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SIMULATION OF POPULATION'S REPRODUCTIVE BEHAVIOUR PATTERNS WITHIN AN AGENT-ORIENTED REGIONAL MODEL[1]

The study focuses on the research on how the unevenness of demographic transition affects the social and demographic characteristics and their dynamics of a region's population. The research was conducted by means of computerized experiments (simulations) set within an original agent-oriented model. The study features the structure of the model represented by an artificial society, with its members (agents) being attributed their personal characteristics in such a way that they would imitate the gender and age of the region's population. The agents are divided into two groups which differ in their reproductive strategy. Agents from Group 1 adhere to the traditional strategy characterized by a high birth rate, while the agents from Group 2 follow the modern strategy resulting in a markedly low birth rate.

With the application of probabilistic mechanisms, the natural birth-death processes are imitated within the model. The extinction of agents occurs in accordance with the death rates adjusted for age and gender but remaining the same for the whole population. In the model, the appearance of new agents (birth of children) results from the choice made by reproductive-aged female agents, and their choice is influenced by the subjective traits determined by their group. The age and social structure of the regional population are generally formed as a result of the aggregation of particular agents' activity.

The model has been applied in a range of experiments on forecasting the number and structure of the population in an assumed region. The results showed that despite the apparent simplification of the reality, the developed agent-oriented model correctly represents both the initial condition of the regional population including the gender, age and social structure and the dynamics of the population's basic characteristics.

Keywords: agent-based modeling, demography, types of population reproduction, forecasting of population size and structure of the region

Introduction

Development forecasting for all socio-economic processes, taking place both on the territory of the whole country and on the territory of its separate regions shall, obviously, be based on a high-quality forecast of population reproduction dynamics, taking population structure and spatial distribution into account. It is especially important to evaluate the ratio (and its development) of major social groups (e.g., urban and rural) both in the context of the various age cohorts and according to major age groups, such as children, adolescents, working-age population and population of above working age.

The processes determining the dynamics of population size and structure include such reproduction processes as fertility, mortality and migration. In this paper, we focus on analysis and modeling of the impact of the demographic transition on socio-demographic characteristics of the population. This phenomenon is considered in detail in the works of many well-known demographers, both foreign and domestic, and it is sufficient for us to refer to the work of A. G. Vishnevsky [1].

Recently, for behavior forecasting of complex social and economic systems, simulation modeling has increasingly been used, especially one such as the thriving agent-based modeling [2, 3]. The basic idea behind agent-based models (ABM) is in the construction of a computational tool, which is a set of agents, an artificial society consisting of interacting autonomous agents with a particular set of properties.

Besides being able to interact with each other, agents can also interact with their environment, a macro level of the model. For that, characteristics of the environment (external for agents) having a significant (in the light of these processes) impact on the state and behavior of the agents, as well as the rules regulating the agents behavior, depending on internal properties and the environment characteristics, are specified in the model. The rules are implemented in ABM as follows: agents are provided with procedures of information searching (important in terms of choosing actions acceptable for them), as well as procedures for such choices and "actions implementation"—independent changes

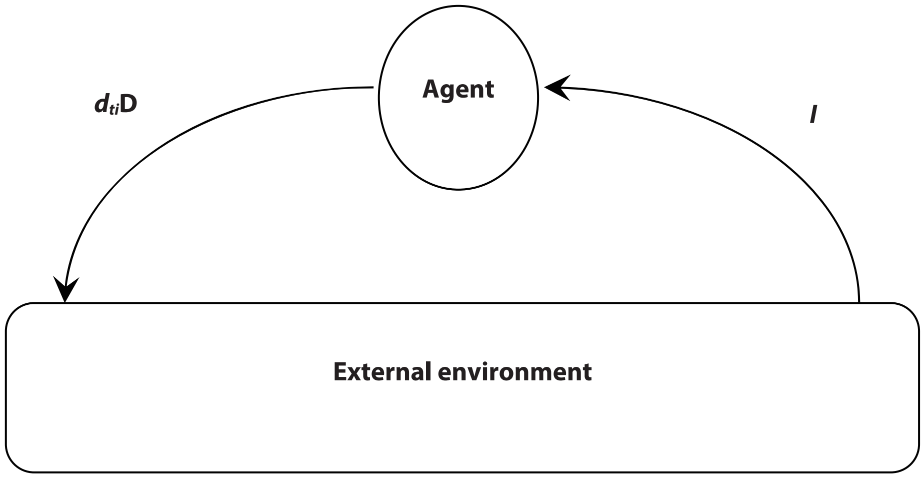

Fig. 1. *Scheme of Agent Interaction with Environment*

of their characteristics. The response influence of agents' actions on the state of the macro level is specified in the model via the procedures of individual agents aggregation actions.

The scheme of agents interaction with the environment is shown in Fig. 1, where dti is a specific action chosen by i agent in t moment of modeling time, and D is a set of actions available to i agent at this moment of time:

$$d_{ti} \in D = \{d_{ti}\}.$$

At the same time, *I* is a set of the environment indicators, which the agent is able to perceive at *t* moment of modeling time: $I = \{i_{tj}\}$

Thus, the work of ABM is based on the simulation of individual behavior of each agent (a member of this society), while changes in the general state of the whole system is an integral result of individual agents actions. It is important to note, that using an agent-based model you can abandon averaging characteristics of agents and recreate a social, socio-economic and/or social and demographic structure of a simulated real society (depending on objectives) taking the diversity of its members into account. Complete implementation of ABM only became possible with the appearance of modern computing tools, and transfer to ABM programming with the help of supercomputers allows models developers to bring the agents population in ABM into compliance with the number of members of the simulated society. On the one hand, this approach allows one to adequately describe the behavior of each individual agent in a model, bringing its image and behavior to an image and behavior of real society members. On the other hand, it allows to set up experiments by changing key environmental parameters affecting an agent's behavior (by means of computer simulations), and to observe the response to such changes of separate agents, different groups of them, as well as of the entire system.

Considering the fact that demographic trends in society are largely determined by individual choices of individuals, the widespread utilization of ABM in this field modeling is not at all surprising. Let us examine the most well-known models developed abroad, where ABM has been used for demographic processes modeling for more than 10 years [4–10].

In the article "When Demography Met Social Simulation: A Tale of Two Modelling Approaches" [4], the ABM of people population designed to reflect potential synergies from agent-based approach usage to demographic processes study is considered. Agents in the model have a complex structure with a large number of states and a population dynamics forecast is possible at different levels—from individual households to the whole population of the UK.

In the paper "An Agent-Based Marriage Model" [5], the ABM in which agents interacting in society are getting married, while the probability of this event depends mainly on the number of available partners, is considered. At that, the tendency for marriage is also determined by a share of agents from the total number of already married agents. The paper "Agent-Based Models on Social Interaction and Demographic Behavior" [6] is a continuation of the previous research. This exact work describes three ABMs, considering various components of the demographic system, in particular, the process of marriage creation, fertility changing and so on.

The book "Population Dynamics and Projection Methods" [7] studies the demographic problems in Western Europe connected with population aging, increase in number of divorces, decrease in number of marriages, increase in number of migrants, etc. Agent-based models are used to study these processes, interlinked with an economic situation, as well as with migration donating countries.

Unfortunately, it is necessary to note that despite numerous studies dedicated to demographic processes forecasting, carried out by scientific centers of Russia (for example, the Higher School of Economics, Institute of Social and Economic Studies of Population of the Russian Academy of Sciences, the Moscow State University, the European University in St. Petersburg, and others), the agent-based approach to the simulation of a social system of Russia is almost never used. In connection with it, the model we have developed, the general concept of which is shown in the article [11], can be regarded as one of the first models.

Method: Model Concept

In this paper, we will focus on the specification of fertility processes, on the justification of the chosen approach to their simulation, we will show the structure of the model implementing this approach, and will discuss the results obtained during the experiments performed for a conditional region.

Coming back to the above-raised topic of a demographic transfer—a transfer from a traditional type of reproduction to a modern one—we should mention significant differences in the rates of these processes in different countries. While in industrialized countries, the transfer from high levels of mortality and fertility to low levels of these processes has already been passed, in other countries, these figures vary asynchronously, at that decrease in fertility lags behind mortality decrease by one or two generations. It is caused by the fact that reproductive behavior of people in traditional and modern societies are different—marriage age, as well as an average number of children born from every woman. Thus, the total fertility rate in modern society is often reduced to a level that does not even ensure a simple reproduction. Special aspects of these processes in our country are well represented, for example, in a collected book [12], devoted to results of a unique social and demographic survey "Parents and Children, Men and Women in Family and Society." This study was conducted within the framework of the international Generations and Gender Program, bringing together researchers and demographers from more than 30 countries. The reproductive strategies of modern Russian women are also studied in [13]. For us, it is important that results of these studies allow us not just to shift the focus of demographic processes simulation to a micro level and to apply the agent-based approach, but also to create a sufficiently intelligent, intentional agents [14], i.e. agents, endowed with their own motivation mechanisms. For such agents the internal beliefs, desires, intentions, and motives that generate objectives that in their turn determine the actions of the agents can be modeled through different methods.

In our model, the role of such "beliefs" will be performed by the desired maximum number of children and the distribution of these children's birth during the reproductive period of women. At the same time, on the same territory in a model there will be agents presented from both traditional and modern types of reproduction—both these types of reproduction are present in our country, although in different proportions for different ethnic and social groups (for example, the difference between urban and rural populations is quite obvious).

In order to simulate such demographic processes, as fertility and mortality of population (migration was not taken into account in our model), we used a combination of two methods [15]:

1) The method of age shifting—every year those who survived, in accordance with age and gender survival rates, become a year older and take part in the reproductive process (according to the data on fertility for women of childbearing age);

2) A component-wise method, based on taking the dynamics of basic demographic indicators—mortality and fertility—into account. In other words, based on the observations trends in these indicators changes are revealed and corresponding indices are formed (the formed indices are later used in the simulation, changing demographic indicators in the method of age shifting for each forecasting year).

Different scenarios with such a procedure of prospective calculation of the population size are obtained by varying the indices, actually meaning different assumptions on the development of individual processes.

Mortality Imitation. The model uses mortality rates to calculate the probability of dying for an agent of all ages—separately for men and women. When passing to the next step (a year in reality) mortality rates before their application are multiplied by an appropriate index. Thus, for the simulation of this process, gender and age-specific mortality rates and indices of their change are to be used. Mortality rates for the two types of agents are assumed to be the same.

Death (not considering suicide) occurs not through the will of agents, while fertility in the model is largely dependent on the choice of each individual agent.

Fertility Imitation. Agents of reproductive age in the model can make a decision on the birth of children. At the same time, we started from the assumption that fertility indices must be obtained in accordance with the internal beliefs and thoughts of agents differing according to their types. Therefore, the initial data for the simulation of fertility processes is the data on the ratio of numbers of agents of various types, as well as statistics on fertility rates, differentiated by types of agents and maternal age at the moment of children birth.

In accordance with this approach, the minimum set of agents and environment characteristics needed to simulate reproduction processes was generated.

For agents:

— Type of reproductive behavior;
— Gender;
— Age;
— Maximum (desired) number of children;
— Actual number of children.

For environment:

— Total population size of agents;
— Share of traditional type agents;
— Age and sex structure of the population of agents;
— Share of traditional type agents in each age cohort;
— Mortality rates, disaggregated by sex and age;
— Indices of changes in mortality rates;
— Total fertility rate for the two types of agents;
— Indices of changes in fertility rates;
— Distribution parameters, by which the number of children for agents—representatives of each type—is randomly determined;
— Distribution of births by age of mother for two types of agents.

When performing simulation modeling, it is really important to not only have a proper organization of all the processes, taking place within the modeling period, but also to re-create a precise initial state of the system at the beginning of the model operation.

Results: Structure of Developed Model

Let us show you now, how it is implemented in our developed AnyLogic[2] environment for a conditional region demographic model, the general scheme of which is given in Figure 2.

A1. Starting the simulator after the launching of the model.

1. Setting Initial State of System

A2. Work with the model is started by reading from the database (presented as an Excel table), of initial information array. Thus, the information, required to create the model, is separated from software tools, and can be replaced at any moment, for example, by data of an actual region.

The model parameters are the total population of agents and the share of traditional type agents in this population. In order to re-create the agent population structure we used initial information provided in the form of standard age-gender pyramid, corresponding to the two types of reproduction (the population of traditional type agents is characterized by a relatively big number of newborns and children, so the pyramid has a broader base).

A3. On the basis of the initial data we calculated both the number of male agents and female agents in different age cohorts, and the share of traditional type agents (in these gender-divided categories of agents), which will obviously differ from the set value for the population as a whole.

A4. After that we created a specified number of agents, and assigned such an age, a gender and a type to each agent that the structure of created population was the same as the structure, calculated

[2] AnyLogic is a simulation tool that supports all approaches to the creation of simulation models: a process-oriented (discrete event); systematic and dynamic and agent-based approaches, as well as any other combination of them. In more details: http://www.anylogic.ru.

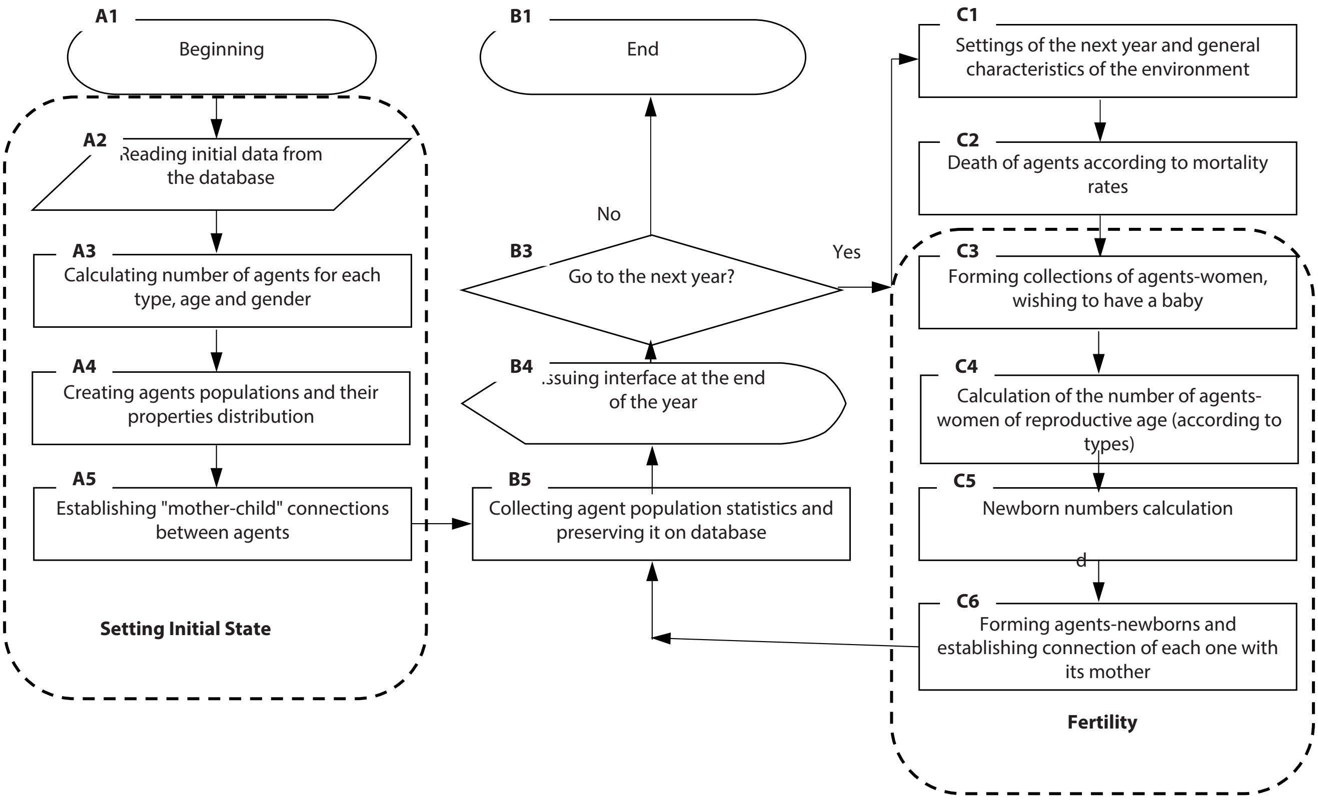

Fig. 2. *General Scheme of Demographic Model*

on the basis the initial data. To each female agent there was also a desired number of children assigned (in the range from minimum to maximum for its type), randomly chosen via beta-distribution.

A5. We established relationships between created agents, using the data on births distribution by the age of a mother. In fact, for each agent under the age of twenty there was randomly (via beta-distribution) an age determined of its mother, and then (from the determined age cohort) there was a same type female agent selected, the desired number of children of which is more than the number of already born ones. In other words, it is believed that the type of the child will match the type of the mother. The child-agent and the mother-agent remember each other, and, in addition, the number of the female agent's children is increased by one. Parameters of used beta-distributions were chosen so that the resulting frequencies of age selection corresponded to empirical data on distribution of births according to maternal age for the two types of agents, shown in Figure 3.

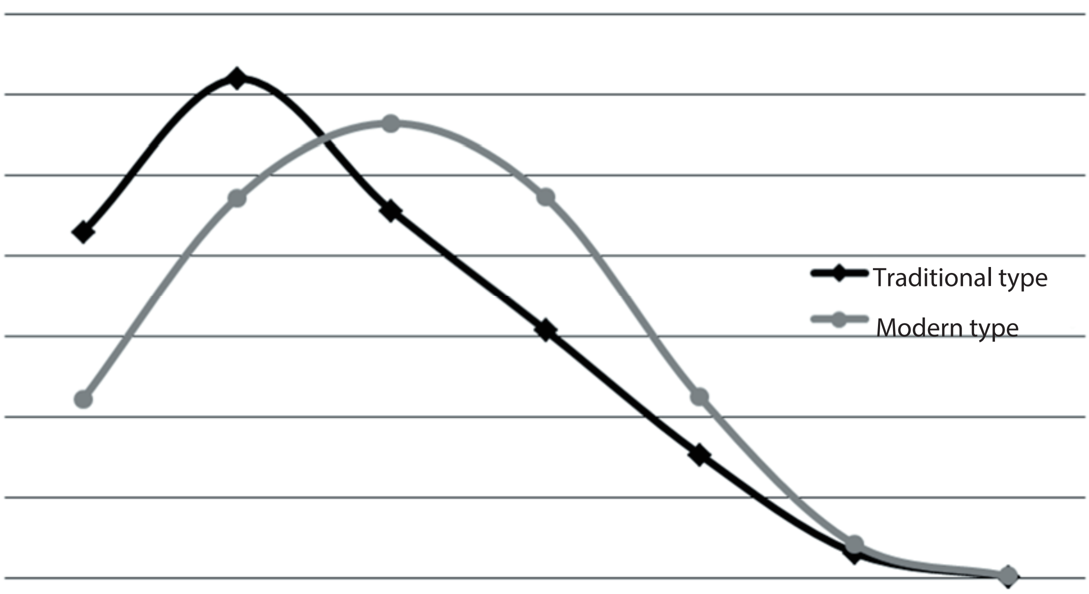

Fig. 3. *Shares of the total number of newborns to mothers of different age groups*

2. Analysis of Current State of Agents Population

B5. We collected statistics on agent populations—its total population, the number of male agents and female agents by age groups and types. The collected statistics is to be stored in tables of the output Excel file.

B4. The model interface demonstrates an "actual" state of the population in a current year (as well as graphs, showing changes in monitored results of model operation within a modeling time) to a user.

3. Passing to Next Step of Simulation

B3. Here the software waits for a user's decision whether to terminate or to continue the simulation. In the first case, the model operation is stopped (block B1), and in the second one—we go to the implementation of block C1.

C1. The value of "year" variable is increased by one, while fertility and mortality rates are multiplied by the corresponding indices.

4. Mortality Procedure

C2. For each agent of the population, with a probability corresponding to its gender, age, and type, it is determined whether he/she will die this year or not. If the agent is to die, he/she is removed from all the collections it was present in—collections of women wishing to give birth and/or collections of relatives, and then—it is to be removed. If the agent is going to live, its age is increased by one.

After completion of the agent population processing, all collections of agents associated with age cohorts are moved into the next age cohort.

5. Fertility Procedure

C3. For each age from 15 to 49—a reproductive age for women—separate collections of female agents of each type, wishing to have a baby, are formed. These collections are supplemented by female agents themselves according to their age and type, if their desired number of children is more than the number of born children—it is a choice, which is an action available to agents in this model. Thus, the desired number of children is the main factor, responsible in the model for the reproductive activity of female agents.

C4-C5. For each type we have separately calculated the total number of female agents of reproductive age and the total number of newborns, whom they have to bear in a current year, corresponding to the total predetermined fertility rates.

C6. For each type, a calculated number of agents of zero age was created, while each newborn agent's gender was determined randomly (for women—with a probability of 0.488 [16]).

For each newborn we selected a mother, out of the collections female agents of reproductive age, wishing to give birth to a baby this year. The procedure of a mother selection and for the establishment of relationships with her is described above. If the number of children born by a female agent becomes equal to the number of desired children, then such an agent is to be removed from the collection of women, wishing to give a birth to a baby, and it will not take part in the reproductive process any more.

Upon completion of this block we go to the analysis of the current state of agents populations—we return to B5–B6 blocks.

Conclusion

Using the model, we have conducted experiments to forecast changes in population of agents living in a conditional region, to forecast the age structure of this population, as well as the balance between the agents of different types for the main age groups and for the population in total. Twenty experiments were conducted at the following values of parameters:

— Total population of agents: 100,000;

— Share of traditional type agents: 10%;

— Mortality rates for the two types of agents (correspond to the data for Russia as a whole);

— Total fertility rate for traditional type female agents: 3, and for a modern type: 1.4;

— Minimum number of desired children for traditional type agents: 2, and maximum number: 10; for modern type agents: 0 and 3, respectively;

— Base year: 2007;

— Simulation period: 20 steps (years);

— Mortality and fertility rates remain constant throughout the period.

Since in the process model operation (in order to get agents characteristics) various probability distributions are used repeatedly, so the experiments results could not coincide completely. Therefore,

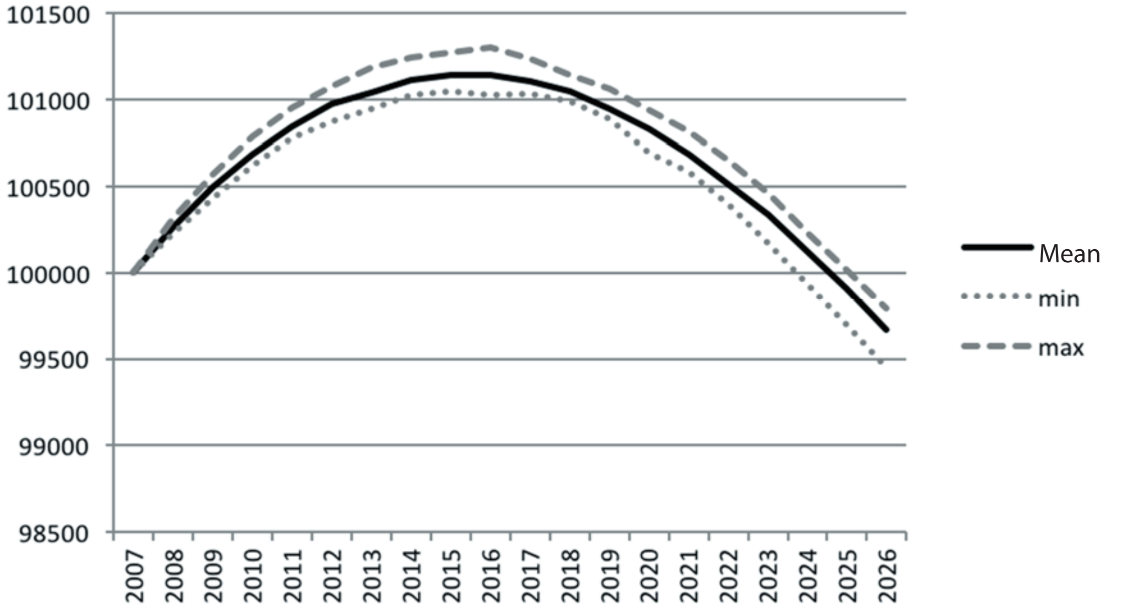

Fig. 4. *Dynamics of Agent Populations*

we took mean values of population characteristics as forecasted ones for all the experiments. Besides, the analysis of the model stability (as a value of relative deviation of these characteristics from mean values) has been conducted. Thus, for the total population the deviation from mean value for twenty years was in the range from—0.23% to 0.16%, which can be considered a very good result.

The analysis of the experiment results showed that the model adequately simulated such processes, observed in real life, as the total population reduction (depopulation) and population aging. Starting from 2016, the reduction of the number of agents in Figure 4 is obvious. In the figure, one can also see the maximum and minimum number of agents over through the years. The population aging can be seen in Figure 5: here you can see, that the number of agents under the age of fifty has been declining steadily throughout the period, while the number of agents of over eighty—has been increasing (see in more details in Table 1).

If we look at the agent populations structure in terms of their adherence to different strategies of reproductive behavior, it becomes clear that the balance between the numbers of the two types of agents will vary in different age groups. This effect is shown in Figure 6, where you can see that even at small general increase in the share of traditional type agents at each step of the simulation, this share, among others, varies remarkably for different age groups—the younger an age group, the higher its share. It is shown in details in Table 2.

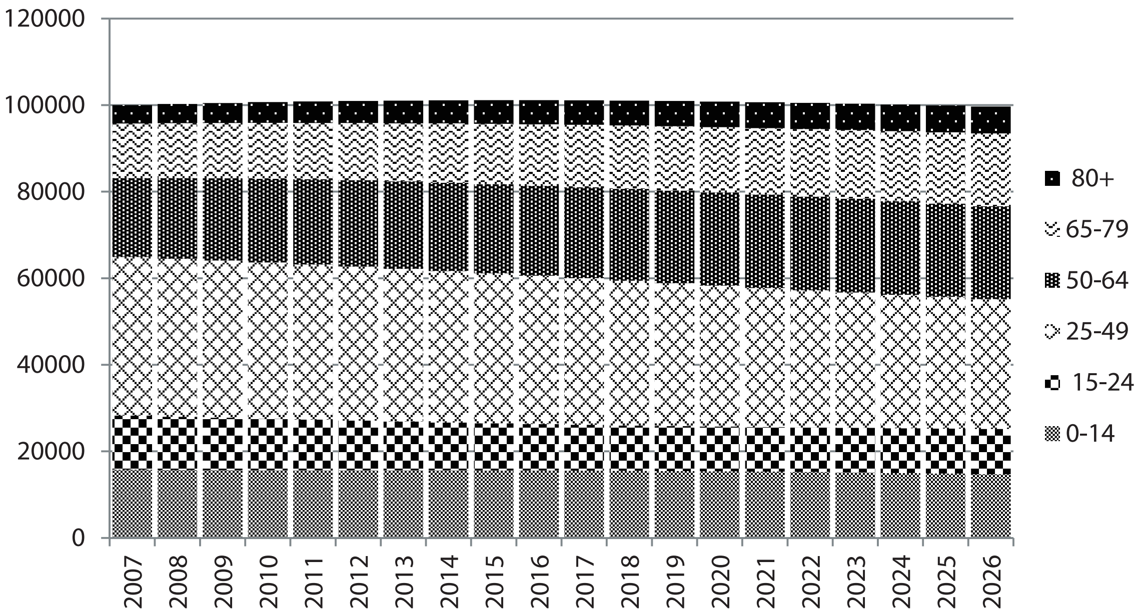

Fig. 5. *Dynamics of Age Structure of Age Population*

Table 1

Absolute and Relative Aging Observed in Agents Population

Age Groups	2007		2026		Increase in Number within Period, %
	Number of Agents	Share in Population, %	Number of Agents	Share in Population, %	
0–49 years old	64,898	64.9	55,194	55.4	15.0
Older than 80 years old	4,249	4.2	6,215	6.2	46.3
Whole Population	100,000		99,666		0.3

Table 2

Growth in Number of Traditional Type Agents and Their Significance for Population as Whole and for Separate Age Groups

Age Groups	2007		2026		Share Growth for Period, %
	Number of Agents	Share in Age Group, %	Number of Agents	Share in Age Group, %	
Whole Population	10,000	10.0	13,202	13.2	3.2
0–14 years old	2,659	16.9	3,632	24.6	7.7
15–24 years old	1,636	13.1	1,973	18.9	5.8
25–49 years old	3,292	9.0	4,107	13.7	4.7
50–64 years old	1,357	7.4	1,811	8.4	1.0
Older than 64 years old	1,056	6.3	1,679	7.3	1.0

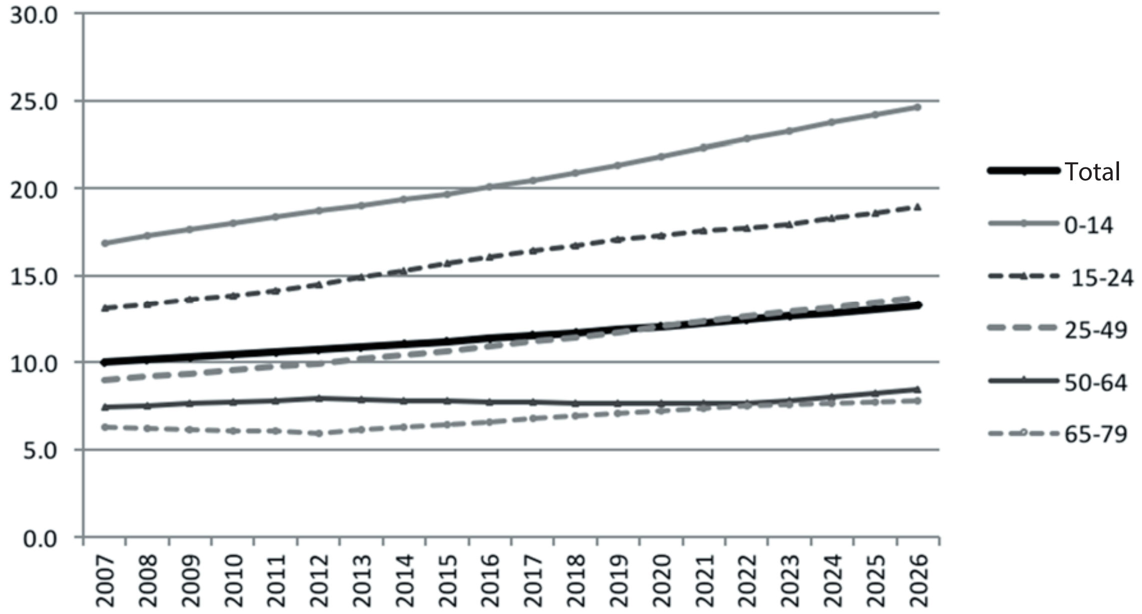

Fig. 6. *Shares of Traditional Type Agents in Total Agent Population and Divided by Main Age Groups, %*

Thus, we can conclude that the developed agent-based model, in spite of the apparent simplification of reality, correctly reproduces both the initial state of population in a conditional region, including its age-and-gender and social structure and the dynamics of the main characteristics of this population.

In our opinion, it is already possible for us using the presented model to conduct studies of dynamics and structure of the population in actual regions (having prepared the necessary initial information).

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