AGENT DYNAMICS MODEL OF ECONOMIC SYSTEM WITH LIMITED RESOURCES

E. A. Kalashnikova*

1. Introduction

One of the most common ways to investigate complex-organized dynamic systems is computer simulation. Methods of computer simulation are generally used in cases where there are difficulties in developing a strict mathematical model of the studied object or it has too many links between its elements, or a variety of nonlinear constraints, a huge number of parameters, etc. Simulation models, in contrast to the analytic ones, are not a closed set of equations, but an extended scheme of the object under study with known structure and principles of behavior.

However, traditional approaches to computer simulation of enterprises, products, customers, partners etc. consider them as passive applications/resources in a process. For example, models based on system dynamics include many assumptions, such as, “we have 120 employees, they can develop about 20 new products per year,” or “we have 1,200 trucks, they can carry a certain amount of cargo per month, and 5 percent of them must be written off every year and must be replaced”. These methods are much better than analytical modeling regarding their ability to examine the dynamic of the system, various non-linearity, but they ignore the fact that all these people, projects, products, equipment and assets are different.

In a real economy, all these entities have their own history, intentions, desires, properties, and complex relationships. For example, people may have different careers and income, enterprises may have different productivity; projects may interact and compete or may depend on one another; consumers may consult with members of their family before making a purchasing decision.

Agent-based modeling is a relatively new (1990–2000) direction in simulations, which has not such restrictions, because it focuses immediately on individual objects, on their behavior and communication. Agent model is a set of interacting active entities (agents) that represent objects and their relationships taken from the real world. Each agent is completely autonomous and independent: it makes decisive actions; it meets other agents; agents are able to make decisions, to move, and to adapt to the environment (evolve), etc. [1]

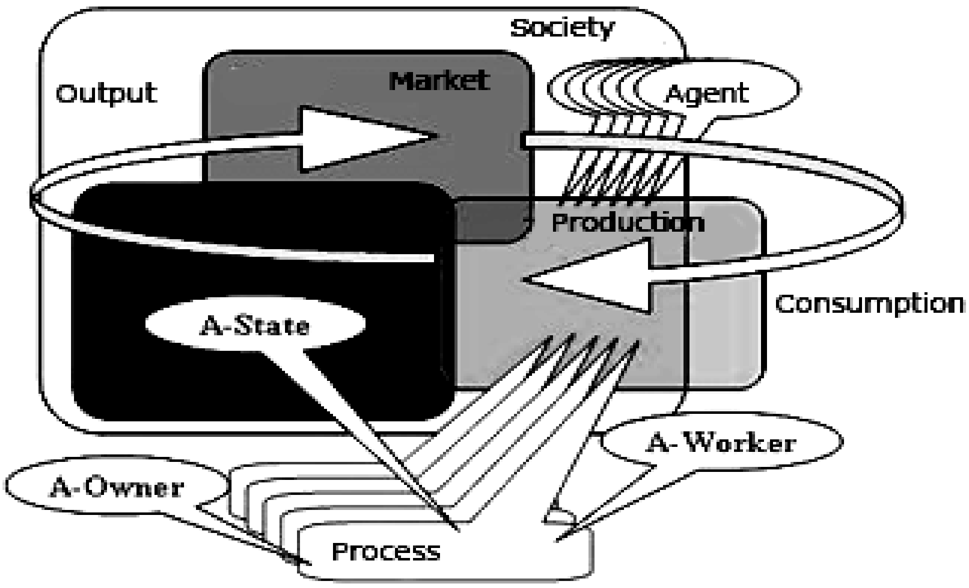
Multi-agent models are normally used in the study of decentralized systems. Global rules and laws do not determine the dynamics of functioning of such systems, but on the contrary, these global rules and laws are the result of the activity of individual members of the group. The purpose of agent-based models is to get an idea about these global rules, the general behavior of the system, based on the assumptions about the individual, the private behavior of its individual active objects, and the interaction of these objects in the system.

The most promising direction in agent-based modeling is the use of hybrid models. Here agents act on the background of environment, which is modeled by non-agent means, for example, within so called system dynamics approach [2]. Many modern means of computer simulation [3] support agent-based modeling in combination with system dynamics and other approaches, which give the possibility to develop effective hybrid models of complex systems including economic systems.

The aim of this article is to discuss and illustrate new opportunities offered by the agent-based modeling within a certain hybrid model architecture called agent dynamics approach [2]. The basics of the agent dynamics modeling are outlined in the next section, and the following sections examples of its implementation in the AnyLogic environment [3] are provided.

* © E. A. Kalashnikova; postgraduate student; Cybernetics Department; Odessa National Economics University; E-mail: <helenaube@gmail.com>.

Fig. 1. Agent dynamics model of a closed economy



2. Von Neumann model

The basic idea of the agent dynamics simulation (ADS) is combining of the classical von Neumann model of an expanding economy [4] as a background for the agent-based modeling. Using this approach to construct a hybrid model gives the possibility to correct many well-known shortcomings of the classical von Neumann model and apply the ADS approach in solving many real economic modeling problems.

Von Neumann model [4] is a model of an economy, in which all the output and expenses increase in the same proportion. The model is closed. That means all outputs of one period become expenses of the next period. It does not use primary factors and consumption is treated as a kind of expenses in the technological process, so all the expenses are reproducible, and there is no need to consider the primary resources.

The model assumes that the real level of wages corresponds to the minimum subsistence level, and any excess income is reinvested, real wages and incomes have residual nature.

The model describes the economy characterized by a linear technology of production processes. Balanced economy contains *m* processes producing and consuming *n* products. In the matrix notation, the economic dynamics within the von Neumann model is reduced to two fundamental balance equations written in discrete time:

$$\mathbf{y}(t)\mathbf{A}\mathbf{x}(t+1) = \mathbf{y}(t)\mathbf{B}\mathbf{x}(t) \quad (1)$$

$$\mathbf{y}(t+1)\mathbf{B}\mathbf{x}(t) = \mathbf{y}(t)\mathbf{A}\mathbf{x}(t) \quad (2)$$

Here vector $\mathbf{x} = \{x_1, x_2, ..., x_m\}$ describes intensities of all processes, and vector $\mathbf{y} = \{y_1, y_2, ..., y_n\}$ represents prices of all products in the current period, **A** and **B** are matrices of consumption and production of all products by these processes [4].

Equation (1) is a general condition of the material balance (the current output is consumed in the next period), and the equation (2) is the equation of the financial balance (current expenses must be reimbursed in the following period).

Von Neumann model is a rather general model of a closed balanced economy but it does not contain any assumptions about the driving forces of the economy (the way of production and exchange; motives and preferences determining the behavior of individual economic agents).

Therefore, the equations of the dynamics of individual processes and changes of prices for some products cannot be derived and uniquely defined from the von Neumann balance equations.

3. Agent dynamics approach

The economic theory has two main approaches for analyzing and modeling of economic systems. Microeconomic approach is based on a detailed study of the minimal elements of the economic system, which have all the features necessary for an economic subject (for example, a company).

Macroeconomic approach, on the contrary, describes economic processes in average, using aggregated indicators, which characterize a set of interacting economic objects, which constitute together for example a national or global economy. ADS modeling links these two approaches, combining von Neumann economic dynamics at macro-level, and micro-economic dynamics of the individual processes and prices of individual products.

For this purpose, various types of agents are involved in ADS (A-Owner, A-Worker, A-State, etc.), interacting with each other and with von Neumann dynamic processes. Fig. 1 illustrates the general scheme of the ADS economy, the correspondence between von Neumann dynamic processes and A-Owner, A-Worker and A-State agents.

Within ADS, the system of equations (1)–(2) is replaced by a somewhat more detailed set of equations, which are related to each specific process and each specific product. Nevertheless, the solution of this system is consistent [2] with balance equations (1) and (2).

The mathematical formulation of the ADS equations in discrete time includes equations for increments of the individual processes intensities $(j = 1,..,m)$:

$$\frac{\Delta x_j}{x_j} = \varepsilon \sum_{i=1}^{n} \delta_{ij} \alpha_i + (1-\varepsilon)\beta_j , \tag{3}$$

and equations of dynamics of price increments for each product $(i = 1,..,n)$:

$$\frac{\Delta y_i}{y_i} = \sigma \sum_{j=1}^{m} \frac{\gamma_{ij}}{\beta_j} + (1-\sigma)\frac{1}{\alpha_i} \tag{4}$$

Here α_i denotes the change of output of *i*-th product:

$$\alpha_i = \frac{\sum_{k=1}^{m} b_{ik} x_k}{\sum_{k=1}^{m} \alpha_{ik} x_k} - 1 \tag{5}$$

and β_j is the profit factor of *j*-th process:

$$\beta_j = \frac{\sum_{k=1}^{n} y_k b_{kj}}{\sum_{k=1}^{n} y_k \alpha_{kj}} - 1 , \tag{6}$$

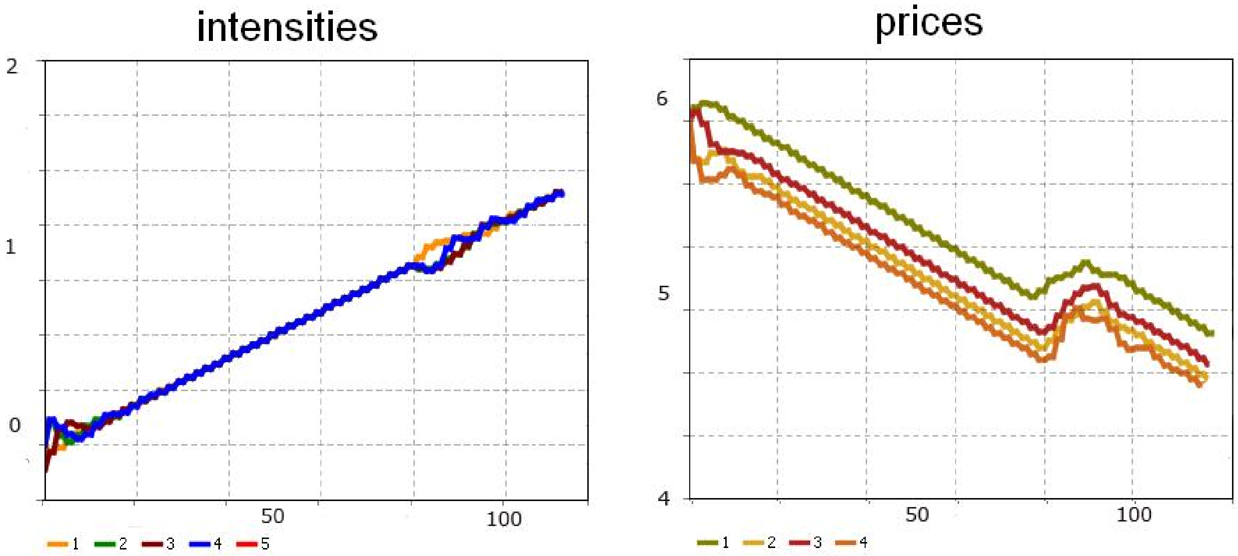
γ_{ik} denotes the share of *k*-th process in production of *i*-th product:

$$\gamma_{ik} = \frac{b_{ik} x_k}{\sum_{p=1}^{m} b_{ip} x_p} \tag{7}$$

and δ_{kj} is the share of *j*-the process in consumption of *k*-th product:

$$\delta_{kj} = \frac{y_k a_{kj}}{\sum_{p=1}^{n} y_p \alpha_{pj}} \qquad (8)$$

Fig. 2. Dynamics of intensities and prices (good investment climate)



The ADS model has two additional parameters: ε and σ. It should be noted that the increments of intensities $\Delta x_j = x_j(t+1) - x_j(t)$, and increments of prices $\Delta y_i = y_i(t+1) - y_i(t)$ for one period calculated according to ADS equations (3) and (4), when substituted into the balance equations of von Neumann (1) and (2), turn them into identities independently from values of ε and σ parameters.

Let us consider the meaning of these two parameters. When $\varepsilon \to 0$, the rate of change of intensity of *j*-th process in equation (3) tends to its profit factor β_j (6). When factor $\varepsilon \to 1$ the rate of change of intensity of *j*-th process tends to the weighted-average of the increments of their output (here weight are shares of consumed products).

Thus, variation of ε in the range 0<ε<1 in equation (3) describes the economic policy (or marketing strategy) which always takes into account two controversial factors: profitability of production and possibility of the market expansion.

The dynamics of the *i*-th product price, according to equation (4) is determined by factors α_i (5) and β_j (6) and is inversely proportional to both factors. When $\sigma \to 0$ in equation (4), the price of *i*-th product decreases with the rate inversely proportional to the dynamics of output of this product. When $\sigma \to 1$, the rate of the of *i*-th product price change becomes equal to the weighted-average of their inverse profitability (weighted over all processes involved in the production of *i*-th product).

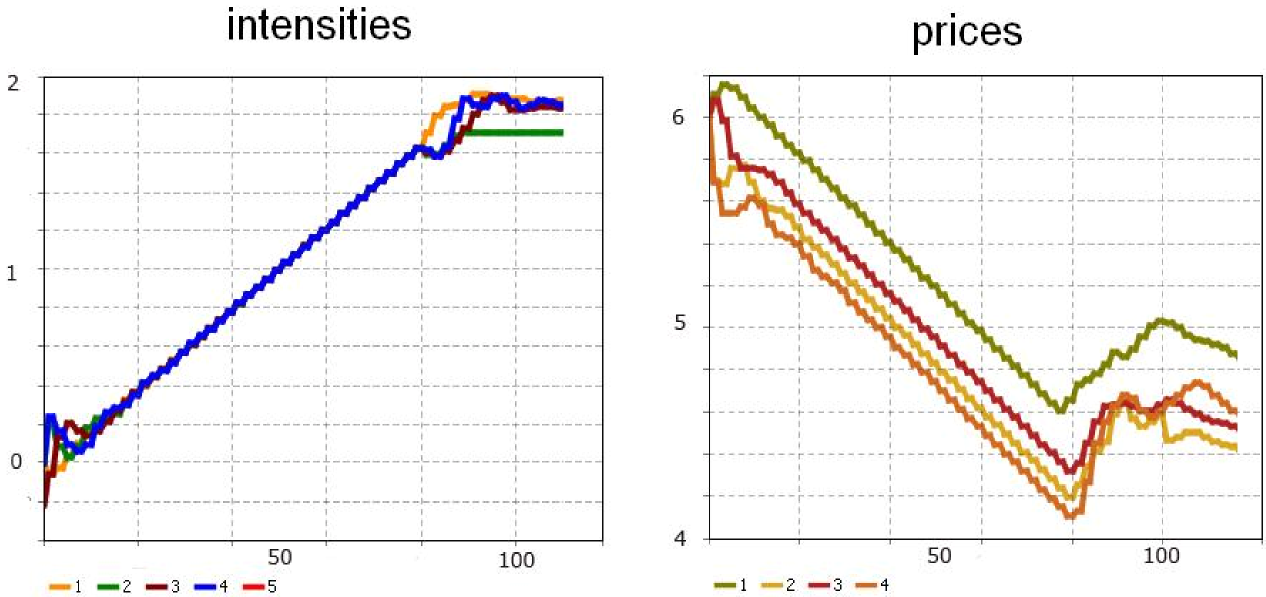
Thus, σ characterizes the pricing policy of the whole economy. With increasing σ from 0 up to 1, the pricing policy becomes increasingly market-oriented, profit-oriented and less expansionary.

As it was already mentioned above, ADS allows overcoming the limitations of the classical von Neumann model [4], extending this model by including real technological progress, more realistic dynamics of prices and intensities. One of such possibilities is the account of restrictions on human and production resources existing in the real economy. We illustrate such possibility by an example discussed below.

4. Implementation of ADS within AnyLogic environment

The first version of ADS system, «ECO-Dynamics», was developed and implemented in C++ language in Visual Studio system [2]. It showed the advantages of combining of agent-based approach and a theoretical model of the economy. The first step in this direction was the inclusion of agents of A-Owner type who administrated their processes by changing parameters ε and σ, and trying to maintain financial balance of each process and profitability of every manufactured product.

Fig. 3. Dynamics of intensities and prices (poor investment climate)



In this work, we have made the next step, porting the «ECO-Dynamics» system into AnyLogic environment. This system has many tools for the development of simulation models. Further we report the results of testing of that new system by simulation of an economic system, where only one type of agents (A-Owners) are implemented. These agents run their own processes by making decisions about the realization of investment projects.

In the original von Neumann model [4] the production capacities of all processes are unlimited and hence the increase of their intensities is unlimited. In the real economy, every process has certain limits of its production capacity. To overcome this problem, the intensity of each process in our example is limited by a maximal intensity x_j^{max}. When the intensity of j-th process reaches this limit, x_j^{max}, agent A-owner decides whether to invest in capital assets to increase the maximal intensity.

This investment allows the continued growth of output but also leads to an additional increase of goods prices. When the investment climate is good, all owners are involved in the investment process.

We illustrate this case in fig. 2. Here we present the results of ADS modeling of a simple system consisting of five processes that produce four products consumed by other processes. Initial dynamics of this system corresponds to von Neumann turnpike (straight line in semi-logarithmic scale).

After reaching limiting intensity, A-Owners of all processes decide to get a bank loan and raise the limit of intensity of its process. Repayment of credits leads to the increase of prices for manufactured products and, consequently, financial balance of each process is affected by prices of all consumed products. This leads to certain increase of all prices, which nevertheless later returns on a new turnpike.

Fig. 3 shows the result of modeling the same system but under conditions of poor investment climate when only one A-Owner agent decided to take a loan to increase its limiting intensity $x_1^{\max}$. Other agents A-Owner, even when reached their limits of intensity, decided do not invest to increase. As a result the intensity of all processes stopped on a mark $x_j^{\max}$ (j=2,3,4,5). The first agent A-Owner, despite the investment, has failed to increase significantly the intensity of its own process because its output depends on outputs of the rest of processes in the previous period.

As one can see, the ADS is able to overcome at least some of shortcomings of the classical theoretical model of von Neumann and it is possible to build on its basis the agent-based models of real systems in which there are restrictions on the basic factors of production.

5. Conclusions

System modeling of agent-based dynamic ADS approach helps in the study of complex, hard formalized, self-organizing processes of the economy and is one of the promising ways for modeling of socio-economic processes [5]. This method provides new prospects for extending tools implemented in modern simulation systems. The examples provided above illustrate this conclusion and show some directions of possible application of this method.

References

1. Borshchev A. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools [Electronic source] / A. Borshchev // XJ Technologies. – Access: www.xjtek.com.
2. E. S. Yakub. Agent dynamics simulation system “ECO-Dynamics”, Conference “Problems of economic cybernetics”, October 8–9, 2009, Abstracts, Kharkov.
3. Karpov Yu. G. Imitating modeling of systems. Introduction to simulation with AnyLogic5 / Yu. G. Karpov. – St. Petersbourg: BXB-Petersbourg, 2005. – 400 p.
4. J. von Neumann. A Model of General Economic Equilibrium / J. von Neumann // The Review of Economic Studies. – 1945–1946. – Vol. 13. – No. 1. – pp. 1–9.
5. Bakhtizin A. R. Agent-oriented models in economics / A. R. Bakhtizin. – Moscow: Ekonomika, 2008. – 279 p.
6. Bonabeau E. Agent-based modeling: methods and techniques for simulating human systems / E. Bonabeau // Proc. National Academy of Sciences. – 99 (3). – 2002. – pp. 7280–7287.

Key words: agent dynamic model, model of economic system, agent-based modelling, computer simulation, system dynamics simulation.

UDK classification: 33:004.942

Date of acceptance: 14.08.2013