DOI: 10.15838/esc/2016.5.47.15
UDC 330.4, LBC 65.050.03

Using Agent-Based Models in the Analysis and Forecast of Socio-Economic Development of Territories*

Vitalii Nikolaevich MAKOVEEV
Institute of Socio-Economic Development of Territories of RAS
56A, Gorky Street, 160014, Vologda, Russian Federation
makoveevvn@mail.ru

Abstract. The purpose of the paper is to study the essence of agent-based modeling, defining its features and prospects of usage in the modeling of socio-economic development of territories and systematization of domestic and foreign approaches to the development of prototypes for agent-based models of territories. Information basis for the research comprised the works on agent-based modeling by Russian and foreign scholars, especially articles and monographs of scientists of the Central Economics and Mathematics Institute under the Russian Academy of Sciences, papers presented in an international journal The Journal of Artificial Societies and Social Simulation and other sources available on the Internet. The article presents theoretical and methodological foundations of agent-based models of territories. The author considers the concepts of "agent-based modeling" and "agent" and defines specifics of agent-based models in comparison with other types of simulation modeling. The paper also describes major stages of building agent-based models for territories and considers qualification requirements to a modeling subject. Furthermore, it reviews Russian and foreign approaches to the development of prototypes for agent-based models of territories. It has been determined that most of them deal with the modeling of spatial,

* The research received support from the Russian Science Foundation in the framework of research project # 16-18-10296 "Development of a set of agent-based models that simulate socio-economic system on the Eurasian continent and that are detailed to the level of individuals".

For citation: Makoveev V.N. Using agent-based models in the analysis and forecast of socio-economic development of territories. *Economic and Social Changes: Facts, Trends, Forecast*, 2016, no. 5, pp. 272-289. DOI: 10.15838/esc/2016.5.47.15

territorial and socio-economic development of regions, cities and municipal entities. Agents in such models are presented by households, residents of regions and cities, enterprises and organizations operating in their territory, and public administration authorities (their inclusion in the model makes it possible to test different options of management impacts on territories by changing the model parameters, for instance, the introduction of certain prohibitions and quotas, issuance of permits, distribution of financial resources, etc.). At the end of the paper, the author formulates major conclusions. He shows the complexity faced by developers of agent-based models of socio-economic development and prospects for further research in this field. It has been established that the agent-based approach to the modeling of socio-economic development of territories is very promising, it helps improve the efficiency of forecasting regional development and management decisions due to a very detailed and realistic reconstruction of the internal structure of a region in the form of separate independent economic entities that interact with each other and with external environment, and also due to the possibility of fast processing and analysis of large amounts of data.

Key words: economy, mathematical modeling, agent-based models of socio-economic development.

In the post-Soviet period, the growth of the domestic economy was mainly achieved by increasing exports of raw materials, particularly hydrocarbons, and a favorable pricing environment for energy products. The domestic economy has evolved over the last 25 years under this model of raw materials export. However, the financial crisis of 2008–2009 and the events of 2014 demonstrated the vulnerability and instability of this type of development. The sharp decline in oil prices in 2014 led to a significant reduction of budget funds at all levels and reduction of investment activity that adversely affected the dynamics of economic growth and people's welfare. The situation was aggravated by the restrictions on imports of new technology and high-tech equipment from some foreign countries introduced against Russia.

This situation necessitates a more effective use of available resources, especially in the regions. In turn, this is impossible without the development of systems for simulation and forecasting of socio-economic development at the regional level.

In 2014, the law "On strategic planning in the Russian Federation" was adopted, it "establishes the legal framework for strategic planning in the Russian Federation, coordination of state and municipal strategic management and budget policy, powers of the federal bodies of state power, bodies of state power of subjects of the Russian Federation, bodies of local self-government and their cooperation with non-governmental, scientific and other organizations in the field of strategic planning" [18].

Currently, for the purpose of forecasting socio-economic development of territories, state authorities mostly use methods of time series (trending), input-output balances, production functions and expert interviews. A lot of models for socio-economic development of territories have been developed on the basis of these methods (Cross-sectoral interactions model (Central Economics and Mathematics Institute, RAS), Balance-econometric forecasting model (Center for Macroeconomic Analysis and Short-term Forecasting), Macroeconomic inter-industry model RIM (Institute of Economic Forecasting, RAS), the Model of the modern Russian economy (Dorodnicyn Computing Centre of RAS), the System for analyzing and forecasting socio-economic development of the region (KSTU), "Input-output" model by W. Leontief (USA), the Interindustry model of the U.S. economy LIFT (USA), AIDADS demand model (China), the Model of the Eurozone (EU), etc.) [9, 21, 22, 30, 37, 41]. However, it should be noted that many of such models are not applicable at the regional level because their calculations are based on the data from expert surveys and on the number of indicators, for which it is extremely difficult to obtain information. This creates the need to design socio-economic development models that would be applicable at the regional level and would take into account specific features of the territory and a wide variety of relationships between economic agents located there.

It is necessary to note that such models should be capable to perform a quick and efficient analysis of very large volumes of information. This is due to a rapid growth of the total amount of information in various economic sectors in recent years. According to a market research company IDC[1], the total amount of data will increase 29-fold in 10 years: from 1,200 exabytes in 2010 to 35,000 exabytes in 2020. Analysts say that the greatest increase in information will be observed in the Internet, financial sector, healthcare, astronomy, and bioinformatics. The need for processing and analyzing such considerable amounts of data sets makes it necessary to create information-analytical systems of a new level based on advanced computing methods, methods of pattern recognition, organization of storages, gathering statistical information with the goal of extracting meaning from data and obtaining information context [1].

Since the human brain is not capable of perceiving more than three or four interrelated parameters of a dynamic process, the creation of such systems at the regional level will improve the efficiency of decision-making, including public administration in a given territory, and a more efficient use of available resources in the region [16].

[1] International Data Corporation.

When building such models, one of the key elements of the new information-analytical systems can be the agent-based approach to the simulation of socio-economic development of territories, which is relatively new in simulation modeling and becomes increasingly popular. According to researchers from CEMI RAS, the emergence of this approach can be viewed as a result of a long evolution of modeling methodology: the transition from mono-models (one model describes a single algorithm) to multi-models (one model contains multiple independent algorithms) [13].

In accordance with this approach, the economic system can be represented as a set of interacting agent subsystems. By modeling the behavior of individual elements in a system, setting the parameters of their interaction, it is possible to investigate regularities in the behavior of a global system and analyze its features [7]. In other words, agent-based modeling approach is an artificial society that consists of independent agents that interact with one another and can simulate a system as close to reality as possible [20].

In building agent-based models researchers do not describe the behavior of the system as a whole (this applies in the development of traditional simulation models by using linear or differential equations that establish relationships between items), rather, they describe the behavior only of its elements and their independence. The behavior of the entire system is determined by the system itself in the course of emulation experiment, and functional relationships arising in the course of interaction of the system elements remain beyond the narrative part and, in fact, are the subject of research [8].

Thus, the relevance of studying the issues of development of agent-based modeling of socio-economic systems for various territories is due primarily to a significant increase in the volume of information, the need for its processing and analysis, and the increase in the efficiency of managerial decisions.

The purpose of the present paper is to study the nature of agent-based modeling, determine its specifics and prospects of use in the modeling of socio-economic development of territories, as well as to review domestic and foreign approaches to the development of prototypes for agent-based models of territories.

Information base of research is presented by the works of domestic and foreign scholars on agent-based modeling; first of all, these include articles and monographs of scientists of the Central Economics and Mathematics Institute of the Russian Academy of Sciences, proceedings of the international *Journal of Artificial Societies and Social Simulation*, as well as other sources available on the Internet.

The essence of simulation process, according to A.G. Granberg, is reduced to the cyclic and sequential execution of the following phases: construction of a model, study of the model, transfer of knowledge from the model to original, and validation and application of knowledge [5].

Let us try and find out which models can be named agent-based models and in what ways they differ from other types of simulation.

Domestic and foreign researchers formulated various definitions of agent-based models.

For example, A.R. Bakhtizin, and M.R. Fattakhov define agent-based models as a special class of models based on the individual behavior of agents and created for computer simulations [2; 25].

V.L. Makarov specifies the agent-based model by enumerating its properties among which he points out autonomy, limited intelligence of the agents, location in space, and heterogeneity. The author points out that the main difference between agent-based models and other types of simulation is "the presence of a large number of agents interacting with one another" [11].

E.D. Sushko specifies the agent-based model as "an artificial society of interacting independent agents, each of which has a given set of personal characteristics ("resources"), an objective function ("interests") and is subject to the rules of behavior that determine its reactions in various situations involving the scope of its interests" [23].

According to N. Gilbert, agent-based modeling is a computational method that allows the researcher to create and analyze a model composed of agents interacting in the environment, and conduct experiments using the models constructed. The main feature of agent-based models, according to N. Gilbert, is the ability of the agents to interact with each other and with the environment, to carry information messages and perform actions on their basis. In this case, information messages can present a direct "dialogue" between the agents, and indirect means of obtaining information (impact of another agent, observation over another agent). According to N. Gilbert, the possibility of modelling agent interactions is the main difference between agent-based modeling and other types of computational models [36].

A.R. Bakhtizin says that "the ultimate goal of the process of creating agent-based models is to track the influence of fluctuations of the agents operating at the micro-level on the indicators at the macro-level" [2].

The concept of "agent" is one of the main terms in agent-based modeling. M.R. Fattakhov believes that currently there is no precise definition of this term in agent-based modeling. According to his viewpoint, "the agent is an intelligent autonomous computerized entity located in its surrounding environment and interacting with other similar entities to achieve the goals of its existence" [25].

According to V. D. Boev, the "agent" is an active object that possesses its own behavior and has the opportunity to interact with other agents and with the environment [3].

Exploring the term "agent", V.L. Makarov emphasizes that each agent has a given set of characteristics and an objective function. On this basis, there is an imitation of the agent's reaction to changes in the external environment that affects its interests [13].

According to M.R. Fattakhov, the main properties and attributes of agents are "autonomy, intelligence, representativeness, location in time and space, the presence of life cycle, independence from the model developer or an external operator, interaction, purpose, perception of the world, the ability to learn and adapt, the availability of a resource in the agent" [25].

Thus, researchers engaged in agent-based modeling and defining the term "agent", name among its main features the ability to behave individually and interact with other agents and with the environment. Bearing this in mind, we can point out the following key characteristics that distinguish agent-based models from other computational models [12]:

1. Heterogeneity of the agents (including those within one class). In the class of enterprises, each agent (a company) is different while possessing the appropriate set of characteristics of behavior inherent in this class. In non-agent simulation models an entire class of companies is represented by a single enterprise, i.e., all agents in this class act synchronously and equally as one, which does not correspond to reality. For example, when solving the problem in the economy by using computable models describing the connection between its two sectors – industry and agriculture – these sectors behave like two huge enterprises. In an agent-based model in each of these classes there will be many agent enterprises that will differ from each other by the number of workers, amount of profit, production efficiency, types of products, etc.

2. Autonomy (independence of the actions of one agent from the actions of other agents). The actions of the agents in the model (e.g., humans) occur simultaneously and in parallel. Also, the agents' actions vary even within the same class. For example, in the class of enterprises, ceteris paribus, one agent enterprise can make a decision about investing all profits into the modernization of its production, another agent enterprise can decide to send all profits to the payment of dividends, and a third one will implement both these decisions in a certain proportion.

3. Implementation of actions of the agents in a given space that has a certain structure. For example, if the agents in a model (people, cars, etc.) use roads and rivers where they exist in a given space, then mountains are a barrier for them.

4. Local interactions. Each agent in the model interacts with other agents in a certain neighborhood, and interaction of this type does not occur with agents outside of it. This brings the model closer to real life, because interaction between people is carried out within a certain territory (even the interaction via the Internet does not occur simultaneously with the entire population of the world).

5. Bounded rationality. This feature in the model refers to individuals, enterprises and the government. In contrast to the concept of the economic man (homo economicus), the concept of bounded rationality proceeds from the fact that an individual fails to achieve the maximum individual utility function due to natural objective constraints (constraint of time and speed in decision-making, limitations of memory and the availability of information about possible options, etc.). It helps bring an agent-based model closer to reality.

6. Non-equilibrium nature of the dynamics of the processes. Whereas conventional modeling problems (for example, general equilibrium problems) are busy looking for equilibrium solutions, the dynamics of processes in agent-based models is non-equilibrium in nature [8].

The specifics of constructing agent-based models lead to the presence of several stages in this process. Along with the general stages of simulation modeling (analysis of the system; formulation of a goal for the simulation of the system; development of conceptual structure for the model; implementation of the model in the modeling environment; implementation of animated representation of the model; validation of the model's implementation; calibration of the model; planning and carrying out computer experiment [3]), for developing agent-based models the researcher has to determine individual characteristics of the agents, to simulate their behavior and rules of interaction with the environment, to calibrate the model (at this stage the correspondence between the actually observed data on the simulated object and the data calculated using the results of individual actions of agents in the model is achieved).

Despite the complexity of building agent-based models, interest in them is increasing, as evidenced by the increasing number of publications on this topic [39]. It should be noted that about half of the prototypes of agent-based models are developed in the social and economic spheres.

The *Table* presents the most interesting and sophisticated, in our opinion, domestic and foreign agent-based models in the social and economic development of various territories.

Domestic and foreign agent-based models

No.	Model	Model structure	Authors
Russian models			
1.	Regional model "Governor"	Individuals (people – the region's inhabitants), legal entities (enterprises and organizations) and municipal districts	E.D. Sushko
2.	Demographic agent-based model "Russia"	Two types of agents that differ in reproductive strategies. The first type of agents follows the traditional strategy and the second – the modern strategy.	V.L. Makarov, E.D. Sushko, A.R. Bakhtizin
3.	Complex Agent-Based Model of Urban Development (CUBMUD)	Enterprises and people, and three types of environment: public transport, city sectors, roads	M.R. Fattakhov
4.	Multi-agent model for development of the territorial system	Economic regions that consist of territorial production complexes and sites where they can be placed	K.S. Chirkunov
5.	Interregional inter-industry "input-output" model	Firms, households, foreign markets, and commodity markets	V.I. Suslov
Foreign models			
6.	Model for the European economy – EURACE (Italy, France, Germany, UK, Turkey, USA)	Households, firms and banks	Researchers from European countries, Nobel laureate J. Stiglitz
7.	Agent-based model of the virtual economy in Hradec Králové (Czech Republic)	Consumers; producers; mining companies; transportation	P. Cech, P. Tucmk, V. Bures, M. Husrakova
8.	Model for expanding urban territory (China)	Urban residents, farmers and authorities	H. Zhang, Y. Zeng, L. Bian, X. Yu
9.	Intra-Urban Migration Model (USA)	Households, developers and government	S. Sun, S. M. Manson.
10.	Shrinking City Model (Germany)	Population, space, decision-making	D. Haase, S. Lautenbach, R. Seppelt
Source: compiled by the author.			

Let us consider each of the presented agent-based models in more detail.

1. The regional model "Governor", developed by E.D. Sushko, [14] is designed to simulate the socio-economic state of the region based on the reconstruction of its internal structure and simulating the behavior of autonomous economic agents operating in its territory [23]. The model includes three types of agents: individuals (people – the region's inhabitants), legal entities (enterprises and organizations) and municipal districts. The high degree of elaboration of the model is proved by the fact that it has a very complex structure and includes a model of demographic development of the region and its individual municipal districts; the model of labor potential and work behavior of an individual; the labor market model; production model; the model of formation and use of the budget.

The model "Governor" is intended for testing different options of management actions at the regional level, the model can also be used as a planning tool in the result-oriented budgeting, i.e. in the allocation of resources in accordance with the goals, objectives and functions of the authorities.

The model is tested on the example of the Vologda Oblast. It helped carry out numerical experiments on simulating the dynamics of the status of the population in the oblast, its municipalities and enterprises in their territories under different values of the model's managed parameters. The results of the testing showed that the model accurately reflects characteristics of regional socio-economic development and can be used in its simulation [23].

2. Demographic agent-based model "Russia" developed by researchers at CEMI RAS to simulate people's reproductive behavior based on their internal attitudes [15].

The agents in the model are divided into two types that differ in reproductive strategies. The first type of agents follows the traditional strategy and the second – the modern strategy.

At the first stage of the work of the model the initial state of the environment is established and the agents are generated, the features of which (age, gender, the sign of belonging to a certain type, desired number of children) are assigned in such a way as to reproduce a given sex-age and social structure of the population in the modeled region.

At the second stage the processes of natural movement of population – the death and birth rates – are simulated by using the method of regrouping ages and probabilistic mechanisms. According to the authors, "extinction of the agents takes place in accordance with the death rates differentiated by sex and age, but the same for the entire population. The creation of new agents (child birth) in the model is a result of the agents' actions. First, agent people interact in the formation of couples when the partners agree on the desired number of children. And then, "family couples" agree on the time of birth of each child, and this choice depends on their internal settings associated with their belonging to a certain type" [15].

3. Complex Agent-Based Model of Urban Development (CUBMUD) [25] developed by M.R. Fattakhov consists of two types of agents: people (inhabitants of the metropolis), city enterprises and organizations, and three types of environment: city sectors, public transport and public roads, which are situated in these sectors. In the operation of the model, one kind of agents interacts with the other ("agent-agent" type of connection), i.e. they are either working and receiving a monthly income or are on the job market and looking for a job, interacting with the environment of the model ("agent-environment" type of connection). Here they pay for the cost of living (utility bills, rent). In the model, human agents can change their area of residence based on their preferences or financial situation. When they commute between home and work, human agents interact with the environment – public transport and roads. The choice of the type of vehicle determines the amount of time they spend on the road and the amount of monthly expenses. Human agents have the following set of characteristics: age, memory, monthly income, monthly transport expenses, cash balance, area of work, area of residence, time when their working day starts, presence or absence of a personal vehicle. Human agents can be in one of four states: satisfaction, frustration, waiting, and neutral state [27].

This model was tested on the example of Moscow [24]. The CABMUD model that has been designed helps make long-term forecasts and develop scenarios of socio-economic development of cities, and to make a quantitative assessment of the results of management decisions.

4. *Multi-agent model for development of the territorial system* was developed and tested by K.S. Chirkunov [29]. The main agents in it are economic regions that consist of agents of the lower level of the hierarchy: territorial production complexes and sites where they can be placed. The sites are characterized by geographical location and available natural and human resources. The external environment in the model is represented by a variety of external resources and markets. In the process of functioning of the territorial system, agents interact with each other, for example, they can agree on a set of production specializations of the system and thereby determine the behavior of the territorial system as a whole [28].

5. *Interregional inter-industry "input-output" model* developed by V.I. Suslov and his colleagues to solve the problems of modeling the spatial structure of Russia's economic system taking into account its vast territory. The model contains four types of agents: firms, households, foreign markets, and commodity markets. The model has a geographical structure and is attached to the conventional map of Russia using GIS approach [19].

6. *In September 2006, a project was launched to develop a model for the European economy – EURACE (Agent-based Computational Economics).* In this model, many autonomous agents interact in the framework of the socio-economic system [34]. The project involves experts from eight research centers in Germany, Italy, UK, France and Turkey, and a consultant from Columbia University, Nobel laureate Joseph Stiglitz [20].

The model uses a geographical information system that covers a wide range of facilities: shops, enterprises, schools, transportation networks, etc.

In its scale and complexity EURACE is unique because it presents the whole European Union. In order to fill the model with statistical information, the data (presented by GIS maps) of the statistical service of the European Union of the NUTS-2 level representing data on the 268 regions of 27 countries were used[2].

The model has three types of agents: households, firms and banks. They all have a geographical reference and relate to each other through social networks, business relationships, etc. With the help of the developed model a series of experiments were carried out in order to study the labor market. One of the main conclusions of the study consists in the fact that the macroeconomic indicators of the two regions with similar conditions (resources, economic development, etc.) for an extended period (10 years or more) can significantly differ because of the initial heterogeneity of the agents.

7. Agent-based model of the virtual economy developed by P. Cech, P. Tucmk, V. Bures and M. Husrakova, recreates the processes of production and consumption in the real economy. It is designed to study economic processes in the Czech town of Hradec Králové [45].

[2] NUTS (French: Nomenclature des unites territoriales statistiques) is a geocode standard for referencing the subdivisions of countries for statistical purposes. The standard is developed by the European Union, and covers the member states of the EU. There are three levels of NUTS, the second level (NUTS-2) corresponds to administrative districts in Germany, counties in the UK, etc.

In the model, the authors identify four types of agents: consumers (C-agents); factory agents (F-agents); mining companies (M-agents); transportation (T-agents). *C-agents* can purchase essential goods, normal goods and luxury items. The structure and rate of consumption are determined by the individual consumption function that depends on the welfare of the agents. The level of welfare is determined by the job and qualifications. Making a choice between investment into consumption or investment in training, the agents can manage their well-being. *F-agents*, consuming raw materials and other products, produce the final product that is purchased by C-agents, or the intermediate product that is purchased by other manufacturers. With the help of the consumption function, the proportions of purchased raw materials and products are determined, and the range of products is specified with the help of the production function. The output volume depends on the technology used and on the skills of C-agents employed in the production. *M-agents in the model* convert natural resources into commodities that F-agents use, and each M-agent supplies only one type of raw material. The cost of production is determined by the consumption function that reflects the necessary energy and technology. *T-agents* in the model act as intermediaries between producer agents and mining companies. The task of T-agents is to find the optimal route. Capacity, travel speed and technology define the performance of T-agents. Transportation costs depend on distance.

The authors have implemented a simplified computer model of the virtual economy on the NetLogo platform. It simulates the processes of raw materials production, their transfer to transport agents, transportation, obstacle detection during transportation, production of products, purchase, sale and final consumption of products by consumer agents. According to the intent of the researchers, the final model should be based on real statistical data and be consistent with the behavior of economic entities of Hradec Králové [27].

8. Agent-based model of the Chinese city of Changsha developed by H. Zhang, Y. Zeng, L. Bian, and X. Yu [46]. The model includes three types of agents: residents, farmers and authorities. One of the main driving forces behind the expansion of the city in the model is inhabitant agents who choose a new place of residence.

Farmer agents in search of a more comfortable life want, on the one hand, to live closer to the city and "civilization" and on the other – not to lose the lands that "feed" them, because these very lands near the city limits and major roads are most likely to be transferred to the city. Decision-making by farmer agents in the model depends on a set of factors: proportion of protected agricultural land, proportion of the land for development and the areas of possible development, distances to railroads and highways, distances to main urban roads and to the city center, population density, etc. The authorities in the model are an agent of a special type, which has no spatial characteristics in contrast to the agents of the other two types; however, it can make decisions that promote the most rational use of land and ensure sustainable development of the city while protecting and preserving fertile agricultural lands [27].

The described model is based on statistical data on the socio-economic development of the city of Changsha in China (since 1990) and uses a GIS map of the city.

9. Intra-Urban Migration Model developed by American scientists S. Sun and S. M. Manson. The main agents in the model are households (they create demand in the real estate market), developers (creates supply of new housing) and government (regulates land use). The process of modeling intra-urban migration is carried out in several stages: first, features of the environment and spatio-temporal framework are defined; second, data about the agents is loaded; third, the model is run and, fourth, the results of the simulation are analyzed. The model is verified and calibrated on data from the Minneapolis–St. Paul metropolitan area, Minessota [50].

10. Shrinking City Model designed by German researchers D. Haase, S. Lautenbach and R. Seppelt, is used to study migration and land use in Leipzig. The model is based on three blocks of components: "Population" (population dynamics affect the life cycles and types of households and is determined by migration growth, birth and death rates), "Space" (every point of the urban space, with the exception of the territorial jurisdiction, is described by the composition of households, type of residential development, transportation access, cost of purchase and rent of real estate, security, crime situation, medical and educational institutions, shopping centers, places for recreation and leisure), "Decision-Making" (on the basis of assessing the attractiveness of the place of residence each household makes a choice between relocation and preservation of its former residence) [38].

The model helps assess the level of release of the housing in the city based on the relocation of households, and in the absence of demand for the housing for more than 5 years – the level of its demolition.

Based on the analysis of approaches of domestic and foreign researchers to the development of agent-based models in the social and economic spheres, we can conclude that the majority of them are devoted to the modeling of spatial, territorial and socio-economic development of regions, cities and municipalities. The main agents in such models are households, inhabitants of regions and cities, enterprises and organizations operating in their territory, and state authorities (their inclusion in the model helps test different options of management actions in the territory by changing the model parameters, such as the introduction of certain prohibitions and quotas, issue of permits, allocation of financial resources, etc.).

In order to implement agent-based models of socio-economic development at the regional level, the developers must overcome the difficulties associated with the definition of agent types, their number and characteristics, understanding of the mechanism of interaction between the agents and the external environment, implementation of model calibration and selection of simulation period. The situation is also complicated by the problem of filling agent-based models of socio-economic development of territories with real data. This problem can be partially solved by carrying out surveys. However, techniques of their realization not always help ensure the comparability of the data obtained at different levels of modeling. One of the problems hindering the use of the agent-based approach in the forecasting of socio-economic development of territories is the lack of awareness of public authorities and management on the opportunities and prospects of this method and feasibility of its application in the study of economic dynamics, management decision-making and selecting strategic priorities.

Summarizing all of the above, we can conclude that the agent-based approach to the modeling of socio-economic development of territories is very promising, it improves the efficiency of forecasting of regional development and management decisions due to very detailed and realistic reconstruction of the internal structure of the region in the form of separate independent economic entities that interact with each other and with the external environment, and also due to the possibility of fast processing and analyzing large amounts of data

In our opinion, further research in the field of agent-based modeling of socio-economic development of territories can be directed at solving the problems related to the study of the interaction of agents with each other and with the environment, developing theoretical and methodological foundations for agent-based approach, analyzing software and technological implementation of agent-based models on supercomputers, and developing the algorithms for calibration and verification of agent-based models.

The author expresses his gratitude to Konstantin Anatol'yevich Gulin, Doctor of Economics, Associate Professor, ISEDT RAS Deputy Director, Head of the Department of Scientific and Technological Development and Knowledge Economy for his assistance in preparing this paper.

References

1. Makarov V.L., Bakhtizin A.R., Sushko E.D., Vasenin V.A., Borisov V.A., Roganov V.A. Agent-orientirovannye modeli: mirovoi opyt i tekhnicheskie vozmozhnosti realizatsii na superkomp'yuterakh [Agent-based models: world experience and technical capability of implementation on supercomputers]. *Vestnik RAN* [Herald of the Russian Academy of Sciences], 2016, no. 3, p. 253. (In Russian).
2. Bakhtizin A.R. *Agent-orientirovannye modeli ekonomiki* [Agent-based models for the economy]. Moscow: Ekonomika, 2008. 279 p. (In Russian).
3. Boev V.D., Kirik D.I., Sypchenko R.P. *Komp'yuternoe modelirovanie: posobie dlya kursovogo i diplomnogo proektirovaniya* [Computer simulation: a handbook for simulation in term and graduation papers]. Saint Petersburg: VAS, 2011. 348 p. (In Russian).
4. Borshchev A.V. Imitatsionnoe modelirovanie: sostoyanie oblasti na 2015 god, tendentsii i prognoz [Simulation modeling: current state of the field as of 2015, its trends and forecast]. *IMMOD 2015.* Available at: http://www.anylogic.ru/upload/pdf/immod15_borshchev_statia.pdf. (In Russian).

5. Granberg A.G. *Modelirovanie sotsialisticheskoi ekonomiki: uchebnik dlya vuzov* [Modeling of the socialist economy: textbook for universities]. Moscow: Ekonomika, 1988. 487 p. (In Russian).
6. Denisova S.V., Bakhtizin A.R. Modelirovanie protsessa sliyanii organizatsii s pomoshch'yu agent-orientirovannoi modeli [Modeling of the process of mergers of organizations using an agent-based model]. *Problemnyi analiz i gosudarstvenno-upravlencheskoe proektirovanie* [Problem analysis and public administration projection], 2011, no. 2, p. 60. (In Russian).
7. Zvyagin L.S. Prakticheskie priemy modelirovaniya ekonomicheskikh sistem [Practical techniques for modeling economic systems]. *Problemy sovremennoi ekonomiki: materialy IV mezhdunar. nauch. konf. (g. Chelyabinsk, fevral' 2015 g.)* [Problems of modern economics: proceedings of the 4th international scientific conference (Chelyabinsk, February 2015)]. Chelyabinsk: Dva komsomol'tsa, 2015. P. 14-19. (In Russian).
8. Zul'karnai I.U. Zadacha agent-orientirovannogo modelirovaniya raspredeleniya funktsii po vertikali v asimmetrichnoi federatsii [Task of agent-based modeling for vertical distribution of the function in an asymmetric federation]. *Vestnik Bashkirskogo universiteta* [Bulletin of Bashkir University], 2014, vol. 19, no. 4, pp. 1249-1255. (In Russian).
9. Ivanter V.V. Strategiya perekhoda k ekonomicheskomu rostu [Strategy for transition to economic growth]. *Problemy prognozirovaniya* [Studies on Russian Economic Development], 2016, no. 1, pp. 3-8. (In Russian).
10. *Laboratoriya agentnogo modelirovaniya* [Laboratory for agent-based modeling]. Available at: http://abm.center. (In Russian).
11. Makarov V.L., Bakhtizin A.R. *Sotsial'noe modelirovanie – novyi komp'yuternyi proryv (agent-orientirovannye modeli)* [Social simulation – a new computer breakthrough (agent-oriented models)]. Moscow: Ekonomika, 2013. 295 p. (In Russian).
12. Makarov V.L. Iskusstvennye obshchestva [Artificial societies]. *Iskusstvennye obshchestva* [Artificial Societies], 2006, vol. 1, no. 1, pp. 10-24. (In Russian).
13. Makarov V.L., Bakhtizin A.R. Sovremennye metody prognozirovaniya posledstvii upravlencheskikh reshenii [Modern methods for forecasting the effects of management decisions]. *Upravlencheskoe konsul'tirovanie* [Management Consulting], 2015, no. 7, pp. 12–24. (In Russian).
14. Makarov V.L., Sushko E.D., Bakhtizin A.R. *Obshchee opisanie modeli Vologodskoi oblasti "Gubernator"* [General description of Vologda Oblast model "The Governor"]. Available at: http://abm.center/publications/index.php?ID=276. (In Russian).
15. Makarov V.L., Sushko E.D., Bakhtizin A.R. *Obshchee opisanie demograficheskoi modeli "Rossiya"* [General description of the demographic model "Russia"]. Available at: http://abm.center/publications/index.php?ID=278. (In Russian).
16. Makarov V., Bakhtizin A., Sushko E. Modelirovanie demograficheskikh protsessov s ispol'zovaniem agent-orientirovannogo podkhoda [Simulation of demographic processes using the agent-based approach]. *Federalizm* [Federalism], 2014, no. 4, p. 37. (In Russian).
17. Musaev A., Shevchik A. Tikhaya kognitivnaya revolyutsiya [Quiet cognitive revolution]. *Ekspert* [Expert], 2016, no. 4, p. 45. (In Russian).
18. O strategicheskom planirovanii v Rossiiskoi Federatsii: Federal'nyi zakon: prinyat Gosudarstvennoi Dumoi 20 iyunya 2014 g. №172-FZ [On strategic planning in the Russian Federation: Federal Law: adopted by the State Duma on 20 June 2014 No. 172-FZ]. *Konsul'tant-plyus* [Consultant-plus]. (In Russian).

19. Suslov V.I., Domozhirov D.A., Kostin V.S., Mel'nikova L.V., Ibragimov N.M., Tsyplakov A.A. Opyt agent-orientirovannogo modelirovaniya prostranstvennykh protsessov v bol'shoi ekonomike [Agent-based modeling of spatial processes in big economy]. *Region: ekonomika i sotsiologiya* [Region: Economics and Sociology], 2014, no. 4, pp. 32-54. (In Russian).

20. Okrepilov V.V., Makarov V.L., Bakhtizin A.R. et al. Primenenie superkomp'yuternykh tekhnologii dlya modelirovaniya sotsial'no-ekonomicheskikh sistem [Application of supercomputer technologies for simulation of socio-economic systems]. *Ekonomika regiona* [Economy of Region], 2015, no. 2, pp. 301-313. (In Russian).

21. Savchishina K. Prognozirovanie pokazatelei nalogovo-byudzhetnoi sfery v ramkakh kvartal'noi makroekonomicheskoi modeli "QUMMIR" [Forecasting the performance of the fiscal sector in the framework of the quarterly macroeconomic model "QUMMIR"]. *Nauchnye trudy* [Scientific works]. MAKS Press, 2008. (In Russian).

22. Sayanova A.R. Tablitsy "zatraty-vypusk" v analize i prognozirovanii strukturnykh parametrov regiona ["Input-output" tables in the analysis and forecasting of structural parameters of the region]. *Problemy prognozirovaniya* [Studies on Russian Economic Development], 2004, no. 6, p. 38. (In Russian).

23. Sushko E.D. *Mul'tiagentnaya model' regiona* [A multi-agent model of the region]. Available at: http://www.artsoc.ru/publications /index.php?ID=155. (In Russian).

24. Fattakhov M.R. Agent-orientirovannaya model' sotsial'no-ekonomicheskogo razvitiya Moskvy [An agent-based model of socio-economic development of Moscow]. *Ekonomika i matematicheskie metody* [Economics and mathematical methods], 2013, no. 2, pp. 30-42. (In Russian).

25. Fattakhov M.R. Agent-orientirovannaya model' sotsial'no-ekonomicheskogo razvitiya megapolisov: avtoref. dis. na soisk. uch. st. k.e.n.: 08.00.13 [An agent-based model for socio-economic development of megacities: Ph.D. in Economics dissertation abstract]. Moscow, 2011. 30 p. (In Russian).

26. Fomin A.V., Akopov A.S. *Agent-orientirovannaya dinamicheskaya model' rossiiskogo farmatsevticheskogo rynka* [Agent-based dynamic model of the Russian pharmaceutical market]. Available at: http://abm.center/publications/ index.php?ID=187. (In Russian).

27. Chekmareva E. A. Obzor rossiiskogo i zarubezhnogo opyta agent-orientirovannogo modelirovaniya slozhnykh sotsial'no-ekonomicheskikh sistem mezourovnya [Overview of the Russian and foreign experience of agent-based modeling of complex socio-economic systems of the meso-level]. *Ekonomicheskie i sotsial'nye peremeny: fakty, tendentsii, prognoz* [Economic and social changes: facts, trends, forecast], 2016, no. 2, pp. 225-246. (In Russian).

28. Chirkunov K.S. Agentnoe modelirovanie razvitiya territorial'noi sistemy [Agent-based modeling of development of territorial systems]. *Informatika i ee primeneniya* [Informatics and its applications], 2011, vol. 5, no. 1, pp. 58-64. (In Russian).

29. Chirkunov K.S. *Mul'tiagentnyi podkhod i modelirovanie povedeniya vzaimodeistvuyushchikh ierarkhicheskikh sistem ekonomicheskoi prirody: avtoref. dis. ... kand. fiz.-mat. nauk: 05.13.11* [Multi-agent approach and simulation of the behavior of interacting hierarchical systems of economic nature: Ph.D. in Physics and Mathematics dissertation abstract]. Novosibirsk, 2012. 26 p. (In Russian).

30. Shirov A.A., Gusev M.S., Yantovskii A.A. Obosnovanie vozmozhnykh stsenariev dolgosrochnogo razvitiya rossiiskoi ekonomiki [Substantiation of possible scenarios for the long-term development of the Russian economy]. *Vserossiiskii ekonomicheskii zhurnal – "EKO"* [All-Russian economic journal – ECO], 2012, no. 6. (In Russian).

31. Batty M. Urban Modeling. *International Encyclopedia of Human Geography*. Oxford: Elsevier, 2009. Pp. 51-58.

32. Bures V., Tucnik P. Complex agent-based models: Application of a constructivism in the economic research. *Economics & Management,* 2014, no. 17 (1), pp. 152-168.

33. Collier N. *Repast HPC Manual. 2012.* Available at: http://repast.sourceforge.net

34. Deissenberg C., van der Hoog S., Herbert D. EURACE: A Massively Parallel Agent-Based Model of the European Economy. *Document de Travail No. 2008, vol. 39, 24 June.*

35. Epstein J.M., Axtell R.L. *Growing Artificial Societies: Social Science from the Bottom Up. Ch. V.* Cambridge, Massachusetts: MIT Press, 1996.

36. Gilbert N. *Agent-based models.* Sage Publications Inc., 2008. 112 p.

37. Grassini M. *Accumulation and Competitiveness.* Available at: http://inforumweb.umd.edu/papers/conferences/ 2009/grassini_paper.pdf.

38. Haase D., Lautenbach S., Seppelt R. Modeling and simulating residential mobility in a shrinking city using an agent-based approach. *Environ. Model. Softw.,* 2010, no. 25, pp. 1225-1240.

39. Heath B., Hill R., Ciarallo F. A Survey of Agent-Based Modeling Practices (January 1998 to July 2008). *Journal of Artificial Societies and Social Simulation,* 2009, no. 12 (4) 9. Available at: http://jasss.soc.surrey.ac.uk/12/4/9.html.

40. Heppenstall A., Malleson N., Crooks A.T. "Space, the Final Frontier": How Good are Agent-based Models at Simulating Individuals and Space in Cities? *Systems*, 2016, no. 4 (1) 9. Available at: http://www.mdpi.com/2079-8954/4/1/9/pdf.

41. Jiang X. *Statistical and Economic Applications of Chinese Regional Input-Output Tables.* Groningen, 2011.

42. Kravari K., Bassiliades N. A survey of agent platforms. *Journal of Artificial Societies and Social Simulation,* 2015, no. 18 (1) 11. Available at: http://jasss.soc.surrey.ac.uk/18/1/11.html.

43. Lynar T.M., Herbert R.D., Chivers W.J. Implementing an agent based auction model on a cluster of reused workstations. *International J. of Computer Applications in Technology*, 2009, vol. 34, no. 4, pp.13-24.

44. Magliocca N., Safirova E., McConnell V., Walls M. An economic agent-based model of coupled housing and land markets (CHALMS). *Computers, Environment and Urban Systems,* 2011, no. 35, pp. 183-191.

45. Cech P., Tucnik P., Bures V., Husrakova M. Modelling complexity of economic system with multi-agent systems. *5th International Conference on Knowledge Management and Information Sharing (KMIS 13), Vilamoura, Algarve, Portugal, 19-22 September 2013.* Pp. 464-469.

46. Zhang H., Zeng Y., Bian L., Yu X. Modelling urban expansion using a multi agent-based model in the city of Changsha. *Journal of Geographical Sciences,* 2010, no. 20 (4), pp. 540-556.

47. Nikolai C., Madey G. Tools of the trade: a survey of various agent based modeling platforms. *Journal of Artificial Societies and Social Simulation,* 2009, no. 12 (2) 2. Available at: http://jasss.soc.surrey.ac.uk/12/2/2.html.

48. Parker J. A *Flexible, Large-Scale, Distributed Agent Based Epidemic Model. Center on Social and Economic Dynamics. Working Paper No. 52,* 2007. P.25.

49. Rui Y., Ban Y. Multi-agent simulation for modeling urban sprawl in the Greater Toronto Area. *Proc. of the 13th AGILE International Conference on Geographic Information Science*. Guimaraes, 2010. Available at: https://agile-online.org/Conference_Paper/CDs/agile_2010/ ShortPapers_PDF/124_DOC.pdf.

50. Sun S., Manson S.M. Simple Agents, Emergent City: Agent-Based Modeling of Intraurban Migration. *Computational Approaches for Urban Environments.* Berlin: Springer, 2015. Pp. 123-147.

Information about the Author

Vitalii Nikolaevich Makoveev – Ph.D. in Economics, Acting Head of the Laboratory, Institute of Socio-Economic Development of Territories of Russian Academy of Science (56A, Gorky Street, 160014, Vologda, Russian Federation, makoveevvn@mail.ru)

Received September 13, 2016