ТЕОРЕТИЧЕСКИЕ И МЕТОДОЛОГИЧЕСКИЕ ПРОБЛЕМЫ

Agent-based modeling for a complex world. Part 2

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Abstract. The main goal of this paper is to summarize selected developments in the field of artificial societies and agent-based modeling and to suggest, how this fundamentally new toolkit can contribute to solving some of the most complex scientific and practical problems of our time. The entire field of agent-based modeling has expanded dramatically over the last quarter century, with applications across a remarkable array of fields, at scales ranging from molecular to global. The models described in this paper are a small part of worldwide scientific and practical developments in the field of agent-based modelling and related areas. We have attempted to give an impression of the vast range of application areas (epidemiology, economics, demography, environment, urban dynamics, history, conflict, disaster preparedness), scales (from cellular to local to urban to planetary), and goals (simple exploratory models, optimization, generative explanation, forecasting, policy) of agent-based modeling. Agent-based models offer a new and powerful alternative, or complement, to traditional mathematical methods for addressing complex challenges.

Keywords: agent-based models, epidemiology, pedestrian traffic, demographic processes, transport systems, ecological forecasting, land use, urban dynamics, historical episodes, conflict simulation, social networks, economic systems.

JEL Classification: C63, D91.

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6. GEOGRAPHY AND ENVIRONMENT

Forecasting the state of the environment using an agent-based approach can be distinguished as a separate major area. An overview of the most well-known models simulating the processes of environmental pollution due to human activities, the influence of the environment condition on the morbidity and mortality of the population, as well as the processes of managing the environmental aggravations is given in a recent publication by the staff of Central Economics and Mathematics Institute of the Russian Academy of Sciences (Makarov, Bakhtizin, Sushko, 2020). This article also reviews best practices in socio-ecological and economic agent-based modeling. The CEMI RAS Model includes two types of agents — people and enterprises.

The first type of agents determines the demographic dynamics and participates in the work of enterprises, and the second type of agents produces the products and releases emissions into the ecosystem of the territory (atmosphere and water). The polluted environment affects the level of health and mortality of people, but the model provides a mechanism for regulating emissions, which affects their amounts.

An important challenge is to popularize large-scale climate models with agents whose behaviors affect the climate itself. At the October 8–9, 2020 meeting of the BRICS[1] Working Group on information and communication technologies (ICT) and High-Performance Computing Systems chose the advance of these models as the flagship priority for all participating countries. The project "*Digital modeling of the Earth system*" was unanimously supported, and will couple an agent-based model representing human behaviors to the large scale climate model developed at Moscow State University by M.V. Lomonosov. This model forecasts the weather and climate of the Earth, taking into account a large number of factors (atmosphere, changes in the ocean conditions, ocean biogeochemistry, ionosphere dynamics, ice cover evolution) — for several dozen simulated layers of our planet with a resolution of 10 km (Stepanenko et al., 2020).

It will be among the first similar integrated human-climate models, and will help advance the monitoring and prediction of feedback effects between individual behaviors and environmental effects on worldwide scales.

7. LAND USE

Agent-based modeling of land use methods should be recognized as a special area. An early example is a model of irrigation systems in Indonesia (Lansing, Kremer, 1993). Since then, many agent-based land use models were developed (Matthews, Gilbert, Roach, 2007).

Interesting results were obtained by researchers from the University of Edinburgh, Heriot–Watt University (United Kingdom), the University of Waterloo (Canada), and the University of Ljubljana (Slovenia). The scientists developed an agent-based model for the municipality of Koper (Slovenia), considering the impact of changes in the land use regime on the quality of life of population. In particular, it showed an important trade-off, while industrial development results in the loss of high-quality agricultural land. However, the new residential areas improve the quality of life of the population (Murray-Rus et al., 2013).

An extended model including international effects was built by the scientists form five countries — USA, Netherlands, UK, Brazil, China (Dou et al., 2019). To study how changes in the land use regimes were influenced by international trade of agricultural products, an agent-based model (TeleABM) was developed. It was applied to the trade of soybeans between China and Brazil. One of the model's most important parameters was the price of a traded product, which influenced decisions on land use made at the farm-agent level. Recalling the micro-macro gap discussed earlier, the following feedback was found — changes in land use at the micro level affect the balance of supply and demand at the macro level.

To say more about the trading mechanics, farmer agents in the receiving system allocate their resources to grow soybeans, rice, and corn. Farmer agents in the sending system allocate their resources to grow a single-season soybeans, a double-season soybeans and corn, and/or a double-season soybeans and cotton (Dou et al., 2019). Fig. 11 shows the interface of the TeleABM model designed to change the control parameters and view the results. The screen displays two municipalities: (a) Sinop, Mato Grosso, Brazil and (b) Gannan, Qiqihaer, China, where land use regime depends on the values of exogenous parameters input by the user (panels (c) and (d)). It thus permits carrying many experiments.

Another related field is natural disaster resilience. Damage minimization against possible floods was studied with an agent-based model developed at RWTH[2] Aachen University (Germany). Micro-level agent (farmer) makes decisions on land use based on climat conditions, crop yields, price levels, and anticipated flood damage (Nabinejad, Schüttrumpf, 2017). Fig. 12 displays the operation window of the model, showing how agents (farmers, in yellow) are distributed over the territory, areas of which are partially flooded (highlighted in red). Each farmer communicates with his neighbours within a certain radius. Incoming information influences the decisions of the agents who receive it.

The diversity of agent-based land use models prompted researchers from three countries (USA, UK, Germany) to suggest using a common ODD (Overview, Design concepts, and Details) protocol to categorize many developed simulators (Polhill et al., 2008).

[1] BRICS is the acronym coined to associate five major emerging economies: Brazil, Russia, India, China, and South Africa.

[2] Rheinisch-Westfälische Technische Hochschule.

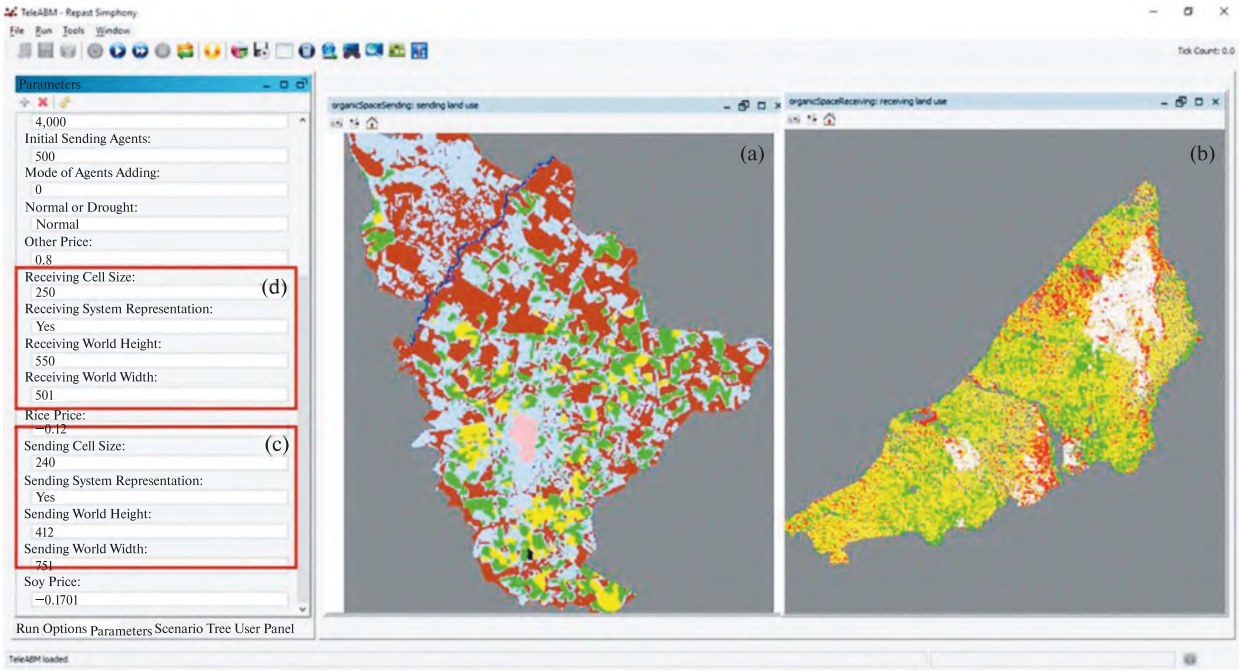


Fig. 11. TeleABM model interface: on the left panel (a): light blue — grassland, brown — forest, green–yellow — soybean corn, black — cotton; on the right panel (b): blue — water, green — soybean land, yellow — corn, white — rice paddy, and brown — built-up land

Source: Image from "Land-use changes across distant places: design of a telecoupled agent-based model" (Dou et al., 2019).

Fig. 12. Operation window of the model: agricultural land (damaged and used), farmers and their social networks

Source: Image from "An agent-based model for land use policies in coastal areas" (Nabinejad, Schüttrumpf, 2017).

8. URBAN DYNAMICS

We turn now to agent-based models of urban agglomeration, being closely related to the previous discussions. Recall that strength of ABMs is to give a formal account of how interactions at the micro-scale generate the macro-scale patterns and dynamics of interest, in this case — at the city level. Ideally, these ABMs would include micro modules simulating social, transport, environmental/ecological and other systems, interacting within a unified model. These would reveal how aggregate urban dynamics emerge ‘from the bottom up’.

An example is a paper by researchers from several French research centers: “*Exploring intra-urban accessibility and impacts of pollution policies with an agent-based simulation platform*” (Fosset et al., 2016).

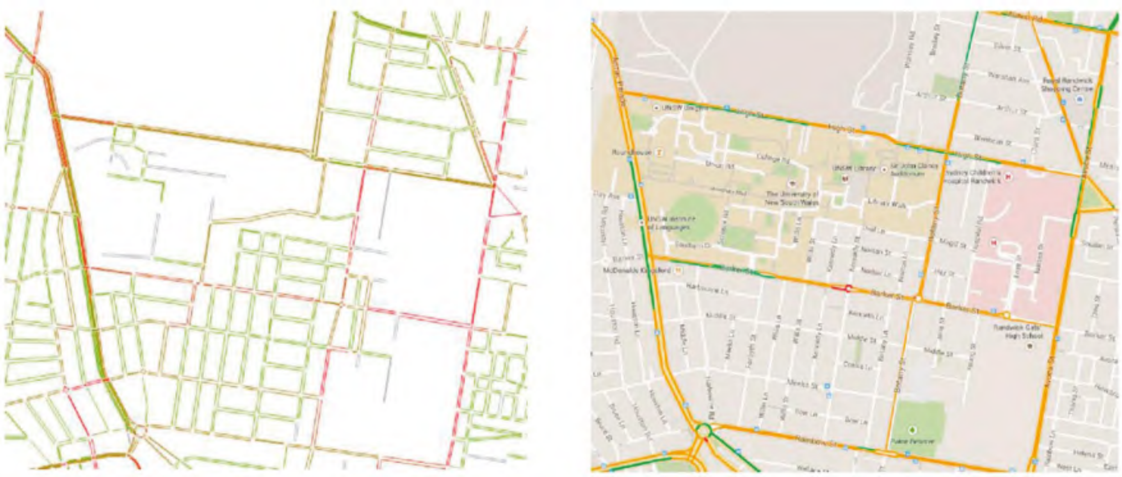
It represents a digital twin of Grenoble, a city of 160,000 inhabitants. The agents of the model reproduce daily activities of the townspeople (trips from home to work or school, business trips, walks, etc.) in accordance with the schedules compiled from surveys and statistical data collected from various sources. The simulator contains infrastructure facilities (schools, enterprises, etc.), a transport system, houses, etc., implemented on a geographic information system.

A module of the system calculates the changing environmental situation in the city and its impact on the residents. This project is demanding both in terms of resources and time, and has been underway for more than 15 years (Fosset et al., 2016).

Relatedly, a team of researchers from the University of Wollongong, Australia, describes an agent-based TransMob simulator that examines people living in Southeast Sydney and their needs for housing, transportation and social infrastructure. One of the output parameters of the model is the level of satisfaction of residents, which depends on a number of influencing factors. The authors note that TransMob is one of a few models that combine population dynamics, a traffic simulator, various land use modes, and other modules (Huynh et al., 2015). This ABM reproduces the daily life of the city quite accurately (Fig. 13). Planned extensions include traffic of freight transport and non-working trips of agent residents.

This research area was actively developing, within the international conferences dedicated to urban dynamics studied with the use of agent-based models. For example, one of the latest conferences on this topic — The 6th International Workshop on Agent-Based Modeling of Urban Systems — was held in May 021, and abstracts of selected reports are available at: http://modelling-urban-systems.com/abmus2021/proceedings/main.pdf

A common feature in this field is the use of geo-information technologies; here we would mention an aggregator site that collects information about projects implemented in this area: “*GIS and Agent-Based Modeling*.”[3]



(a) (b)

Fig. 13. Traffic density around the University of New South Wales at 8:00 am: (a) screenshot of the TransMob simulator; (b) screenshot of Google Traffic Map.

Source: Image from “Simulating transport and land use interdependencies for strategic urban planning — An agent based modeling approach” (Huynh et al., 2015).

[3] https://www.gisagents.org

9. COMPUTATIONAL RECONSTRUCTION OF HISTORICAL EPISODES

The Artificial Anasazi Project, origins were recounted in (Epstein, 2006) was collaboration between the Brookings Institution, the Santa Fe Institute, and the World Resources Institute. It sought to model the rise and fall of the American Kayenta Anasazi over the period 900 AD to 1350 AD, at which point this civilization vanished from its lands. For archaeologists, the central question was, why? On the model of Sugarscape (Epstein, Axtell, 1996), the project digitized the entire environmental history (hydrology, soil fertility, maize potential, drought severity) and settlement patterns of the Anasazi from data accumulated by the Tree Ring Laboratory at the University of Arizona. Then, Artificial Anasazi households were built, with ethnographically based nutritional requirements, and rules for the founding of new families and households. Left to their own devices, the Artificial Anasazi replicated the main population and spatial dynamics of the true history over the entire period, with populations tracking the rise and fall of environmental conditions. The model showed that the environment could have sustained a small population of Anasazi, pointing to a combination of purely environmental and social factors to explain their enigmatic abandonment of the Longhouse Valley study area (see (Axtell et al., 2002)). For a colorful popular account of the research in "*Nature*", see "*Life with the artificial Anasazi*" (Diamond, 2002). Note that agent-based archaeology has grown into a vibrant field (e.g., (Kohler, Gumerman, 2000)).

The Anasazi model has been replicated many times (Janssen, 2009). This is an important point. Not only are agent-based models frequently calibrated to data, they are also replicated. Indeed, it is a strong norm in the agent-based modeling community that code should be an open source. And, in fact, the open source libraries available are now extensive (e.g., Netlogo, OpenABM).

Ancient warfare. Ancient warfare is another area where the agent-based computational reconstruction of historical events is promising. An impressive example is "*Modelling medieval military logistics: An agent-based simulation of a Byzantine army on the march*" by (Murgatroyd et al., 2012). This is part of their larger modeling project, "Medieval Warfare on the Grid" (MWGrid). They write: "MWGrid seeks to study behaviour dynamics at a larger scale, involving tens of thousands of agents, all within the context of modelling logistical arrangements relating to the march of the Byzantine army to the battle of Manzikert (AD1071). The defeat of Emperor Romanus Diogenes' IV army at Manzikert was a key event in Byzantine history, resulting in the collapse of Byzantine power in central Anatolia" (Haldon, 2005).

Needless to say, in explaining this crucial military outcome, historians face many gaps in the data, notably regarding the size of the Byzantine army. Without the check of a model, a consensus can form around certain assumptions despite a lack of hard evidence. Models can function as checks on these assumptions. One notable example is the assumption that the Manzikert army of Emperor Romanus Diogenes IV numbered up to 100 thousand people. Is this plausble, given what *can* be reconstructed?

As the authors write, "This was a major logistical challenge that involved the largest Byzantine army in over 50 years travelling more than 700 miles across what is now part of the modern state of Turkey, from near Constantinople (modern Istanbul) to Manzikert (modern Malazgirt) just north of Lake Van" (Fig. 14).

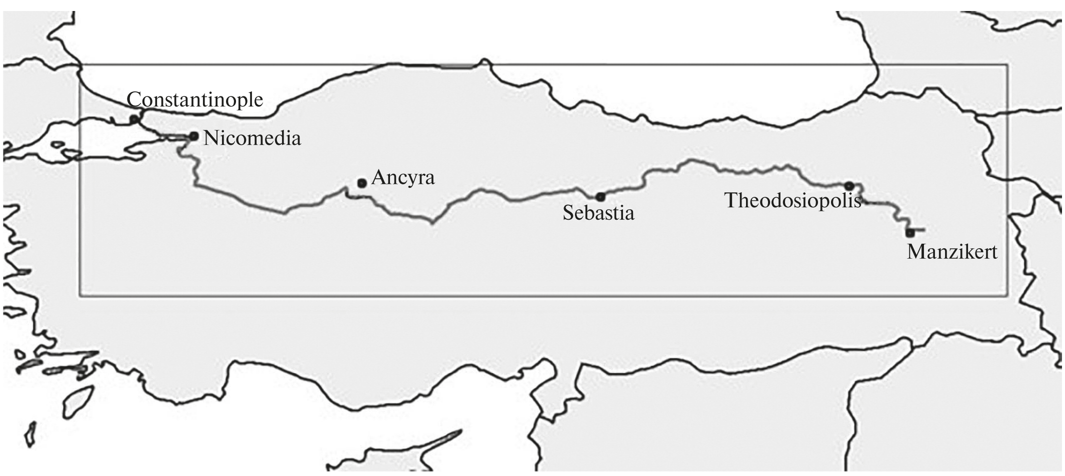


Fig. 14. Anatolia: possible route of a Byzantine army

Source: Image from "Modelling medieval military logistics: An agent-based simulation of a Byzantine army on the march" (Murgatroyd et al., 2012).

Through a very careful reconstruction of the landscape proper, the food supplies available from settlements along the route, cattle, grain and other logistical demands and constraints, their agent-based modeling (conducted at full population scale) calls the prevailing wisdom into question. And the difficulty of sustaining large armies over such great distances sheds new light on the calamitous defeat of the Byzantine army.

This kind of imperial over-reach has foundered on logistics more recently, the failed invasions of Russia by Napoleon and Hitler being examples. On the centrality of logistics in military history see Martin van Crevald "*Supplying War: Logistics from Wallenstein to Patton*" (Crevald, 1977). Agent-based models have also illuminated the size distribution of wars between states (Cederman, 2003).

10. SIMULATION OF CIVIL CONFLICT

Turning from inter-state to intra-state conflict, agent-based models have been used to explain revolutions and rebellions. Epstein's civil violence model has been replicated many times (Epstein, 2002). An implementation of it downloads with "Netlogo" was extended and calibrated empirically by (Lemos, 2017; Lemos, Coelho, Lopes, 2013). In the original model, there are civilian agents and cop agents. These agents move and interact on a landscape of sites.

Civilians can be actively rebellious or quiescent; they rebel if their grievance against the central authority exceeds their (risk-adjusted) likelihood of arrest.[4] A civilian estimates his arrest probability as the ratio of cops to active rebels within his vision. Specifically, he asks, "Were I to rebel, what would be the ratio of Cops to Actives within my vision (so the denominator can never be zero)."[5] Grievance is the product of economic hardship and the perceived illegitimacy of the regime. If grievance exceeds the arrest probability, the agent rebels. Otherwise, the one remains quiescent.

The theoretical model produces several stylized dynamics and counterintuitive results. Among the former are punctuated equilibrium in outbursts, and their spatially localized occurrence. A core experiment compares its two runs. In the first, the regime's legitimacy is reduced from its maximum (100) all the way to zero, but *in small increments*. Each time legitimacy falls incrementally, some agent's threshold is exceeded, and he rebels. But he rebels alone and is picked off. No rebellion occurs.

By contrast, if from the maximum of 100, legitimacy is reduced only to 80, *but in a single shock*, many agents go active at once, reducing the Cop-to-Active ratio for others, who then join and amplify the rebellion. It is not the absolute legitimacy reduction, but the shock that drives the rebellious cascade. Or, as S. Levitsky and D. Ziblatt warned us in their 2018 book, "*How Democracies Die*" (Levitsky, Ziblatt, 2018), it is precisely the slow incremental imperceptible erosion of liberties that requires vigilance.

11. RESEARCH ON SOCIAL NETWORKS

Social networks have long been recognized central in the study of group formation, information diffusion, and disease transmission, for example. Agent-based modeling is changing the study of social networks as well.

Researchers from the University of Surrey, in their paper "*Social Circles: A Simple Structure for Agent-Based Social Network Models*" built an agent-based framework for the creation of social networks with various topologies (Hamill, Gilbert, 2009). In addition to traditional network models (e.g., regular lattice, random network, small world network, scale-free network), their program uses a geometric property of circles (hence their title). As they write, "Taking the idea of social circles, it incorporates key aspects of large social networks such as low density, high clustering and assortativity of degree of connectivity. The model is very flexible and can be used to create a wide variety of artificial social worlds." Network topology can also be dynamic, as the duration of ties (friends, sexual partners) is heterogeneous and drawn from distributions, or generated endogenously (as in (Epstein, 2013)).

By contrast to the transient ties above, the GECS-Research Group on Experimental and Computational Sociology is focused on permanent changes in social network stucture related to the level of trust between market exchange participants. Their experiments on network topologies showed how dynamically changing networks can lead to increased collaboration between agents. Indeed, this suggests that dynamic networks generated endogenously can outperform those with a fixed topology (Bravo, Squazzoni, Boero, 2012).

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[4] Technically, grievance minus arrest probability must exceed a threshold, normally set to zero.

[5] This is misunderstood by several commentators, who correct for the alleged division by zero, which is not possible if the agent includes itself in the denominator, as stipulated.

An overview of agent-based models applied to study social networks is given by the German scholars M. Will, J. Groeneveld, K. Frank and B. Müller in "*Combining social network analysis and agent-based modeling to explore dynamics of human interaction: A review*" (Will et al., 2020). More than 120 scientific publications on this topic were analyzed. The central conclusion is: the quantitative analysis of causal relationships between agent behaviors and network structures can illuminate their coevolution.

12. ECONOMICS

Agent-based modeling is changing the field of economics, at scales from the micro to the macro. At the micro-scale, there is a strong effort to develop next-generation agents that are more realistic cognitively than the canonical rational (expected utility maximizing) actor of traditional economics and game theory. Well-established human departures from textbook rationality include: base rate neglect, asymmetric weighting of gains and losses (Prospect theory), framing effects, anchoring, conformity effects, confirmation bias, contagious fear, and violations of the standard preference axioms (e.g., 'more is preferred to less') as in the Ultimatum Game and other experiments studied in behavioral economics. Moreover, the cognitive underpinnings of these departures from rationality are being identified by neuroscientists in the field of Neuroeconomics (Glimcher, Fehr, 2013). Agent-based modelers are building these cognitive mechanisms into next-generation agents. One recent attempt to incorporate cognitive drivers into an advanced agent is Epstein's Agent-Zero (Epstein, 2013), discussed earlier.

At a far larger scale, one of the most famous agent economics projects is a massively parallel agent-based model of the European economy — EURACE (Europe Agent-based Computational Economics). This is a collaboration of scientists from eight research centers in Great Britain, Germany, France and Italy, as well as the 2001 Nobel Laureate in economics Joseph Stiglitz (Deissenberg, van der Hoog, Dawid, 2008).

There are three types of agents in the model — households (tens of millions), manufacturing enterprises (hundreds of thousands), and financial organizations (hundreds). Regulators (government, central bank, etc.) are specified as a set of restrictions for the agents listed above. The model includes five types of markets (consumer, investment, labor, financial, and credit). For greater realism, agents are geo-referenced and data for model initialization is presented in the form of a geographic information system, which also contains infrastructure facilities — roads, educational institutions, shops, etc.

The calculations using the EURACE basic module made it possible to assess the degree of impact of the quantitative easing mechanism (after the 2008 financial crisis) on the duration of the economic downturn and the effectiveness of this method of monetary policy in combination with fiscal measures (Raberto, Cincotti, Teglio, 2014; Teglio et al., 2015).

On another topic, markets and inequality, German sociologist Niklas Luhmann famously hypthesized that economic systems amplify, and must amplify, initial inequalities in order to persist (Luhmann, 1988, p. 112). His ideas were tested in an agent-based Luhmann Economy model by A. Fleischmann (Fleischmann, 2005). The author is very guarded in his support of Luhmann's hypothesis, writing that "This timeframe may be long enough (our example with only 36 agents, 3 goods altogether 900 in number, needed more than 150,000 trade runs) to justify Niklas Luhmann's observation that the economy produces unevenness from unevenness." Fleischmann goes on to note several important qualifications and to suggest extensions required for a more decisive test. This illustrates how ABMs are being used not just to generate hyothesies, but to challenge them.

Agent-based modeling of financial markets should be singled out as a separate area. The Web of Science and SCOPUS bibliographic databases show that hundreds of agent-based models related to financial markets have been developed. The use of this tool is illuminating the micro-mechanisms of financial market operation through simulation[6]. Among the most cited agent-based modelers of financial markets is Thomas Lux, a professor at Keele University (U.K.). In his recent public lecture "*Agent-Based Models in Finance: Foundations, Explanatory Power and Application*" delivered on February 3, 2021, he noted that over the past decade, the validation of agent-based finance models has progressed dramatically with our ability "to extract information on 'hidden' variables such as sentiment which constitutes a salient building block of such models."[7] For a thorough review of agent-based computational models in finance see (LeBaron, 2006). More recently, Blake LeBaron (LeBaron, 2019) obtained fundamental results relating the trajectory of stock indices to expansions in the strategy sets available to traders.

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[6] Agent-based modeling for central counterparty clearing risk, April, 2020. https://www2.deloitte.com/uk/en/pages/audit/articles/agent-based-modelling-for-central-clearing-risk.html

[7] https://wilmott.com/agent-based-models-in-finance-foundations-explanatory-power-and-applications

In 2016, Robert Axtell published a model in which 120 million agents self-organize into 6 million firms (Axtell, 2016). This built on his earlier agent model of firm formation dynamics, which successfully generated the observed Zipf distribution of firms' sizes in the US Economy, a statistical regularity that he also established and published in *"Science"* (Axtell, 2001). In contrast to classical models, which assume that the economy is in the state of equilibrium, in reality there is significant flux in almost all areas. For example, Axtell notes that (at the time of his publication) in the United States about 3 million employees find new jobs every month, i.e. about 1 of 40 employees change his job and 1 of 60 firms were closed. Indeed, for example, one of Axtell's results is: there are no stable equilibrium states in the labor market (Axtell, 2015). Yet, despite this turbulence at the micro level, the skewed Zipf distribution of firms' sizes is stationary.

The emergence of stationary distributions in the economy is the central concern of Econophysics, another recent development, which uses the tools of statistical mechanics to understand emergent phenomena in agent economies, with power law distributions in financial markets being a prominent topic. This approach was well-illustrated in "Colloquium: Statistical mechanics of money, wealth, and income" (Yakovenko, Rosser, 2009).

In this connection, a very interesting study was carried out by Robert Peckham (Peckham, 2013) at the University of Hong Kong. He investigated the spread of various kinds of infections (H1N1, H5N1, SARS, HIV/AIDS, etc.) *in conjunction with* the development of financial crises. This author identifies pairing these processes noting the similarity of their transmission mechanisms. His research indicates that problems in financial markets, conjoined with the spread of a pandemic, cause panic and economic instability, suggesting that the tools of epidemiology may offer economists promising avenues to "inoculate" agents against financial panics, often stimulated by speculators (the initial infectious agents).

According to the physicist, and chairman, and head of research at Capital Fund Management (Paris) Jean-Philippe Bouchaud (Agent-based economic models offer more realism. FT, 2018): "The study of '*complex physical systems'* made significant progress in the last 40 years and offers new ideas and methods. It is relevant for economics because it gained some success in modeling many systems exhibiting abrupt phenomena and tipping points that closely resemble crises. One of the best adapted tools to address these complex systems is agent-based models, which offers much more realism and flexibility than purely formal models from classical economics. Unlike these models, agent-based models are able to encapsulate the inherent 'human desires and misunderstandings' that lead to 'manias and panics.' Advanced economies are still dealing with the fallout from the 2008 crisis and economists still do not agree on its fundamental causes. We can certainly do better" (Bouchaud, 2018).

In applied economics, Agent Based Computational Economics (ABCE), should not go without mention. Leigh Tesfatsion, at Iowa State University, one of the pioneers in this sphere, defines the process of building models according to the ACE methodology as analogous to laboratory biological experiments with the use of a Petri dish. It is assumed that the developer sets the initial conditions and agent rules for the modeled system including its goals. Then the dynamics of this virtual world are generated endogenously, exclusively through the interaction of its agent constituents. L. Tesfatsion emphasizes that the ACE approach was developed as an addition to modern economic theory but without presupposing classic rationality, optimal choice, or equilibrium (Tesfatsion, 2002). For example, ACE posits unpredictable behavior by agents in relation to one other, and also models their adaptation to exogenous macro shocks. Many researchers are involved in the ACE project with several results available at http://www2.econ.iastate.edu/tesfatsi/ace.htm.

Since Alan Kirman's influential critique of the Representative Agent model of macroeconomics (Kirman, 1992), there was an attempt to develop Heterogeneous Agent Macroeconomics.

Included in this general movement, there are some attempts to relax several assumptions of Computable General Equilibrium Theory (CGET) and its extension, Dynamic Stochastic General Equilibrium Theory (DSGET), to obtain more realistic results. Central to this is a replacement of the single Representative Agent of macroeconomics with a larger number of heterogeneous agents. Diverse efforts were collected in "*Computational economics: Heterogeneous agent modeling*" (Hommes, LeBaron, 2018).

All of this led to several highly visible popular calls for agent modeling in Economics. In the 2003 article "*Agents of creation*"[8] in the "The Economist", agent-based models were advocated as a new tool for modeling complex systems, an appeal reiterated in the 2010 "*The Economist*" article "*Agents of change*."[9] There, agents are considered as an alternative to dynamic stochastic general economic equilibrium models. In an editorial in the

[8] Article from "*The Economist*" magazine published in 2003: https://www.economist.com/science-and-technology/2003/10/09/agents-of-creation

[9] Article from "*The Economist*" magazine, published in 2010: https://www.economist.com/finance-and-economics/2010/07/22/agents-of-change

journal "*Nature*", agent-based modeling was advocated as a promising tool for studying complex socio-economic processes including markets (Farmer, Foley, 2009).

Agent-based modeling in the private sector

The agent-based approach is also used in modeling business processes. In their paper "*Agent-based modeling in marketing: Guidelines for rigor*" (Rand, Rust, 2011) discussed agent-based applications. They wrote: "Agent-based modeling can illuminate how complex marketing phenomena emerge from simple decision rules. Marketing phenomena that are too complex for conventional analytical or empirical approaches can often be modeled using this approach. Agent-based modeling investigates aggregate phenomena by simulating the behavior of individual 'agents' such as consumers or organizations". The authors used an agent-based model to replicate the Bass model of the diffusion of innovations. They also showed how extensions of the Bass model could be executed with a rigorous agent-based approach, but difficult to implement using traditional marketing research techniques.

At a more detailed level, researchers (Halaška, Šperka, 2018) from Silesian University (Czech Republic) with colleagues from Denmark developed a Multi-Agent Resource-Event-Agent (MAREA) framework integrated with an ERP (Enterprise Resource Planning) system. Their paper, "*Is there a need for agent-based modeling and simulation in business process management?*" presents the results of a model simulating a trading company selling computer cables. The impact of changes in a set of various kinds of input resources on the company's financial results was specifically assessed. Calculations showed that even small mico-level input changes have a statistically significant effect on the company's aggregate output and financial performance.

Software-analytical complex "MÖBIUS"

Over the course of many years, the Central Economics and Mathematics Institute of the Russian Academy of Sciences has developed methodological principles for constructing complex software-analytical complexes combining approaches to model. socio-economic processes, agent-based being prominent. Evolutionarily, CEMI RAS built a model complex "MÖBIUS"[10], which incorporated the advantages of different approaches and consisted of several blocks (Fig. 15).

All blocks of the MÖBIUS complex, although they were originally developed separately, are closely related to one another and represented a single integrated entity. The demographic agent module is the basic

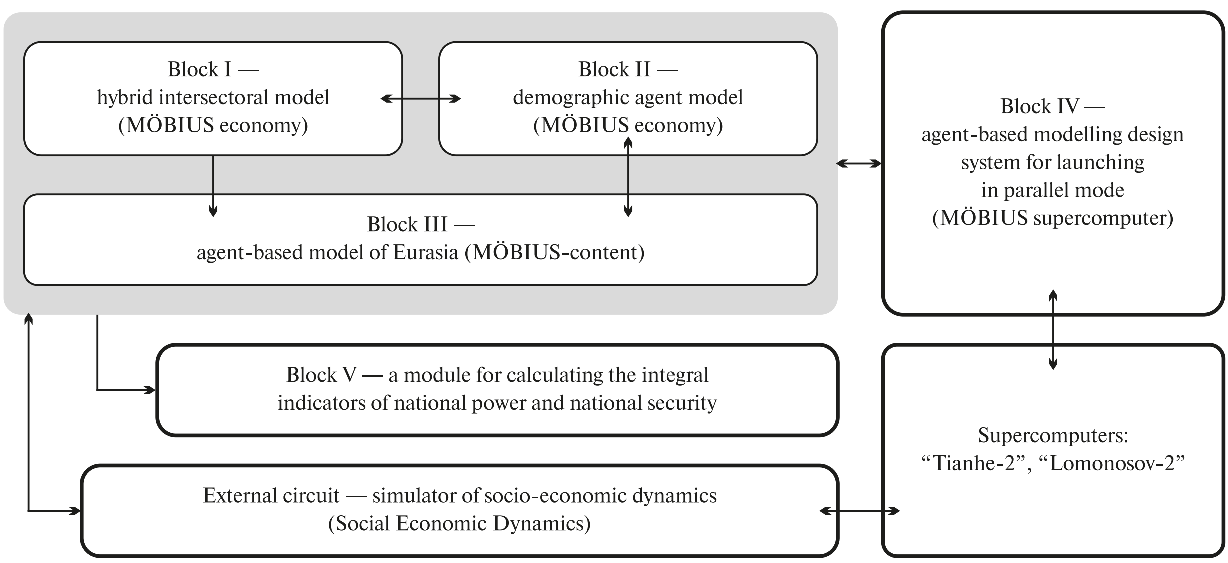

Fig. 15. Schema of the software-analytical complex "MÖBIUS"

Source: Image from "Software and analytical complex 'MÖBIUS' — a tool for planning, monitoring and forecasting the socio-economic system of Russia" (Bakhtizin, Ilyin, Khabriev et al., 2020).

[10] The name of the software-analytical complex is associated with two circumstances. First, the Möbius strip is the main symbol of the Central Economics and Mathematics Institute of the Russian Academy of Sciences, and its high relief adorns the Institute building. Secondly, this sign is the physical embodiment of infinity, which corresponds to the scale of the computational capabilities of one of the modules — "MÖBIUS-supercomputer", capable of technically implementing models with about 10^9 agents on the world's most productive systems (including exascale supercomputers).

element for the agent-based model of the Eurasian continent, and also governs the dynamics of households for the inter-sectoral block “MÖBIUS-economy.” This, in turn, is linked to the Eurasian scale model. To speed up the calculations, the “MÖBIUS-supercomputer” system can be connected to the tools which automatically distribute the executable program code over a user-specified number of processors for parallel execution (Bakhtizin et al., 2020).

Diverse calculations were carried out using MÖBIUS, including the following:

- forecast of changes in the age-sex structure of the population in the Russian regions (Bakhtizin et al., 2021);
- demographic changes in the European Union, taking into account such important factors, as the attitudes of people, influencing their reproductive behavior, as well as in-migration (Makarov et al., 2019);
- dynamics of labor migration between Russia and China (Makarov et al., 2017);
- the level of pollution in some regions of the Russian Federation, taking into account the spatial location of industries and stationary sources of emissions (Makarov, Bakhtizin, Sushko, 2020);
- forecast of the main macroeconomic indicators of Russia and its constituent entities as a result of changes in the rates of basic taxes, budget subsidies, the amount of money supply, key interest rate, prices for basic energy resources, dollar exchange rate, and other variables (Makarov, Bakhtizin, Khabriev, 2018).

A separate block is a module for calculating integral indicators of national power and national security for 193 UN member states. The weights of several dozen selected factors were calculated using methods of multivariate statistics.

Conclusion

The models described in this paper are a small part of the worldwide scientific and practical developments in the field of agent-based modelling and related areas. We have attempted to give an impression of the vast range of application areas (epidemiology, economics, demography, environment, urban dynamics, history, conflict, disaster alert), scales (from cellular to local to urban to planetary), and goals (simple exploratory models, optimization, generative explanation, forecasting, policy) of agent-based modeling. Agent-based models offer a new and powerful alternative, or complement, to traditional mathematical methods for addressing complex challenges. Ubiquitous processes in which heterogeneous individuals interact in space and in networks, driven by internal cognitive and external social, dynamics invite the use of agent-based models.

There are specialized journals publishing agent-based models developed for various spheres (for example, “*Journal of Artificial Societies and Social Simulation*”), and a growing number of Centers internationally. At our Centers specifically, on the Russian side, an international online-seminar “Artificial societies and information technologies”[11] was held at the premises of CEMI RAS since 2020. Scientists from many countries made reports on the developed agent-based models during the first year of its operation:

1) Russia (over 10 organizations);

2) China (Guangdong Science & Technology Infrastructure Center, Milestone software company, Joint Center for Mathematical and Economic Research, Sichuan Normal University, Guangdong University of Finance & Economics, Shanghai company Tianjin, University of Chinese Academy of Sciences);

3) Switzerland (Swiss Federal Institute of Technology, Zurich);

4) Germany (Technical University of Munich, University of Hamburg);

5) India (National Institute of Technology Durgapur, West Bengal);

6) Bulgaria (American University in Bulgaria (AUBG));

7) Kazakhstan (L.N. Gumilyov Eurasian National University, Nur-Sultan);

8) Ireland (University College, Dublin);

9) France (Institute National de la Recherche Agronomique);

10) Korea (Korea Advanced Institute of Science and Technology, Department of Industrial and Systems Engineering);

11) Canada (University of Alberta);

[11] https://www.abm-online.org

12) Brazil (Institute for Applied Economic Research, Pontifical Catholic University of Rio de Janeiro, Federal University of Juiz de Fora);

13) Colombia (Pontificia Universidad Javeriana);

14) Sweden (The Institute for Analytical Sociology);

15) Japan (Computational design studio ATLV);

16) United Kingdom (Simudyne) etc.

In the US, Epstein's New York University (NYU) Agent-Based Modeling Lab offers a two-semester curriculum, plus an online Introductory Course, on Agent-Based Modeling. NYU also held International conferences on Agent-based modeling in global health and recently formalized collaboration with the New Approaches to Economic Challenges (NAEC) initiative at the OECD in Paris to apply *Agent_Zero* epidemiology to economic and financial dynamics. In collaboration with NYU's Courant Institute for Mathematical Science, Epstein plans to build very large-scale epidemic models populated with cognitively plausible agents to forecast the effects of behavioral adaptation on global pandemic dynamics.

A cautionary note

While the future of agent-based modeling is bright, an important imperative — in terms of model transparency and statistical testing — is to follow Einstein's admonition to keep the models "as simple as possible, but no simpler." Freely adjustable parameters and agent decision rules should be added only if they truly add explanatory power. It is too easy to make complex agent models using the friendly development environments that have emerged of late. This temptation need be avoided. Even with elegant parameter sampling approaches (a simple example being Latin Hypercube), the evaluation of large-scale models with many parameters, each of which assuming many values, with many stochastic realizations for each combination quickly becomes computationally daunting. While large mathematical models are rarely interpreted analytically, large agent-based ones should be, in this sense, "interpretable computationally" if they are to fill the gap.

Important directions and challenges

The main goal of this paper was to summarize selected developments in artificial societies and agent-based modeling and to suggest how this fundamentally new toolkit can contribute to solving some of the most complex scientific and practical problems of our time.

Clearly, the entire field of Agent-Based Modeling expanded dramatically over the last quarter of a century, with applications across a remarkable array of fields, at scales ranging from molecular to global. The early (ca. 1990s) computational challenges to large-scale explanatory modeling have been largely overcome, with real-time policy modeling visible on the horizon. Of the many fruitful directions the field might take, we feel that three are especially effective.

One of them is to continue building models at the scale of entire economic, ecological, and epidemiologic regions — whether these correspond to the present political units or not. Obviously, pandemic diseases like COVID-19 are oblivious to political boundaries in a highly connected world, but so are climate changes and other forces.

Second, many of these phenomena are coupled. Disease epidemics affect economic dynamics. Climate change pushes mosquito ranges north, driving new diseases to mega-cities of the northern hemisphere. How would urbanization affect access to health and economic opportunity, as well as the political stability? These are important questions. While the data landscape is changing dramatically with the advent of massive global and social media, we cannot wait for "validation data" to these models. They are essential headlights in a highly uncertain future.

Third, we need propagating models with cognitively plausible agents. In some settings, human behavior is canonically rational, with well-informed individuals maximizing utility subject to budget constraints. But in other settings, non-deliberative emotional forces, like contagious fear, can eclipse deliberations, igniting collective behaviors like financial panics, ethnic violence, and the refusal of safe and effective vaccines (which WHO ranks in the top ten threats to global health) that are very far from optimal.

While focused calibrated agent-based models will continue to advance specific fields, we urge the development of coupled large-scale agent-based models populated by cognitively plausible agents. At the very least, these can inspire an integrated vision of our interconnected future and perhaps help us shape it in equitable and peaceful directions.

REFERENCES/СПИСОК ЛИТЕРАТУРЫ

Agents of change (2010). Conventional economic models failed to foresee the financial crisis. Could agent-based modelling do better? *The Economist,* July 24. Available at: https://www.economist.com/finance-and-economics/2010/07/22/agents-of-change

Agents of creation (2003). Artificial "agents" can model complex systems. *The Economist,* October 11. Available at: https://www.economist.com/science-and-technology/2003/10/09/agents-of-creation

Axtell R.L., Epstein J.M., Dean J.S., Gumerman G.J., Swedlund A.C., Harburger J., Chakravarty S., Hammond R., Parker J., Parker M. (2002). Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. *Proceedings of the National Academy of Sciences*, May, 99 (suppl. 3), 7275–7279. DOI: 10.1073/pnas.092080799

Axtell R.L. (2015). Endogenous dynamics of multi-agent firms. *SSRN Electronic Journal*. DOI: 10.2139/ssrn.2827059

Axtell R.L. (2016). 120 million agents self-organize into 6 million firms: A model of the U.S. private sector. In: *Proceedings of the 2016 International Conference on Autonomous Agents & Multiagent Systems* (AAMAS '16). International Foundation for Autonomous Agents and Multiagent Systems. Richland, SC, 806–816. Available at: https://dl.acm.org/doi/10.5555/2936924.2937042

Axtell R.L. (2001). Zipf distribution of U.S. Firm Sizes. *Science*, 293 (5536), 1818–1820.

Bakhtizin A.R., Ilyin N.I., Khabriev B.R., Makarov V.L., Sushko E.D. (2020). Software and analytical complex "MÖBIUS" — a tool for planning, monitoring and forecasting the socio-economic system of Russia. *Artificial Societies*, 15 (4). DOI: 10.18254/S207751800012303-2 (in Russian). [**Бахтизин А.Р., Ильин Н.И., Хабриев Б.Р., Макаров В.Л., Сушко Е.Д.** (2020). Программно-аналитический комплекс «МЁБИУС» — инструмент планирования, мониторинга и прогнозирования социально-экономической системы России // *Искусственные общества*. Т. 15. № 4. DOI: 10.18254/S207751800012303-2]

Bakhtizin A.R., Makarov V.L., Maksakov A.A., Sushko E.D. (2021). Demographic agent-based model of Russia and assessment of its applicability for solving practical management problems. *Artificial Societies,* 16, 2 (in Russian). DOI: 10.18254/S207751800015357–1 [**Бахтизин А.Р., Макаров В.Л., Максаков А.А., Сушко Е.Д.** (2021). Демографическая агент-ориентированная модель России и оценка ее применимости для решения практических управленческих задач // *Искусственные общества*. Т. 16. Вып. 2. DOI: 10.18254/S207751800015357-1]

Bravo G., Squazzoni F., Boero R. (2012). Trust and partner selection in social networks: An experimentally grounded model. *Social Networks*, 34, 4, 481–492. DOI: 10.1016/j.socnet.2012.03.001

Cederman L.E. (2003). Modeling the size of wars: From billiard balls to sand piles. *American Political Science Review*, 97 (1), 135–150.

Crevald M. van (1977). Supplying war: Logistics from Wallenstein to Patton. New York: Cambridge University Press.

Deissenberg C., Hoog S. van der, Dawid H. (2008). EURACE: A massively parallel agent-based model of the European economy. *Applied Mathematics and Computation*, 204, 541–552. DOI: 10.1016/j.amc.2008.05.116

Diamond J. (2002). Life with the artificial Anasazi. *Nature,* 419, 567–568. DOI: 10.1038/419567a

Dou Y., Millington J.D.A., Bicudo Da Silva R.F., McCord P., Viña A., Song Q., Yu Q., Wu W., Batistella M., Moran E., Liu J. (2019). Land-use changes across distant places: Design of a telecoupled agent-based model. *Journal of Land Use Science*, 14, 3, 191–209. DOI: 10.1080/1747423X.2019.1687769

Epstein J.M. (2013). *Agent_Zero: Toward neurocognitive foundations for generative social science*. Princeton: Princeton University Press. 249 p.

Epstein J.M. (2002). Modeling civil violence: An agent-based computational approach. *Proceedings of the National Academy of Sciences.* May, 99 (suppl. 3), 7243–7250. DOI: 10.1073/pnas.092080199

Epstein J.M. (2006). *Generative social science: Studies in agent-based computational modeling*. Princeton: Princeton University Press. 352 p.

Epstein J.M., Axtell R. (1996). *Growing artificial societies: Social science from the bottom up*. Washington: Brookings Institution Press. The MIT Press.

Farmer J., Foley D. (2009). The economy needs agent-based modelling. *Nature*, 460, 685–686. DOI: 10.1038/460685a

Fleischmann A. (2005). A model for a simple Luhmann economy. *Journal of Artificial Societies and Social Simulation*, 8, 2. Available at: https://www.jasss.org/8/2/4.html

Fosset P., Banos A., Beck E., Chardonnel S., Lang C., Marilleau N., Piombini A., Leysens T., Conesa A., Andre-Poyaud I., Thevenin T. (2016). Exploring intra-urban accessibility and impacts of pollution policies with an agent-based simulation platform: GaMiroD. *Systems*, 4 (1), 5. DOI: 10.3390/systems4010005

Glimcher P.W., Fehr E. (Eds.) (2013). *Neuroeconomics: Decision making and the brain*. Second Edition. Academic Press. 577 p. ISBN-13: 978-0124160088.

Halaška M., Šperka R. (2018). Is there a need for agent-based modelling and simulation in business process management? *Organizacija*, 51 (4), 255–269. DOI: 10.2478/orga-2018-0019

Haldon J.F. (Ed.) (2005). General issues in the study of medieval logistics: Sources, problems, methodologies. Leiden, Boston: Brill.

Hamill L., Gilbert N. (2009). Social circles: A simple structure for agent-based social network models. *Journal of Artificial Societies and Social Simulation*, 12 (2), 3. Available at: http://jasss.soc.surrey.ac.uk/12/2/3.html

Hommes C., LeBaron B. (Eds.) (2018). *Computational economics: Heterogeneous agent modeling*. Handbook in Economics. Elsevier.

Huynh N., Perez P., Berryman M., Barthélemy J. (2015). Simulating transport and land use interdependencies for strategic urban planning — an agent based modelling approach. *Systems*, 3 (4), 177–210. DOI: 10.3390/systems3040177

Kirman A.P. (1992). Whom or what does the representative individual represent? *Journal of Economic Perspectives*, 6 (2), 117–136.

Kohler T.A., Gumerman G.J. (2000). *Dynamics in human and primate societies: Agent-based modeling of social and spatial processes*. Oxford University Press. Published to Oxford Scholarship Online. November. DOI: 10.1093/oso/9780195131673.001.0001

Lansing J.S., Kremer J.N. (1993). Emergent properties of Balinese water temple networks: 2 coadaptation on a rugged fitness landscape. *American Anthropologist*, 95, 97–114.

LeBaron B. (2006). Agent-based Computational Finance. In: H.M. Amman, D.A. Kendrick, J. Rust (Eds). *Handbook of Computational Economics*. Vol. 2. Ch. 24, 1187–1233. Elsevier. Available at: https://EconPapers.repec.org/RePEc: eee: hecchp:2–24

LeBaron B. (2019). Microconsistency in simple empirical agent-based financial models. *Computational Economics*, 1, 19. DOI: 10.1007/s10614-019-09917-8

Lemos C. (2017). *Agent-based modeling of social conflict: From mechanisms to complex behavior*. Berlin: Springer Verlag.

Lemos C., Coelho H., Lopes R.J. (2013). Agent-based modeling of social conflict, civil violence and revolution: State-of-the-art-review and further prospects. *CEUR Workshop Proceedings,* 1113, 124–138.

Levitsky S., Ziblatt D. (2018). *How democracies die*. New York: Broadway Books.

Luhmann N. (1988). *Die Wirtschaft der Gesellschaft (Suhrkamp taschenbuch wissenschaft)*. Frankfurt: Suhrkamp Verlag. 112 p.

Makarov V.L., Bakhtizin A.R., Beklaryan G.L., Akopov A.S. (2019). Development of software framework for large-scale agent-based modeling of complex social systems. *Software Engineering (Programmnaya Ingeneria)*, 10, 4, 167–177 (in Russian). [**Макаров В.Л., Бахтизин А.Р., Бекларян Г.Л., Акопов А.С.** (2019). Разработка программной платформы для крупномасштабного агент-ориентированного моделирования сложных социальных систем // *Программная инженерия*. Т. 10. № 4. С. 167–177. DOI: 10.17587/prin.10.167-177]

Makarov V.L., Bakhtizin A.R., Khabriev B.R. (2018). Performance evaluation of the mechanisms strengthening the state sovereignty of Russia. *Finance: Theory and Practice*, 22 (5), 6–26. DOI: 10.26794/2587-5671-2018-22-5-6-26 (in Russian). [**Макаров В.Л., Бахтизин А.Р., Хабриев Б.Р.** (2018). Оценка эффективности механизмов укрепления государственного суверенитета России // *Финансы: теория и практика*. Т. 22. № 5. С. 6–26. DOI: 10.26794/2587-5671-2018-22-5-6-26]

Makarov V.L, Bakhtizin A.R., Sushko E.D., Ageeva A.F. (2017). Agent-based approach for modelling the labour migration from China to Russia. *Economy of Region*, 13, 331–341. DOI: 10.17059/2017-2-1 (in Russian). [**Макаров В.Л., Бахтизин А.Р., Сушко Е.Д., Агеева А.Ф.** (2017). Агент-ориентированный подход при моделировании трудовой миграции из Китая в Россию // *Экономика региона*. Т. 13. Вып. 2. С. 331–341. DOI: 10.17059/2017-2-1]

Makarov V.L., Bakhtizin A.R., Sushko E.D. (2020). Agent-based model as a tool for controlling environment of the region. *Journal of the New Economic Association*, 45, 151–171. DOI: 10.31737/2221-2264-2020-45-1-6 (in Russian). [**Макаров В.Л., Бахтизин А.Р., Сушко Е.Д.** (2020). Агент-ориентированная модель как инструмент регулирования экономики // *Журнал Новой экономической ассоциации*. № 45. С. 151–1712. DOI: 10.31737/2221-2264-2020-45-1-6]

Matthews R.B., Gilbert N.G., Roach A., Polhill J.G., Gotts N.M. (2007). Agent-based land-use models: A review of applications. *Landscape Ecology*, 22, 1447–1459. DOI: 10.1007/s10980-007-9135-1

Murgatroyd P., Craenen B., Theodoropoulos G., Gaffney V., Haldon J. (2012). Modelling medieval military logistics: An agent-based simulation of a Byzantine army on the march. *Computational and Mathematical Organization Theory*, December, 18, 4, 488–506.

Murray-Rust D., Rieser V., Robinson D.T., Miličič V., Rounsevell M. (2013). Agent-based modelling of land use dynamics and residential quality of life for future scenarios. *Environmental Modelling & Software*, 46, 75–89. DOI: 10.1016/j.envsoft.2013.02.011

Nabinejad S., Schüttrumpf H. (2017). An agent-based model for land use policies in coastal areas. *Coastal Engineering Proceedings*, 1 (35), Management. 9. DOI: 10.9753/icce.v35.management.9

Peckham R. (2013). Economies of contagion: Financial crisis and pandemic. *Economy and Society*, 42, 2, 226–248. DOI: 10.1080/03085147.2012.718626

Polhill J.G., Parker D., Brown D., Grimm V. (2008). Using the ODD protocol for describing three agent-based social simulation models of land-use change. *Journal of Artificial Societies and Social Simulation*, 11 (2), 3. Available at: http://jasss.soc.surrey.ac.uk/11/2/3.html

Raberto M., Cincotti S., Teglio A. (2014). *Economic policy and the financial crisis. Routledge Frontiers of Political Economy*. Taylor & Francis, ch. 9.

Rand W., Rust R.T. (2011). Agent-based modeling in marketing: Guidelines for rigor. *International Journal of Research in Marketing*, 28, 3, September, 181–193. DOI: 10.1016/j.ijresmar.2011.04.002

Stepanenko V.M., Bopape M.J., Glazunov A.V., Gritsun A.S., Lykosov V.N., Mortikov E.V., Porto F., Rivin G.S., Sithole H., Tolstykh M.A., Vilfand R.M., Volodin E.M., Voevodin V.V. (2020). *HPC and Weather/Climate/Environment applications: Global challenges and opportunities for BRICS-cooperation*. Presentation on 4th Meeting of the BRICS Working group on Information and Communication Technology and High Performance Computing. Nizhny Novgorod, Russia, 2020 October 8–9 Available at: https://istina.msu.ru/conferences/presentations/338451642/

Teglio A., Mazzocchetti A., Ponta L., Raberto M., Cincotti S. (2015). *Budgetary rigor with stimulus in lean times: Policy advices from an agent-based model*. Working Papers 2015/04. Economics Department. Universitat Jaume I, Castellón (Spain). Available at: https://ideas.repec.org/p/jau/wpaper/2015-07.html

Tesfatsion L. (2002). Agent-based computational economics: Modelling economies as complex adaptive systems. December. Available at: http://www.econ.iastate.edu/tesfatsi (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.64.7064&rep=rep1&type=pdf).

Will M., Groeneveld J., Frank K., Müller B. (2020). Combining social network analysis and agent-based modelling to explore dynamics of human interaction: A review. *Socio-Environmental Systems Modelling*, 2, 16325. DOI: 10.18174/sesmo.2020a16325

Yakovenko V.M., Rosser J.B. (2009). Colloquium: Statistical mechanics of money, wealth, and income. *Rev. Mod. Phys*. 81, 1703 (December 2).

Агент-ориентированное моделирование для сложного мира. Часть 2

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Аннотация. Основная цель статьи состоит в обобщении избранных разработок в области искусственных обществ и агент-ориентированного моделирования и определении того, как этот принципиально новый инструментарий может способствовать решению некоторых из самых сложных научных и практических проблем нашего времени. Сфера применения агентного моделирования значительно расширилась за последнюю четверть века, вобрав множество направлений в самых разных масштабах — от молекулярного до глобального. Описанные в статье модели являются лишь небольшой частью накопленных в мире научных и практических разработок в сфере агент-ориентированного моделирования. Дается представление о широком спектре областей применения моделей этого класса (эпидемиология, экономика, демография, окружающая среда, городская динамика, история, конфликты, стихийные бедствия и др.), масштабах использования (от биологических клеток до планетарного уровня) и целях разработки (исследовательских, генерации искусственных обществ, решения оптимизационных задач, прогнозирования, оценки геополитических сценариев и т.д.). Агент-ориентированные модели предлагают, с одной стороны, новую и мощную альтернативу, а с другой, дополняют традиционные математические методы решения сложных задач.

Ключевые слова: агент-ориентированные модели, эпидемиология, пешеходное движение, демографические процессы, транспортные системы, экологическое прогнозирование, землепользование, городская динамика, исторические эпизоды, моделирование конфликтов, социальные сети, экономические системы.

Классификация JEL: C63, D91.

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