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Mathematical Modeling of Fiscal Innovations Based on the Interdisciplinary Synthesis of Fuzzy Logic and Automata Theory

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Abstract. Currently, the subject of acute discussion in the scientific community is the self-development of administrative-territorial entities and increasing their financial independence. In this regard, the problems of budget decentralization as an engine of economic development, as well as related issues of applying mathematical tools for modeling decision support in this area are updated. Budget decentralization is considered in this article as an institutional financial innovation, the dominant factor of which is the ratio between "soft" and "hard" budget constraints. To implement the strategy of "hard" budget constraints implemented in the process of performing the stimulating function of inter-budget regulation, the article suggests the use of economic and mathematical tools as a model innovation. The article offers economic and mathematical models representing fuzzy automata, developed through the application of the interdisciplinary synthesis of the theory of stochastic automata and fuzzy logic. The convergence of the mathematical devices of these theories allowed us to form an intellectual approach for the construction of abstract mathematical objects that have the properties of learning rational behavior in the process of decision-making and adaptation to environmental changes. To confirm these properties, we present a proof of the theorems on the asymptotic optimality of the constructed models. The functioning of economic and mathematical models is detailed through their integration into technological financial innovation in their interaction with the database.
Key Words and Phrases: financial innovations, budget decentralization, mathematical models, fuzzy automaton.
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1. Introduction

Currently, financial technologies are evolving under the influence of digital transformation. Digital technologies and platforms create the prerequisites for

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the development of financial innovations that radically transform traditional financial systems and technologies. Innovative financial technologies are formed and transformed under the influence of the synthesis of information technologies and mathematical modeling. Innovations integrated into FinTech play a key role in maintaining and developing the economic growth of the national economy of any country. In this regard, in modern scientific research on the functioning of economic systems, considerable attention is paid to the establishment of causal relationships between economic growth and financial innovations used in the management process, which confirms the relevance of the problem. As you know, the concept of "innovation" was introduced into scientific circulation by the Austrian - American economist Joseph Alois Schumpeter in the work "Theory of Economic Development", published in 1939 [1]. This theory has not lost its scientific and practical value at the present time. According to the theory of J. A. Schumpeter, any national economy should be studied as a system whose dynamics are directly correlated with technological progress. As the main factor of economic growth, J. A. Schumpeter considered innovations that, as a result of the establishment of equilibrium and its dynamics, support the market economy in continuous motion with alternating phases of boom and bust [1]. Based on the implementation of the Schumpeter innovation model, research is currently being conducted in a wide range of areas. In this aspect, we can cite the work of M. Cardona [2], who conducted theoretical and empirical studies of the impact of effective innovations in the field of information and communication technologies on labor productivity.

This article suggests the use of an interdisciplinary synthesis of the theory of stochastic automata and fuzzy logic to construct a mathematical model that has the properties of an intelligent agent in the implementation of the stimulating function of inter-budget regulation in the aspect of strict budget constraints. The model supports decision-making when setting standards for the distribution of tax revenues between budgets of different levels of the hierarchy. The scientific contribution of the conducted research is that it sheds light on the development and use of model fiscal innovations in the implementation of "hard" budget constraints and their integration into the management of inter-budgetary relations. The structure of the article is organized as follows. After the introduction, Section 2 analyzes the scientific literature on the implementation of "soft" and "hard" budget constraints as institutional financial innovations. Section 3 is devoted to the obtained simulation results. The fourth section reflects the results of experiments conducted on the constructed models and a discussion of their results. The fifth section presents the main conclusions of the study.

2. Literature review

Modernization of innovative sectors of the economy is a priority direction of the national policy of any country, and the provision and maintenance of financial innovations is one of the strategic directions of the state. The articles devoted to the study of financial innovations are W. Frame [3], Laeven L., Levine R., Michalopoulos S. [4], Bara A., Mudzingiri C. [5], Adu-Asare Idun, A. and Q. Q. Aboagye, A. [6], Bara A., Mugano G., Le Roux P. [7], Qamruzzaman M., Jianguo W.[8], Bernier M., Plouffe M. [9], Domeher D., Frimpong J. M., Appiah T. [10], Senchagov V. [11]. Financial innovations are considered in these works as drivers of financial systems in achieving their main goal, focused on improving the efficiency of the economy. The problems of the innovation economy and the ways to solve them are considered in the articles Mau V. [12], Shilov A.[13], Bukharov D. N., Arakelyan S. M. [14].

But the processes of coevolution of financial innovations and the economic system can have both positive and negative effects on economic growth [15]. Nevertheless, the transition to the innovation paradigm of the economy, aimed at accelerating economic growth, initiates the formation of an adequate innovation system of public finance. In this article, financial innovations are understood as new or improved financial instruments, institutions and technologies aimed at improving the efficiency of the allocation of financial resources with minimal risks, as well as at improving the stability of the economic system. Financial innovations introduce new methods and techniques into traditional financial activities. Due to the fact that the financial services industry is currently experiencing the emergence of new technological innovations, the research of modern scientists pays great attention to various technological startups that provide improved financial services. The process of providing financial services is being modernized in line with digitalization. At the same time, new business models are introduced and new business functions appear (Gabor D., Brooks S. [16]), shifting the focus of attention not only to solving traditional problems with new tools, but also to solving fundamentally new problems on a new technological basis (Gomber P., Kauffman R. J., Parker Ch., Weber B. W. [17], Gomber P., Kauffman R. J., Parker Ch., Weber B. W. [18]). New tasks are due to the development of information technologies, as innovation in the financial industry, the technical and financial problems of which are analyzed by Lee I., Shin Y.J. [19], Ozili P.K. [20]. Financial innovation perspective in the study of the competitiveness and competitive advantages of economic systems is presented in the work of Khotinskaya G.I., Shokhin E.I. [21]. The reflection of technological, managerial and social problems of development and the introduction of digital innovations in the process of managing finances of the territories of developing countries was the studies of Deden Witarsyah, Teddy Sjafrizal, MD Fudzee, Mohamad Aizi Salamat [22], Muaadh Mukred, Zawiyah M Yusof [23],[24]. Due to the fact that the digital economy is primarily a scientific field, the subject of a thorough study of its prospects is the use of mathematical models as financial management innovations. This is confirmed by the works of scientists who use mathematical tools to describe economic systems under uncertainty (Chappell, D. R. [25], Ardia, D., Bluteau, K., Boudt, K., and Catania, L. [26], Carnero M. A., Peña D., Ruiz E. [27], Alizadeh A. H., Nomikos N. K., Pouliasis P. K. A. [28]). The development of various aspects of the use of mathematical methods in conducting empirical studies of financial systems, in particular, the tools of econometrics, is reflected in the articles Altman E. I. [29], Zwolak, J. [30]. The work of Dospinescu O., Anastasiei B., and Dospinescu N. is devoted to the development of multiple regression equations for determining the expected benefits for bank card customers of the "Millennials" and "Generation Z" categories [31]. Hierarchical linear regression analysis of financial performance indicators of international strategic groups of small and medium-sized enterprises was carried out in the studies of Cabral A. M. R., Carvalho F. M. P. O., Ferreira J. A. V. [32]. In the context of mathematical modeling, the work of Dospinescu N., Dospinescu O., in which a regression model of profitability in financial communications of companies of the Romanian Financial Exchange is constructed, deserves attention [33]. The constructed model allowed us to determine the relationship between the net profit margin and other composite financial indicators of companies. Currently, the methods of artificial intelligence occupy a central place in scientific research. In this aspect, the works of Bouktif S. [34], Al-Douri Y., Hamada H. and Lundberg J. [35] are useful. The time series forecasting algorithms proposed by them can be considered as innovations used in the process of managing financial activities of various economic entities to anticipate the results of their development. The work of Alkinoos Psarras, Theodoros Anagnostopoulos, Nikos Tsotsolas, Ioannis Salmon, and Lazaros Vryzidis is devoted to the study of factors of economic development around the world using artificial intelligence methods [36]. The authors have constructed intelligent regression models of predictive inference for performing data analysis in the management of the European Financing Program. COVID-19, which caused a systemic crisis in the global economy, required a fiscal response in the field of financial technologies. There was a need for the formation and implementation of a policy of fiscal decentralization, due to not only the goals of improving the efficiency of the public sector of the economy, improving the quality of local public services, but also the creation of conditions conducive to the emergence of incentives for subnational governments to support the economy in their territories in order to accelerate economic growth. There is no doubt that the COVID-19 pandemic dealt a huge blow to the global economy, which implied the setting of the main goal of each country's economic policy-ensuring economic growth, as evidenced by the increasing number of scientific publications on this topic [37],[38],[39],[40]. According to modern scientific publications, the institutional catalyst for accelerating economic growth is fiscal decentralization. In this article, the phenomenon of fiscal decentralization is considered as an institutional financial innovation that arose as a result of the evolution of the interaction of experienced knowledge in the field of inter-budgetary relations and the theoretical provisions of fiscal federalism. Fiscal decentralization is considered by representatives of the world economic community as a mechanism for creating conditions that induce the emergence of positive incentives for sub-federal and subnational authorities to develop the economy in their territories. The theoretical basis for the processes of decentralization was created by W. Oates [41],[42],[43] and is presented in the form of a theorem. Currently, the issues of fiscal decentralization are an area of increased interest of the scientific community, as evidenced by the works published in the scientific literature [44],[45],[46],[47],[48]. The dominant factor of an effective decentralized budget system is the establishment of relations between the concepts of "soft" and "hard" budget constraints within the framework of the theory of budget federalism. Making decisions that achieve a balance between these two concepts requires giving the result a numerical value, i.e. quantification, which makes it necessary to develop mathematical models as model financial innovations and integrate them into financial technologies. Due to the fact that the digital age has come as a result of the development of modern civilization, there is an active discussion in the scientific literature on the introduction of elements of intellectualization in management processes. At the same time, in the publications of researchers, the topic "intelligent modeling" is declared to exist [47],[48],[49],[50],[51],[52]. In this direction, the problems associated with the construction of the entities "intelligent agent" as a mathematical abstraction that can interact with the external environment, adequately respond to its changes and perform rational actions to achieve the goals set.

Fiscal decentralization, as the most important institutional mechanism for improving the efficiency of managing inter-budgetary relations and a source of innovation, is the subject of research by many scientists. So, in the works of Holm-Hadulla F. [53], Alexeev M., Kurlyandskaya G. [54], Qi Y., Peng W., Xiong NN [55], Gross T. [56], Arin KP, Braunfels E. , Doppelhofer G. [57] the impact of fiscal policy on the economic growth of the territory is investigated. Jia J., Ding S., Liu Y. [58], Muinelo-Gallo, L .; Roca-Sagalés, O. [59], Woller GM, Phillips K. [60], Dweck E., Vianna MT, Da Cruz Barbosa A. [61], Tejado I., Pérez E., Valério D. [62] consider the problems arising in the implementation of instruments of fiscal decentralization. Moreover, in the works related to the study of the impact of fiscal decentralization on economic growth, ambiguous conclusions were found. In some studies carried out by the authors Baretti C., Huber B., Lichtblau K. [63], Rizzo L. [64], Buettner T., Krause M. [65], Besley TJ, Rosen HS [66], Ferraresi M. et al.[67], it is argued that various transfers allocated to subnational budgets from the federal budget lead to discouraging regional and local authorities to pursue effective economic policies and reduce fiscal efforts.

There are also opposing statements regarding transfer flows (soft budget constraints), according to which subsidies allocated to subnational budgets do not always lead to dependent attitudes of regional and local authorities, and the use of the concept of "soft" budget constraints continues to be relevant at present [66]. It is indisputable that fiscal decentralization is not an institutional panacea that leads to positive economic effects. Therefore, it is necessary to treat the formation of financial policy selectively, taking into account the peculiarities and patterns of the economies of national and subnational administrative-territorial units. But, nevertheless, the analysis of scientific publications has shown that many authors, such as Barbashova [68], Aboelazm, K. S. and Afandy, A. [69], Guga, E. [70], Rahim, F. U. and Shirazi, N. S. [71], Purbadharmaja, I. B. P., Maryunani, Ananda, C. F. and Santoso , D. B [72], Yang, S., Li, Z. and Li, J. [73] see a source of development of subnational territories that increases the tax burden, the autonomy of the territories, namely in the implementation of the concept of "hard" budget restrictions within the framework of fiscal decentralization.

3. Materials and Methods

The concepts of "soft" and "hard" budget constraints were first used in scientific publications by the Hungarian scientist Kornai János [74], [75] in order to develop scientific provisions and mechanisms for stimulating economic growth. Finding the relationship between "hard" and "soft" budget constraints is a task, the solution of which is put at the forefront of the concept of "federalism that preserves the market" and is implemented by tools for regulating inter-budget relations. In the composition of these relations, the leveling and stimulating functions are distinguished, as the passive and active components. The passive component is implemented through such a tool as inter-budget transfers in order to equalize the level of territorial budget security. Describing the federal states, it should be noted that the peculiarity of many of them is the commonality of federal and territorial tax bases, which sets the task of distributing tax revenues between budgets along the vertical line of power. The result of solving this problem is to establish the values of standards for the distribution of tax revenues from joint tax bases between budgets of different levels of the budget system hierarchy. Granting subnational authorities the right to use part of the taxes collected in the

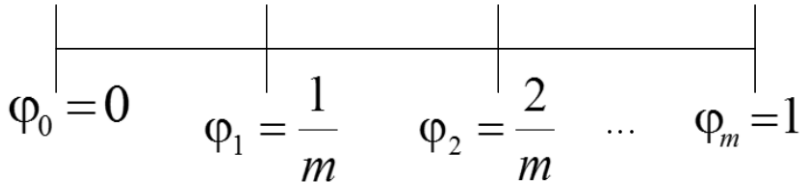

Figure 1: States of the fuzzy automaton AVT

territories under their jurisdiction increases the incentives to strengthen economic activity and thereby increase tax capacity. The analysis of the literature sources showed that currently the distribution of tax revenues between budgets is carried out by subnational governments on the basis of heuristic algorithms. The lack of methodological, theoretical and instrumental basis in this area leads to intuitive management of inter-budgetary relations, which negatively affects the processes of economic development of individual territories and the entire country as a whole. In order to make informed decisions in this area, in the early work of the author of this article, a mathematical model of a fuzzy automaton is proposed, which has the properties of adaptation to environmental changes, and learning appropriate behavior in the process of making decisions on the distribution of tax revenues between budgets vertically [76]. The fuzzy automaton model is based on the application of an interdisciplinary synthesis of mathematical devices of the theories of stochastic automata and fuzzy algebra and is an innovative tool for decision support in the field of inter-budgetary regulation, which has the property of making rational decisions. Let us briefly characterize these properties. One of these properties is the ability to learn appropriate behavior when determining the values of the standards for the distribution of tax revenues between budgets vertically. The property of learnability to expedient behavior is established in [76] by proving theorems. In this article, the property of the asymptotic optimality of a fuzzy automaton is argued, the meaning of which is revealed further. Due to the fact that this study is a continuation of the author's previous research, for a better understanding of the material presented, it is appropriate to provide a description of the model given in [76]. The values $\varphi_i \in \varphi$ of the standards, as a share of deductions of tax revenues to the budget of the sub-region, are denoted by the vector $\varphi = \{\varphi_1, \varphi_2, ..., \varphi_m\}$. Variables take values from the interval [0,1] and are considered as states of the automaton AVT, where m is the number of states, $i = \overline{1,m}$ (Figure 1). Figure 1 shows that the segment [0,1] is divided into m segments and the coordinates of the segments are taken as the states $\varphi_i \in \varphi$ of the automaton AVT. In the course of its functioning, the automaton AVT is immersed in a random environment, with which it actively interacts and responds to the reactions of the environment. The state $\varphi_i \in \varphi$, $i = \overline{1,m}$ of the machine affects the amount of the remaining funds in the budget of the sub-region, causing it to run a deficit or surplus. Budget deficits and surpluses (positive $e_i > 0$ or negative $e_i < 0$ current cash balance at a given time t) are considered as the output signals $Ex = \{e_1, e_2, ..., e_m\}$ of the automaton AVT. The probabilities of the occurrence of a surplus and a deficit in the states $\varphi_i, i = \overline{1, m}$ are denoted by variables p_i, q_i, respectively, and are considered as the set of input signals of the automaton $Inp = \{p, q\}, p = \{p_1, p_2, ..., p_m\}, q = \{q_1, q_2, ..., q_m\}$. The probability of a budget surplus p_i when setting standards $\varphi_i, i = \overline{1, m}$ over a period of time T, is determined by the ratio of the number $\lambda_i(e_i > 0)$ of points in time t_i when positive balances occur $e > 0$ to the period $T : p_i = \frac{\lambda_i(e>0)}{T}$. The probability of a budget deficit q_i when setting the standard $\varphi_i, i = \overline{1, m}$ is determined similarly: $q_i = \frac{\lambda_i(e<0)}{T}$, where $\lambda_i(e < 0)$ is the number of time points t_i during which the balance of funds in the budget takes a negative value $e < 0$. It is obvious that $p_i = 1 - q_i$. The random environment in which the machine AVT is immersed is created by the random nature of changes in budget revenues and expenditures, which are considered as perturbations affecting the machine. Then the automaton AVT is formally described by a tuple $AVT = (Inp, Ex, \varphi, F, \Phi)$, where $F : Inp \times \varphi \to \varphi$ is the transition function of the automaton from state to state, and $\Phi : Inp \times \varphi \to Ex$ is the exit function. The behavior of the automaton model AVT is compiled in accordance with the theory of stochastic automata [77], thanks to which the automaton is trained to make rational decisions. The machine operates according to the following rules. The variables p_i, q_i are interpreted as probabilities of "non-penalty" and "penalty" in the states [76],[77]. The signal "penalty" or "loss" is received at the input of the machine AVT in the event that its state φ_i causes the formation of the current budget deficit, i.e. the amount of cash balances in the budget $e_i < 0$. The signal "non-penalty" or " win " is applied to the input of the machine AVT, if as a result of the environmental impact φ_i on the output of the machine AVT, a value has been formed $e_i > 0$ (i.e., the current budget surplus). At the same time, if the machine AVT, while in the state φ_i, won, (this is evidenced by the appearance of a signal at its input p_i), then it does not change its state. In the case of a "loss" (the "loss" indicator is the appearance of a signal at its input q_i), it selects any other state for the transition. In accordance with this behavior strategy, the transition function of the stochastic automaton is constructed. According to the theory of stochastic automata [77], the transition table of the automaton, which identifies the transition function $F : Inp \times \varphi \to \varphi$, indicates the probabilities of transition from state to state. In [75], an interdisciplinary approach is proposed for constructing the transition function of a stochastic automaton. In accordance with this approach, the probability of the transition of an automaton from state to state is not determined, as proposed in [76], but the measure of the expediency of choosing a particular state φ_i by an automaton is estimated based on the use of the synthesis of mathematical apparatus of the theory of stochastic automata and fuzzy algebra. Due to the fact that the states of automaton φ_i identify the share of deductions to the budget of the sub-region from the tax related to the tax base of the federation or sub-federation, the choice of this state should be treated depending on the level of development of the sub-region. Earlier, a hypothesis was expressed, according to which the formation of financial policy should be treated selectively, taking into account the peculiarities and patterns of economic development of national and subnational administrative-territorial units. According to the proposed hypothesis, the subregions are decomposed into two classes. The first class, denoted as "Undevel", includes sub-regions with a low level of economic development and, consequently, with a low level of self-development ability. The second class, denoted as "Devel", includes sub-regions with a high level of economic development and, consequently, with a high level of self-development ability. The criteria for classifying administrative-territorial units according to the level of socio-economic development have been studied by many researchers. Among them are A. Luczak, M. A. Just [37] and many others. But the development of methods for the decomposition of territories into classes according to the level of socio-economic development is the task of individual studies that go beyond the scope of this article. This article is devoted to the development of research on the development of mathematical models of fiscal innovations that can make rational decisions on inter-budgetary regulation, depending on the level of socio-economic development of administrative-territorial units. In continuation of the implementation of this plan, the following theses are formulated.

Thesis 1. For sub-regions of the "Undevel" class that have a low level of self-development, the use of such an instrument of inter-budgetary regulation as tax deductions is less appropriate for equalizing the level of budget security than transfer payments.

Thesis 2. For sub-regions of the "Devel" class, i.e. those with a high level of self-development, it is advisable to use the instrument of establishing tax deduction standards as an instrument of inter-budgetary regulation, which increases the incentives of sub-regional authorities to increase their tax potential.

Following the formulated theses, for each class of territories "Undevel" and "Devel", a qualitatively defined measure of the expediency of establishing specific tax deductions is established, formally described by a linguistic variable $MEASURE \leq T(MEASURE), U, M >$ with a term set $T(MEASURE) = \{High, Low\}$ [76], in which the components $High$ and Low are the names of fuzzy sets that identify a qualitatively defined measure of the expediency of assigning a standard of a certain value for a given territory. Fuzzy sets $High$ and Low are represented by a set of ordered pairs of the form $High = \{(\varphi, \mu^H)\}$,

$Low = \{(\varphi, \mu^L)\}$ with a universe φ and membership functions $\mu^H : \{\varphi_i\}_{i=1}^m \to [0, 1]$, $\mu^L : \{\varphi_i\}_{i=1}^m \to [0, 1]$ of the triangular form:

$$\mu^H = \begin{cases} 0, \varphi_i < 0; \\ \varphi_i - 0, 0 < \varphi_i < 1; \\ 0, \varphi_i > 1; \end{cases} \qquad \mu^L = \begin{cases} 0, \varphi_i < 0; \\ 1 - \varphi_i, 0 < \varphi_i < 1; \\ 0, \varphi_i > 1. \end{cases} \tag{1}$$

The set of values of the membership functions μ^H and μ^L belong to the segment [0,1], and the domain of definition is the set $\varphi = \{\varphi_1, ..., \varphi_m\}$. Semantics μ^H and μ^L fuzzy sets $High$ and Low are expressed by linear membership functions with the difference that μ^H is increasing, and μ^L decreasing. The choice of the type of functions μ^H and μ^L is determined by the content of the formulated theses, according to which for territories with a high level of self-organization potential "Devel", the measure of expediency of establishing deductions φ_i close to one should be higher than for territories of the "Undevel" class. Guided by the formulated theses, the automaton AVT is represented by a two-component construction of fuzzy automata $AVT = (A^L, A^H)$, where A^L and A^H describe the behavior of the subject making a decision on the size of the standards of deductions to the budget of the territory, respectively, with a low and high level of self-development [75]. The transition functions of the automata when they "win" are described by the matrices

$$\|x_{ij}^H\| = \|x_{ij}^L\| = \begin{cases} 1, \text{if } i = j; \\ 0, \text{if } i \neq j. \end{cases} \tag{2}$$

In the case of a "loss", the transition functions of fuzzy automata A^L and A^H are defined on the basis of the triangular membership functions, and μ^H and μ^L have the following form:

$$\|y_{ij}^H\| = \begin{cases} 0, \text{if } i = j, \\ \frac{j}{m}, \text{if } i \neq j, \end{cases} \qquad \|y_{ij}^L\| \geq \begin{cases} 0, \text{if } i = j, \\ \frac{m-j}{m}, \text{if } i \neq j. \end{cases} \tag{3}$$

In [76], the transition functions of fuzzy automata A^L and A^H, represented by the matrices $\|p_{ij}^H\|$ and $\|p_{ij}^L\|$, are defined independently of their input signals:

$$\|p_{ij}^H\| = \begin{cases} p_i, \text{if } i = j, \\ \frac{j}{m} q_i, \text{if } i \neq j, \end{cases} \qquad \|p_{ij}^L\| = \begin{cases} p_i, \text{if } i = j, \\ \frac{m-j}{m} q_i, \text{if } i \neq j. \end{cases} \tag{4}$$

The obtained expressions for transition matrices $\|p_{ij}^H\|$ and $\|p_{ij}^L\|$ automata A^H and A^L allowed us to create equations for determining the final measures of expediency Φ^H and Φ^L the choice of fuzzy automata A^H and A^L their states:

$$\begin{cases} \Phi_1^H(1-p_1)+\Phi_1^H\frac{1}{m}q_1=\sum_{i=1}^m \Phi_i^H\frac{i}{m}q_i \\ \Phi_2^H(1-p_2)+\Phi_2^H\frac{2}{m}q_2=\sum_{i=1}^m \Phi_i^H\frac{i}{m}q_i \\ \Phi_3^H(1-p_3)+\Phi_3^H\frac{3}{m}q_3=\sum_{i=1}^m \Phi_i^H\frac{i}{m}q_i \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \Phi_m^H(1-p_m)+\Phi_m^H\frac{m}{m}q_m=\sum_{i=1}^m \Phi_i^H\frac{i}{m}q_i \end{cases} \quad (5)$$

$$\begin{cases} \Phi_1^L(1-p_1)+\Phi_1^L\frac{m-1}{m}q_1=\sum_{i=1}^m \Phi_i^L\frac{m-i}{m}q_i \\ \Phi_2^L(1-p_2)+\Phi_2^L\frac{m-2}{m}q_2=\sum_{i=1}^m \Phi_i^L\frac{m-i}{m}q_i \\ \Phi_3^L(1-p_3)+\Phi_3^L\frac{m-3}{m}q_3=\sum_{i=1}^m \Phi_i^L\frac{m-i}{m}q_i \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \Phi_m^L(1-p_m)+\Phi_m^L\frac{m-m}{m}q_m=\sum_{i=1}^m \Phi_i^L\frac{m-i}{m}q_i \end{cases} \quad (6)$$

As a result of solving the compiled equations in [76], expressions for the final measures of expediency $\Phi^L=\{\Phi_1^L,\Phi_2^L,...,\Phi_m^L\}$ and $\Phi^H=\{\Phi_1^H,\Phi_2^H,...,\Phi_m^H\}$ the choice of fuzzy automata A^H and A^L their states are obtained:

$$\Phi_1^L=\frac{1}{\sum_{i=1}^m \frac{q_1(2m-1)}{q_i(2m-i)}},\quad \Phi_2^L=\frac{1}{\sum_{i=1}^m \frac{q_2(2m-2)}{q_i(2m-i)}},\quad ...,\quad \Phi_m^L=\frac{1}{\sum_{i=1}^m \frac{q_k(2m-m)}{q_i(2m-i)}}, \quad (7)$$

$$\Phi_1^H=\frac{1}{\sum_{i=1}^m \frac{q_1(m+1)}{q_i(m+i)}},\quad \Phi_2^H=\frac{1}{\sum_{i=1}^m \frac{q_2(m+2)}{q_i(m+i)}},\quad ...,\quad \Phi_m^H=\frac{1}{\sum_{i=1}^m \frac{q_k(m+m)}{q_i(m+i)}}. \quad (8)$$

In [76], the expediency of the behavior of stochastic automata is argued by proving theorems that establish that the mathematical expectations of the winnings of automata A^H and A^L with the final measures of expediency $\Phi^L=\{\Phi_1^L,\Phi_2^L,...,\Phi_m^L\}$ and $\Phi^H=\{\Phi_1^H,\Phi_2^H,...,\Phi_m^H\}$, determined by the derived expressions, exceed the mathematical expectations of the winnings of automata that choose their actions with equally likely for all states. This means that the machines in the decision-making process will win more often and lose less often.

This paper provides a proof of the theorems on the asymptotic optimality of automata A^H and A^L the proposed construction. According to the theory of automata [77], an automaton belonging to an asymptotically optimal sequence means its good adaptability to external conditions. At the same time, an increase in the memory capacity $m\to\infty$ of the slot machine causes its behavior, which is close to the person who has information in advance about the quantitative measure of obtaining winnings in each state $\varphi_i, i = \overline{1, m}$. In this case, the slot machine chooses only the state, the measure of expediency of which is maximum.

Denote by $A^H(x)$ and $A^L(x)$ automata with a memory capacity equal to x.

Theorem 1. *The sequence of automata $A^H(1), A^H(2), ..., A^H(m)$ has the property of asymptotic optimality.*

Proof. In accordance with the theory of stochastic automata [77], a sequence of automata $A^H(1), A^H(2), ..., A^H(m)$ has asymptotic optimality when the condition is met $\lim\limits_{m\to\infty} M(A^H) = p^H_{max}$, where $M(A^H) = \sum_{i=1}^m \Phi_i^H p_i$ is the mathematical expectation of the win, p^H_{max} is the maximum value of the win of the automaton A^H. When substituting the mathematical expectation of the gain of the obtained expressions for the expediency measure Φ_i^H into the formula, we get:

$$M(A^H) = \frac{p_1}{\sum_{i=1}^m \frac{q_1(m+1)}{q_i(m+i)}} + \frac{p_2}{\sum_{i=1}^m \frac{q_2(m+2)}{q_i(m+i)}} + \frac{p_3}{\sum_{i=1}^m \frac{q_3(m+3)}{q_i(m+i)}} + ... + \frac{p_m}{\sum_{i=1}^m \frac{q_m(m+m)}{q_i(m+i)}} =$$
$$= \frac{1-q_1}{\sum_{i=1}^m \frac{q_1(m+1)}{q_i(m+i)}} + \frac{1-q_2}{\sum_{i=1}^m \frac{q_2(m+2)}{q_i(m+i)}} + \frac{1-q_3}{\sum_{i=1}^m \frac{q_3(m+3)}{q_i(m+i)}} + ... + \frac{1-q_m}{\sum_{i=1}^m \frac{q_m(m+m)}{q_i(m+i)}}. \quad (9)$$

After converting the expression for $M(A^H)$, we get:

$$M(A^H) = \frac{1}{\sum_{i=1}^m \frac{1}{q_i(m+i)}} \left[\frac{1-q_1}{q_1(m+1)} + \frac{1-q_2}{q_2(m+2)} + ... + \frac{1-q_m}{q_m(m+m)}\right] =$$
$$= \frac{1}{\sum_{i=1}^m \frac{1}{q_i(m+i)}} \left(\sum_{i=1}^m \frac{1}{q_i(m+i)} - \sum_{i=1}^m \frac{q_i}{q_i(m+1)}\right) = 1 - \frac{\sum_{i=1}^m \frac{1}{(m+1)}}{\sum_{i=1}^m \frac{1}{q_i(m+i)}}. \quad (10)$$

Take the limit

$$\lim_{m\to\infty}\left(1 - \frac{\sum_{i=1}^m \frac{1}{m+1}}{\sum_{i=1}^m \frac{1}{q_i(m+i)}}\right) = 1 - \lim_{m\to\infty} \frac{\sum_{i=1}^m \frac{1}{m+1}}{\sum_{i=1}^m \frac{1}{q_i(m+i)}}. \quad (11)$$

In the expression $\frac{\sum_{i=1}^m \frac{1}{m+1}}{\sum_{i=1}^m \frac{1}{q_i(m+i)}}$ replace q_i with q_{min} and take the limit $\lim\limits_{m\to\infty} \frac{\sum_{i=1}^m \frac{1}{m+1}}{\sum_{i=1}^m \frac{1}{q_i(m+i)}} = q_{min} = 1 - p_{max}$. As a result, we have $M(A^H) = p_{max}$. Which was exactly what was required to prove. ◄

We prove a similar assumption about the sequence of automata $A^L(1), ..., A^L(m)$ that support decisions on the norms of tax deductions in sub-regions with a low level of self-organization.

Theorem 2. *The sequence of automata $A^L(1), A^L(2), ..., A^L(m)$ has the property of asymptotic optimality.*

Proof. The proof will be carried out by analogy with the previous theorem, i.e. we need to prove that the limit of the mathematical expectation of the loss of the automat is equal to p_{max} : $\lim\limits_{m\to\infty} M(A^L) = p^L_{max}$, where $M(A^L) = \sum_{i=1}^m \Phi_i^L p_i$, p^L_{max} is the maximum win value of the automat A^L. Substituting in the formula for the mathematical expectation winning of the automat A^L the expressions for the final measures of the expediency of the automat Φ_i^L in its states $i = \overline{1,m}$, we get:

$$M(A^L) = \frac{p_1}{\sum_{i=1}^m \frac{q_1(2m-1)}{q_i(2m-i)}} + \frac{p_2}{\sum_{i=1}^m \frac{q_2(2m-2)}{q_i(2m-i)}} + ... + \frac{p_m}{\sum_{i=1}^m \frac{q_m(2m-m)}{q_i(2m-i)}} =$$
$$= \frac{1-q_1}{\sum_{i=1}^m \frac{q_1(2m-1)}{q_i(2m-i)}} + \frac{1-q_2}{\sum_{i=1}^m \frac{q_2(2m-2)}{q_i(2m-i)}} + ... + \frac{1-q_m}{\sum_{i=1}^m \frac{q_m(2m-m)}{q_i(2m-i)}}. \quad (12)$$

After conversion, the expression for $M(A)$ becomes:

$$M(A^L) = \frac{1}{\sum_{i=1}^m \frac{1}{q_i(2m-i)}} \left(\frac{1}{q_1(2m-1)} + \frac{1}{q_2(2m-2)} + ... + \frac{1}{q_m(2m-m)} \right) -$$
$$- \frac{1}{\sum_{i=1}^m \frac{1}{q_i(2m-i)}} \left(\frac{q_1}{q_1(2m-1)} + \frac{q_2}{q_2(2m-2)} + ... + \frac{q_m}{q_m(2m-m)} \right). \quad (13)$$

After a more compact entry, we have:

$$M(A^L) = \frac{1}{\sum_{i=1}^m \frac{1}{q_i(2m-i)}} \sum_{i=1}^m \frac{1}{q_i(2m-i)} - \frac{1}{\frac{1}{\sum_{i=1}^m \frac{1}{q_i(2m-i)}}} \sum_{i=1}^m \frac{1}{(2m-i)} =$$
$$= 1 - \frac{1}{\frac{1}{\sum_{i=1}^m \frac{1}{q_i(2m-i)}}} \sum_{i=1}^m \frac{1}{(2m-i)}. \quad (14)$$

In the last expression, replace q_i with q_{min} and take the limit

$$\lim_{i\to\infty} \left(1 - \frac{1}{\sum_{i=1}^m \frac{1}{q_{min}(2m-i)}} \sum_{i=1}^m \frac{1}{2m-i} \right) = 1 - q_{min}. \quad (15)$$

Given that $p_{max} = 1 - q_{min}$, it is possible to write down $\lim\limits_{m\to\infty} M(A) = p_{max}$, what was required to prove. ◄

The economic meaning of the asymptotic optimality of the constructed automata $AVT = (A^L, A^H)$ is that with an unlimited increase in their memory capacity, i.e. the number of its states, the automaton will choose exactly the state at which the probability of winning is maximum. Recall that the winning of the automat means the probability of a budget surplus, and the states of the automat are the amount of the share of deductions to the budget of the sub-region from the federal or regional tax.

4. Experimental results of research

Analytical expressions $\Phi^H = \{\Phi_1^H, \Phi_2^H, ..., \Phi_m^H\}$ and $\Phi^L = \{\Phi_1^L, \Phi_2^L, ..., \Phi_m^L\}$ for determining the final measures of the expediency of choosing their states by automata include such characteristics as estimates of the probabilities of surplus p_i and deficit q_i, $i = \overline{1, m}$ budget, which are interpreted, respectively, as "winning" and "losing" of automata. In the process of determining these values, the constructed automata $AVT = (A^L, A^H)$ interact with a simulation model that reproduces the dynamics of changes in the reserve of funds in the budget under the influence of the random nature of changes in income and expenses, as well as depending on the variations in the values of the states of the automata $\phi_i, i = \overline{1, m}$. A block diagram of the interaction of a fuzzy automaton with a simulation model is shown in Figure 2.

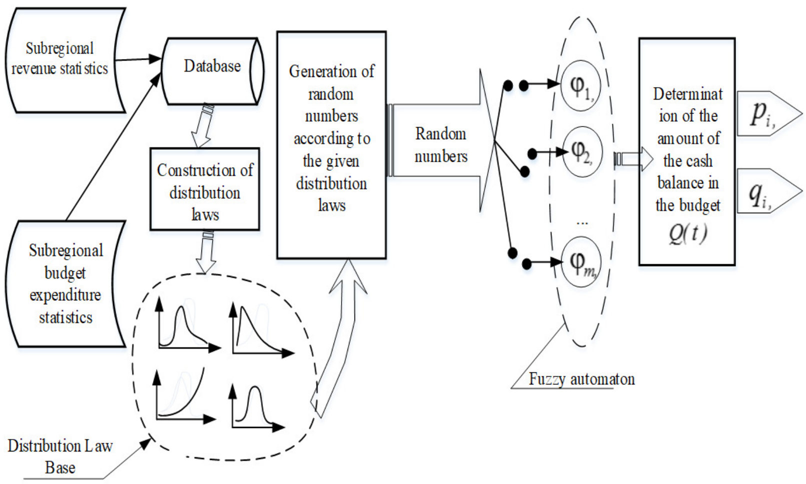

Figure 2: Block diagram of the interaction of a fuzzy automaton with a simulation model

In accordance with the structural scheme, the interaction of the automat with the simulation model begins with the stage of collecting and accumulating statistical data on the types of budget revenues and expenditures. Based on the use of these data, the laws of probability distribution of the values of income and expenses are constructed. These laws serve as the initial data for generating random numbers according to the given distribution laws during the planned time interval T. The generated statistics are considered as possible forecast values of budget revenues and expenditures during the planned period T and are used to calculate the remaining funds $Q(t)$ in the budget, both at the current time $t \in T$ and at the end of the planned period T. For those taxes that belong to the joint tax base $X_r(t)$, when calculating the budget balance $Q(t)$, coefficients are used in the form of regulatory deductions φ_i, considered as the state of the automat AVT. If we denote by $X_r(t)$ the tax revenues distributed vertically among the budgets in accordance with the standards φ_i, by $\overline{X_N}(t)$ all possible non-tax revenues received by the budget of the sub-region, by $X_N(t)$ the income from the payment of local taxes received by the budget, and by $R(t)$ the budget expenditures, then to determine the balance of funds $Q(t)$ in the budget, we can write the following expression:

$$Q(t+1) = Q(t) + \varphi_i X_r(t) + X_N(t) + \overline{X_N}(t) - R(t). \tag{16}$$

When studying the influence of coefficients φ_i on the state of the budget, the researcher varies the values of the states φ_i, $i = \overline{1,m}$ of the automaton, and fixes the probability of a budget surplus p_i and deficit q_i at the end of the period T. Calculated values Φ_i^H and Φ_i^L carry information about the extent to which it is appropriate to establish a standard φ_i for the distribution of tax revenues for a sub-region of a certain level of socio-economic development. Tables 1 and 2 show the results of experiments in the selection of standards φ_i, $i = \overline{1,m}$, the distribution of income from corporate income tax. At the same time, Table 1 shows the results of experiments conducted for a high-level socio-economic development sub-region, and Table 2 shows the results for a low-level region. Figures 3 and Figure 4 show graphs of the dependence of changes in the probability of budget surpluses and measures of the expediency of setting standards φ_i, $i = \overline{1,m}$, both for regions of high Φ_i^H and low Φ_i^L levels of socio-economic development. The results of the experiments showed that for a region of the Undevel class, i.e. with a low level of socio-economic development, a change in the value φ_i of the corporate income tax deduction rate practically does not change the value of the estimate of the probability of a budget deficit p_i. The graph of changes in the measure of expediency Φ_i^L of applying deductions from this tax is a straight line parallel to the abscissa axis (Figure 4). The sideways trend of the Φ_i^L value indicates the senselessness of using the tool of shared distribution of taxes to equalize the level of budget security. At this stage of the development of this sub-region, it is more useful to apply transfer infusions. As for the Devel sub-region under study, i.e., a high level of socio-economic development, the following conclusion can be drawn on the basis of the experiments conducted. The dependences of the values of the estimate of the probability of surplus p_i and the measure of expediency Φ_i^H on the value of the standard φ_i are increasing functions, which is clearly demonstrated by the constructed graphs (Fig. 3).

Table 1: Assessment of the feasibility of establishing different values φ_i, $i = \overline{1, m}$, of deductions from corporate income tax standards for sub-regions of a high level of socio-economic development.

Automaton states $\varphi_i(t)$	**A sub-region capable of self-organization**		
	Estimating the probability of a surplus p_i	**Estimating the probability of a deficit** q_i	**Expediency measures** Φ_i^H
0,05	0,11	0,89	0,008326285
0,1	0,12	0,88	0,008420902
0,15	0,23	0,77	0,009623888
0,2	0,243	0,757	0,009789159
0,25	0,336	0,664	0,01116023
0,3	0,432	0,568	0,013046468
0,35	0,451	0,549	0,013497985
0,4	0,527	0,473	0,015666794
0,45	0,627	0,373	0,019867007
0,5	0,757	0,243	0,030495447
0,55	0,782	0,218	0,033992632
0,6	0,877	0,123	0,060247104
0,65	0,895	0,105	0,070575179
0,7	0,903	0,097	0,076395812
0,75	0,913	0,087	0,085176940
0,8	0,914	0,086	0,086167370
0,85	0,917	0,083	0,089281853
0,9	0,923	0,077	0,096238881
0,95	0,938	0,062	0,119522481
1	0,948	0,052	0,14250757

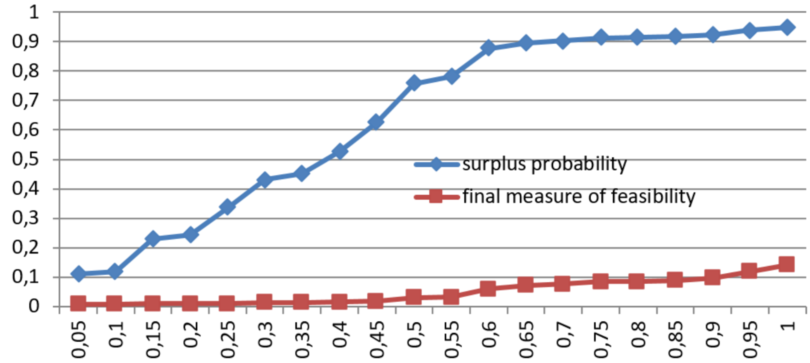

Figure 3: Graphs of the dependence of changes in the probability of a budget surplus p_i and the value Φ_i^H on the value of the standard φ_i for a high-level socio-economic development sub-region.

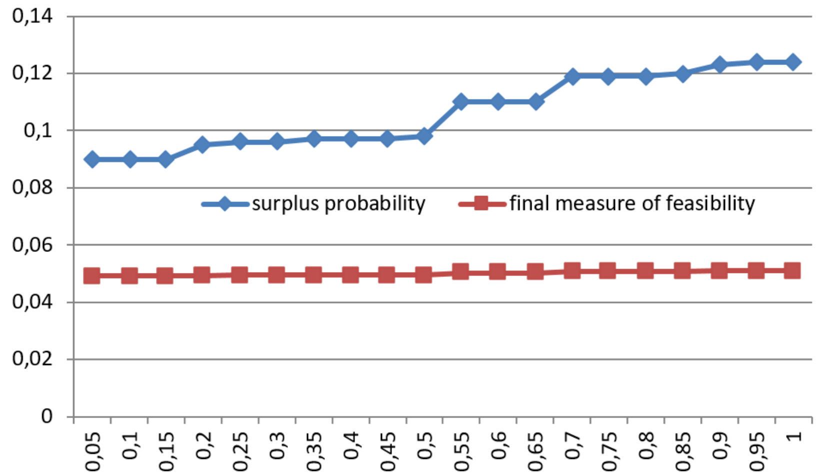

Figure 4: Graphs of the dependence of changes in the probability of a budget surplus p_i and the value Φ_i^L on the value of the standard φ_i for a sub-region of low socio-economic development.

Table 2: Assessment of the feasibility of setting different values φ_i, $i = \overline{1,m}$, of deductions from corporate income tax standards for sub-regions of low socio-economic development.

Automaton states $\varphi_i(t)$	**Sub-region, Not capable of self-organization**		
	Estimating the probability of a surplus p_i	**Estimating the probability of a deficit** q_i	**Expediency measures** Φ_i^L

0,05	0,09	0,91	0,049100392
0,1	0,09	0,91	0,049100392
0,15	0,09	0,91	0,049100392
0,2	0,095	0,905	0,049371665
0,25	0,096	0,904	0,049426279
0,3	0,096	0,904	0,049426279
0,35	0,097	0,903	0,04948101
0,4	0,097	0,903	0,04948101
0,45	0,097	0,903	0,049481015
0,5	0,098	0,902	0,049535872
0,55	0,11	0,89	0,050203771
0,6	0,11	0,89	0,050203771
0,65	0,11	0,89	0,05020377
0,7	0,119	0,881	0,05071663
0,75	0,119	0,881	0,05071663
0,8	0,119	0,881	0,050716636
0,85	0,12	0,88	0,050774269
0,9	0,123	0,877	0,050947955
0,95	0,124	0,876	0,051006115
1	0,124	0,876	0,051006115

The dependences of the values of the estimate of the probability of surplus p_i and the measure of expediency Φ_i^H on the value of the standard φ_i are increasing functions, which is clearly demonstrated by the constructed graphs (Fig.3). A change in the value of the standard φ_i leads to a positive dynamics of the value of the estimate of the probability of surplus in the budget of the sub-region. The value of the expediency measure Φ_i^H also increases with an increase in the value of the standard φ_i. Therefore, when managing the budget security of the territory, an effective solution is to use the transfer substitution tool with deductions from tax revenues.

5. Conclusions

In this article, financial innovations are considered at the following levels: institutional, instrumental, model, and technological. At the institutional level, the phenomenon of fiscal decentralization is attributed to financial innovation, which arose as a result of the interactivity of the provisions of the theory of fiscal federalism and the practice of developing inter-budgetary relations. As a catalyst for economic development, fiscal decentralization is considered as a mechanism for creating conditions for motivating economic entities to strengthen the economy and ensure sustainable economic growth. The ratio between "soft" and "hard" budget constraints, as the dominant factor of fiscal federalism, is attributed to the instrumental level of the analysis of the phenomenon of fiscal decentralization. The proportions of this ratio are established by means of regulating inter-budgetary relations, which perform equalizing and stimulating functions. The equalization function is performed through transfer infusions, and the incentive function is performed by providing revenues to the budgets of the subregions from taxes related to the joint tax base. The adoption of quantitatively based decisions in the implementation of the stimulating function of inter-budgetary regulation required the development of tools based on economic and mathematical methods. This circumstance led to the consideration of the model level of financial innovation. The era of digitalization predetermined the introduction of elements of intellectualization in the mathematical models within the framework of the topic "intelligent modeling". In this article, the use of an interdisciplinary synthesis of the theory of stochastic automata and fuzzy logic is proposed for the construction of intelligent models of decision support in the implementation of the stimulating function of inter-budgetary regulation. In this context, we offered a fuzzy automaton whose intelligent behavior is mathematically strictly argued by proving the theorems of asymptotic optimality. The developed economic and mathematical models in the form of a fuzzy automaton are proposed to be integrated into financial technologies for implementing inter-budgetary relations and to consider financial innovations at the technological level. At the same time, the structure of the system "fuzzy automaton" $\leftrightarrow$ "simulation model", which functions in constant interaction with a database that accumulates information about budget revenues and expenditures, is given.

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