R(2+2\tau), \ldots, R(2+(m-1)\tau))
\]
\[ S(3) = (R(3), R(3+\tau), R(3+2\tau), \ldots, R(3+(m-1)\tau)) ; \]
\[ S(k) = (R(k), R(k+\tau), R(k+2\tau), \ldots, R(k+(m-1)\tau)) ; \]

By means of pseudo-phase reconstruction of the attractor, the coordinates of the point \( S(t) \) describing the state of the dynamical system in the reconstructed phase space are constructed from the time series \( \{ R(t) \}_{i=1}^n \) observed during the experiment. The time delay \( \tau \) is selected by determining the autocorrelation function \( A(\tau) \) that determines the relationship between the observed value \( \{ R(t) \}_{i=1}^n \) and its image, which is a shifted time series by an amount \( \tau \) [20]:

\[
A(\tau) = \frac{1}{N-\tau} \sum_{i=1}^{N-\tau} (R(t) - \overline{R(t)}) \cdot (R(t+\tau) - \overline{R(t+\tau)}) ;
\]
\[
\frac{N}{\tau} \leq R(t) = \frac{N}{\tau} \leq \frac{N}{\tau} ; \quad \tau = 1, n .
\]

In the model for estimating the dimensionality of the reconstructed attractor in accordance with [20], the delay value \( \tau \) was changed within the segment \([1, n]\) and, ultimately, a value \( \tau \) was chosen at which the autocorrelation function takes a value close to zero. After selecting the time delay \( \tau \), the next step in the model’s operation is to determine the dimension of the attractor embedding, as the number of indicators whose variations significantly affect the behavior of the dynamic system. The definition of the attractor embedding space is based on the correlation dimension method in accordance with the Grassberg-Procaccia algorithm. As the source data, the same time series \( \{ R(t) \}_{i=1}^n \) and expressions are used for the m-dimensional vectors \( (R(t), R(t+\tau), R(t+2\tau), \ldots, R(t+(m-1)\tau)) \) of the phase space constructed from it with a time delay \( \tau \) that leads to a close-to-zero value of the autocorrelation function. In accordance with the Grassberg-Procaccia algorithm, a dimension is fixed \( m \), according to which a set of points \( S = (S(1), S(2), S(3), \ldots, S(k)) \) is m-dimensional phase space whose coordinates are \( (R(t), R(t+\tau), R(t+2\tau), \ldots, R(t+(m-1)\tau)) \in R^m \). For the fixed value \( m \), the correlation dimension of the attractor is found. In this case, the correlation integral [20]

\[
C(\varepsilon) = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \Theta(\varepsilon - \|S_i - S_j\|),
\]

where is \( \Theta(\cdot) \) the Heaviside function, and \( \varepsilon \) — the radius of the ball described around each of the trajectory points are calculated. Researchers determined [20] that for relatively small \( \varepsilon \), the function \( C(\varepsilon) \) should change as \( C(\varepsilon) = \varepsilon^d \), \( \ln(C(\varepsilon)) = d \ln(\varepsilon) \), where \( d \) is the dimension of the attractor, which is defined as the inclination tangent \( \frac{\ln(C(\varepsilon))}{\ln(\varepsilon)} \) from \( \varepsilon \) in a way that indicates the presence of deterministic chaos in the system.

In accordance with figure 1, if there is an attractor in the system in the process of inter-budgetary regulation, it is recommended to activate the incentive function, which consists in setting standards for the share distribution of tax revenues between budgets vertically. In [12, 13], a mathematical model of decision support for determining the proportions of tax revenue distribution was developed, represented by a stochastic automaton operating in random environments. The authors developed the construction of a stochastic automaton and determined the final probabilities of the automaton staying in its States [12, 13]:

\[
P_1^s = \frac{1}{q_1} \sum_{j=1}^{q_1} \frac{1}{q_j} ; \quad P_2^s = \frac{1}{q_2} \sum_{j=1}^{q_2} \frac{1}{q_j} ; \quad \ldots ; \quad P_k^s = \frac{1}{q_k} \sum_{j=1}^{q_k} \frac{1}{q_j} .
\]
where the values $p$ and $q$ represent, respectively, estimates of the probabilities of budget deficits in each of the States of the automaton. The role of States is played by norms for the distribution of tax funds between territorial budgets.

4. Experimental research and practical significance of modeling results

The article presents the results of experiments that evaluated the ability of one of the territorial systems to self-organization. The outcome of the experiment is then used to make decisions about the implementation of the stimulating or equalizing function of inter-budgetary regulation. As the initial data, the experiment used a scalar time series $REV(t) = \{R_i(t)\}_{i=1}^{N}$ describing the receipt of budget revenues to the budget of a certain administrative-territorial entity at regular intervals. Due to the limited volume of the article, the initial data of the time series $\{R_i(t)\}_{i=1}^{N}$ is not shown, but its phase portrait is given (see Fig. 2).

![Figure 2](image2.png)

**Figure 2.** Phase trajectory of the time series $\{R_i(t)\}_{i=1}^{N}$.

The time delay $\tau$ was determined by the autocorrelation function method $A(\tau)$, the final graph of which is shown in figure 3. In this case, the Optimal time delay $\tau = 1$.

![Figure 3](image3.png)

**Figure 3.** Autocorrelation function of a time series $\{R_i(t)\}_{i=1}^{N}$.

The dependence of the slope tangent $\ln(C(\varepsilon))$ from $\ln(\varepsilon)$ is shown in figure 4.

![Figure 4](image4.png)

**Figure 4.** Dependence of the slope tangent $\ln(C(\varepsilon))$ on $\ln(\varepsilon)$.
As a result of the experiments, it was determined that the correlation dimension $d = 0.291$ and the dimension of the phase space of the attractor of the reconstructed dynamical system is $m = 1$. Consequently, experiments demonstrate the presence of a chaotic attractor of a dynamic system, which indicates its ability to self-organize. In a state of chaos territorial system is sensitive to external effects and the management of its development can be carried out with the help of weak influences.

5. Practical relevance of the toolkit
The practical significance of the research results lies in the potential possibility of using the constructed economic and mathematical models to solve problems of analyzing territories from the point of view of the ability to self-organize, as well as to support decision-making regarding methods of inter-budgetary regulation.

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