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## From the Researcher's Notebook

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# Creation of a Supercomputer Simulation of a Society with Different Types of Active Agents and Its Approbation

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Received June 28, 2021; revised June 30, 2021; accepted September 15, 2021

**Abstract**—This article continues a series of works devoted to the creation of large agent-based models, built as an artificial society, and the development of software for their implementation—the MÖBIUS design system for scalable agent-based models. The basic core of the system is a demographic model that simulates the natural movement of the population. A new stage in the development of the work discussed in this article was the creation on the basis of this core of an agent-based model of Russia, which includes families as agents of a new type, hierarchically connected with human agents. In addition, objects of a new type were introduced into the model—projects that provide for the creation in an artificial environment of analogues of complex control actions aimed at stimulating fertility. Developed on the basis of simulating the reaction of individual families to the introduced regional support measures, the model makes it possible to track their impact on key demographic indicators. The agent-based model of Russia was tested on data for a long retrospective period using the example of the launch of maternal capital programs and showed good agreement with official statistics.

**Keywords:** digital simulation and modeling of systems, agent-based modeling, supercomputer technologies, parallel computing, simulation of demographic processes, approbation of managerial influences

**DOI:** 10.1134/S1019331622030182

The modern level of the possibilities of computer modeling of socioeconomic processes puts on the agenda the creation of decision-support systems of a new type—not just the selection and preliminary analysis of information necessary for decision making, but virtual grounds to run various scenarios and test options for decisions with simulation of their consequences. The use of such an analysis tool makes it possible during computer experiments to choose combinations of different measures of influence on the controlled system, as well as provide a strategy for their phased implementation, which ultimately leads to the desired results or clearly demonstrates the boundaries of the achievable results.

Recently, the method of agent-based modeling, based on imitation of the individual behavior of socioeconomic actors, has been developing especially rap-

idly [1]. In an agent-based model (ABM), a population of agents is created to represent real economic actors in an artificial environment along with their individual characteristics and procedures that imitate the independent actions (behavior) of these actors. ABMs are successfully used to simulate various processes—demographic, economic, environmental, etc. The agent-based approach makes it possible to consider the differentiation of individual groups of the population in terms of their response to the control action, up to simulating the individual reaction of people to a change in the external environment, depending on their personal characteristics and circumstances. This is what allows an ABM to simulate a situation that was not observed before, which is impossible for statistical methods.

The popularity of this type of modeling is evidenced by the increased number of publications on this topic over the past 20 years. Thus, according to the two largest bibliographic databases SCOPUS and Web of Science, since 2000, the number of articles devoted to agent-based models has increased by more than

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120 times, while the number of works that used other modeling methods has been growing at a slower rate.

Experiments with agent-based models were used in practice, in preparing important managerial decisions. A particularly striking example is epidemiological ABMs. For instance, J. Epstein's model [2] was used by specialists from Johns Hopkins University, as well as the US Department of Homeland Security for research on strategies for rapid response to various epidemics. In 2009, a version of this model was created to simulate the consequences of the spread of the influenza A(H1N1/09) virus on a global scale; it included 6.5 billion agents. We also know the ABM developed under the guidance of N. Ferguson, an epidemiologist and Professor at Imperial College London [3]. It aims to simulate the spread of the SARS-CoV-2 coronavirus among the UK population and was used to analyze government actions that could affect the course of the outbreak.

Agent-based models can be used not only for operational management tasks but also for the preparation of strategic decisions that have deep and long-term consequences for society in general. To this end, more complex ABMs are being developed, which simulate many processes that occur simultaneously in society and influence each other.

#### DEVELOPMENT OF THE AUTHOR'S CONCEPT OF THE AGENT-BASED MODEL AS AN ARTIFICIAL SOCIETY AND SOFTWARE FOR ITS IMPLEMENTATION

For several years, CEMI RAS has been developing its own concept of a complex regional agent-based model as an artificial society, designed to reproduce the spatial distribution and socioeconomic structure of real society, as well as its interaction with the natural and anthropogenic environment [4]. Within the framework of such an ABM, several individual models can be combined—the natural environment of a region, the sociodemographic structure of its population, and the structure of its economy. It can create populations of agents of different types, which are connected hierarchically. For example, human agents form a hierarchy with the enterprise agents they work for. Thus, an ABM models a region as a large system [5] developing on the basis of the actions of numerous independent agents, similar to real economic actors. The term *large system* in this case acquires an additional meaning since the number of agent populations in the ABM can reach the real number of the corresponding communities (for example, the population of a region).

For the practical implementation of an ABM of such a design, CEMI RAS developed the MÖBIUS software tool [6], a system for designing agent-based models to be run on supercomputers that include populations of agents of different types. MÖBIUS supports the dynamic change in the number and spatial

distribution of agents by simulating their disappearance and the emergence of new ones, provides for the formation and maintenance of social connections of agents using a messaging system, and makes it possible to create efficiently scalable agent-based models with populations of agents of different types up to one billion. Scaling means ensuring parallel execution of the model code on several supercomputer processors. Complex scenarios of interactions between agents are imitated by dividing the simulated processes into separate stages, after the completion of which parallel computations are synchronized and messages prepared by agents are exchanged. For example, the imitation of mortality occurs in several stages: first, references to “deceased” agents are removed from all their relatives; then the addresses are recalculated in those cells where agents will be deleted, and new addresses are reported to all affected agents; and only then are the “deceased” physically removed from the cells (for more details, see [7]). The core of the MÖBIUS system is a demographic model that reproduces the age–sex and social structure of a region's population, as well as its spatial distribution over the territory of the region's administrative units with the corresponding addresses of spatial cells related to a particular processor. The base demographic model simulates the processes of natural population movement based on the behavior of human agents.

Paper [8] presents the results of approbation of the author's approach to modeling an artificial society in the MÖBIUS system by the example of the demographic ABM of Russia with the addition of modeling the consequences of the introduction of the maternal capital program [9]. The study is aimed at evaluating the applicability of this ABM in the system of public administration of demographic processes, which implies compliance with high requirements on the plausibility of the obtained modeling results; otherwise, it would have been impossible to extend the conclusions obtained in computer experiments to the existing social system. In [8], the processes of natural population movement were simulated in the context of the regions of Russia and, as a result of aggregation, in Russia as a whole. After that, the obtained indicators of the population size of the regions were supplemented with information on the actual migration flows during the period under study (2002–2018) with account for the subsequent natural increase/decrease of migrants, which made it possible to improve significantly the agreement between the modeling results and the official statistical data. Thus, without accounting for migration, the number of regions with a deviation of model data from factual data within  $\pm 2\%$  was 72 in 2003 and only 19 in 2018, while with account for migration, the number of such regions increased to 80 and 40, respectively. Obviously, the model did not consider other factors that significantly influenced the processes of fertility.

To increase the plausibility of the simulation, it was worth, in the first place, paying attention to other family support measures implemented in the regions. The effect of regional programs is noted by many authors [10, 11]. Work [11] analyzes the dynamics of indicators such as the ratio of births of the second and third children to the number of firstborns, as well as the total fertility rate (average number of births per woman) over the past 30 years. It is noted that the sharp change in the upward trend of both indicators exactly coincided with the introduction of the federal maternal capital program in 2007 and similar regional programs adopted in 2012, which were aimed at stimulating the birth of second and third children. Thus, modeling the operation of regional programs was chosen as the priority direction for further expanding the functionality of the developed demographic ABM of Russia.

#### DEVELOPMENT OF THE AGENT-BASED DEMOGRAPHIC MODEL DESIGN

The model presented in [8] received as initial data information on the federal maternal capital program by years, such as that on the conditions for its receipt (number of children in the family) and the amount in rubles. During the operation of the model, the impact of this program on the likelihood of having a child was simulated for women who had not yet given birth to as many children as they would like and had not received maternal capital earlier. That is, an important role in simulating the process of fertility was played by such characteristics of agents as the desired number of children in the family, in the distribution of which on the population of agents, the data of [12] were used. Thus, if in a current year the amount of maternal capital was greater than zero, for female agents who met these conditions, the probability of having a child calculated for the current year increased, depending on their age and region of residence (with account for regional trends in the total fertility rate). The size of the increase in the probability of having a child depended on the subjective significance of this amount for each female agent, namely, on the amount of maternal capital in the cost of 1 m<sup>2</sup> of housing in the region of residence (the greater the significance, the greater the increase).

To introduce into the model of simulating the impact of regional maternal capital programs as a one-time payment at the birth of a child, this construction was generalized, and a new class was created—a “project,” representing regional measures to support families in the model. It was taken into account that in some regions, to receive support, families with children had to meet an additional condition on the average per capita income. As a result, the following characteristics were chosen for the project class:

- index of the region in which the measure of family support is introduced;

- individual project number;
- year of commencement and year of completion of project implementation;
- minimum number of children in a family to qualify for support;
- threshold relation of the average per capita family income and the regional subsistence minimum that gives the right to receive support;
- how many times a family can receive support;
- support amounts by years (2002–2018) in rubles.

The introduction of an additional condition for obtaining regional maternal capital created a completely new situation since it was no longer a question of checking the individual characteristics of a female agent applying for financial assistance, but of considering the characteristics of an object of a different type—the family, of which the female agent is a part. This task required the introduction of the family as a new type of object into the demographic model. Its main properties are the following:

- a large number of families (of the same order as the population of human agents);
- hierarchical connectedness of the family and human agents: human agents are members of families;
- common features with human agents: families are spatially distributed, as are human agents; families can appear and disappear during the operation of the model; they must maintain links with human agents in the process of establishing and maintaining kinship relationships.

With account for these properties, it was decided to include in the model not just objects of a new type, but a class of agents of a new type capable of independent behavior, and agents of the two types are connected by a hierarchy: human agents → family agents. Since the family agent class is derived from the more general “agent” class, it inherits the following properties from it:

- individual address (spatial cell number plus serial number in the cell),
- collection (list) of addresses of social links (message mailing list),
- mark for deletion.

In addition, the characteristics of the “family” class are the following:

- index of the region where the family lives;
- total income;
- collection of human agents—family members, which becomes a mailing list of messages;
- collection of programs of the support that the family received;
- deletion procedure: a family is marked for deletion if only one agent remains in it.

Note that the concept of a family in the model differs from the generally accepted concept of a house-

hold. This is determined by the kinds of families that can apply for maternal capital. Thus, according to the model, a family cannot contain agents such as relatives of three generations; families are formed by agents connected by partnership (marital) and/or mother–child (children) relations if these children do not have their own partners or children.

The addition of the new type of agents to the model led to significant changes in the design of the demographic ABM of Russia. Thus, in different classes of the model, the following were added

at the main level:

- number of families;
- procedure of entering new initial data by region (average salary and pension, subsistence level);
- procedure of entering data on regional maternal capital projects;
- in the procedure for setting the starting state, blocks of the formation of all family ties between human agents and the formation of families;
- block of stages associated with the removal of families, which is performed at each simulation step corresponding to one year, after the block of stages providing the addition (birth) of human agents;

- collection of statistics on the size of families;

at the regional level:

- size of families;
- average salary by years (2002–2018) in rubles,
- average pension by years (2002–2018) in rubles,
- subsistence minimum by years (2002–2018) in rubles,
- collection of all regional family support projects,
- collection of regional projects operating in the current year and updated at every step,

at the level of human agents:

- the “income” variable (for agents of working age, it is calculated based on the average salary in the region, and for agents older than working age, based on the average pension);
- collection of social ties—family, partner, brothers and sisters, as well as the corresponding expansion of the message mailing list;
- procedure of increasing the probability of having a child if there are existing projects in the region where the female agent lives, if she can qualify for assistance, completely similar to the mechanism of the influence of federal maternal capital;
- procedure of searching for a partner for a female agent—a male agent, a resident of the same region with an age difference of no more than 10 years, not a relative, and without a partner;
- procedure of establishing partnerships and forming a new family with the appearance of the first child.

The changes made are important from the standpoint of the model’s requirements on computational

resources. Thus, the emergence of a population of agents of a new type, comparable in size to the population of human agents, will require the use of a larger number of processors. It is also obvious that the time needed to set the initial state of the model should increase noticeably to reconstruct the structure of the population and family ties. In addition, the inclusion of new stages of the simulated processes and the corresponding new synchronization points will inevitably cause an increase in the simulation time of each step. The latter circumstance, as well as the growth in the traffic of messages exchanged by agents, including during the formation of families and the establishment of family ties, may affect the efficiency of the supercomputer model.

#### APPROBATION OF THE NEW DESIGN OF THE AGENT-BASED DEMOGRAPHIC MODEL

We have considered the dynamics of the previously obtained results of modeling the population size with account for the influence of federal maternal capital and migration growth, as well as the deviation of the values obtained from Rosstat data for 2003–2018. [8]. As a result, 17 regions were identified for which during the entire period there was a downward deviation of the forecast from the fact, and by 2018 the model data lagged behind the actual information by more than 2%. It became obvious that the model did not consider the influence of several factors that increased the fertility rate in these regions during that period. For our experiment, it was important to choose regions in which we could trace the influence of regional maternal (family) capital. Therefore, from the resulting list, we excluded regions, in particular, Moscow and the Republic of Tatarstan, in which regional measures to support families did not include maternal capital programs, as well as regions for which the deviation from the actual values of the population increased evenly throughout the entire period under review; that is, the deviation was caused by permanent factors and not by the implementation of any project. As a result, nine regions remained to test the new design of the model, where the deviation of the modeling results from the fact increased noticeably, starting from 2012, and where regional maternal capital programs were introduced. This group consisted of the Yamalo-Nenets Autonomous Okrug (forecast deviation from the fact in 2018, –7.8%), the Khanty-Mansi Autonomous Okrug (–6.8%), Krasnodar krai (–2.9), St. Petersburg (–6.3), Tyumen’ oblast (–4.9), Stavropol’ krai (–3.2), Novosibirsk oblast (–2.4), Republic of Sakha (Yakutia) (–2.1), and Rostov oblast (–1.7). A special situation was observed in Stavropol’ krai. Thus, the announced start of the regional maternal capital program from January 1, 2011, did not take place, and in 2015 new Law no. 127-KZ was adopted [13], which from January 1, 2016, completely abolished regional

maternal capital. Nevertheless, in our opinion, the announced support for families with children could affect the reproductive behavior of people since it could be received only three years after the birth of a child in the family, that is, the first payments should have begun in 2014. Therefore, this region was left on the list, especially since, during the specified period, there was a certain increase in the total fertility rate (TFR) in Stavropol' krai.

On a separate basis, let us dwell on the situation in Rostov oblast: there, the right to receive regional maternal capital, introduced from January 1, 2012, was received at the birth of a third child only by poor families, the average per capita income of which did not exceed the regional subsistence minimum, which narrowed the scope of this family support measure and was bound to reduce the effect of its introduction. We consider this region as a good example, which made it possible to test a more complex system of stages of imitation since here the family acted as a single entity having received the right to maternal capital when this condition was met.

The legitimacy of the choice of these regions is also confirmed by the nature of changes in the total fertility rate in these regions. The dynamics of the median value of the TFR for the sample is shown in Fig. 1, which demonstrates an abrupt increase in the average total fertility rate not only in 2007 (obviously thanks to the launch of the federal maternal capital program) but also in 2012, when most regional programs started.

Thus, to test the new design of the demographic ABM of Russia, regions with projects corresponding to regional maternal capital programs were selected (Table 1 shows only those program conditions that were used in the experiment).

The experiment was carried out according to the scheme “without a project and with a project,” that is, all the numerous parameters of the model (year of start and period of simulation, mortality/fertility rate

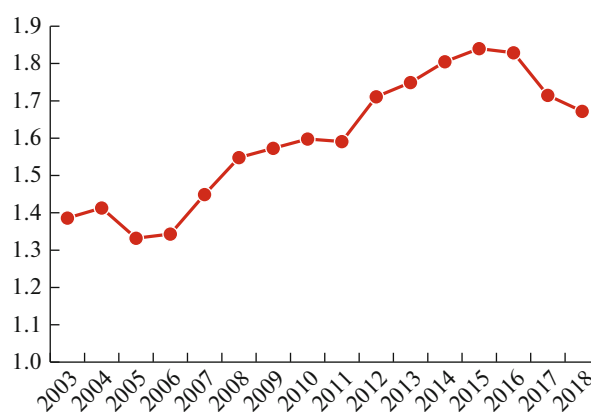


Fig. 1. Dynamics of the median value of the total fertility rate for the sample of regions. Source: Rosstat data.

and indices of their change, the federal maternal capital program, etc.), as well as the procedures of accounting for migration flows, remained unchanged, and only the file of initial information on regional projects changed. In the base case, there were no regional projects, while in the second option, the above-mentioned nine projects were introduced, after which the resulting modeling options were compared for these regions. The results of the experiment are shown in Tables 2 and 3.

The data in Table 2 testify to the effect of adding a block that simulates the reaction of agents to the introduction of regional maternal capital programs. Although the relative significance of the increase in the number of births at each step of the simulation in these regions is insignificant, in general, the absolute increase in the number of births by regions of the sample amounted to more than 400 000 people over the entire period under consideration. The increase in the number of births naturally led to an increase in

Table 1. Parameters of regional programs of maternal (family) capital that participated in the experiment [14–22]

Region	Amount, thousand rubles	Validity period, years	Terms of service
St. Petersburg	100 (annual indexation)	2012–2026	Birth of the third child
Krasnodar krai	100 (annual indexation)	2011–2021	Birth of the third child
Stavropol' krai	100	2011–2015	Birth of the third child
Rostov oblast	100	2012–2018	Birth of the third child
Tyumen' oblast	40	2012–2021	Birth of the third child
Khanty–Mansi AO–Yugra	116	2012–2021	Birth of the third child
Yamalo-Nenets AO	350 (annual indexation)	2011–2021	Birth of the third child
Novosibirsk oblast	100	2012–2021	Birth of the third child
Republic of Sakha (Yakutia)	100 (annual indexation)	2011–2021	Birth of the third child

**Table 2.** The increase in the number of births associated with the implementation of regional maternal capital projects (thousand people) and its significance (share of the population of the region in the current year, %)

Region	Year								
	2011	2012	2013	2014	2015	2016	2017	2018	Total
St. Petersburg		7.7 (0.2)	4.1 (0.1)	5.8 (0.1)	6.9 (0.2)	6.4 (0.2)	6.1 (0.1)	5.7 (0.1)	<b>42.7</b>
Krasnodar krai	17.1 (0.4)	15.7 (0.3)	15.3 (0.3)	12.1 (0.3)	12.0 (0.2)	11.6 (0.2)	10.8 (0.2)	9.0 (0.2)	<b>103.6</b>
Stavropol' krai	18.6 (0.7)	13.5 (0.5)	10.6 (0.4)	6.6 (0.3)	6.3 (0.2)				<b>55.7</b>
Rostov oblast		13.2 (0.3)	10.7 (0.3)	10.0 (0.2)	6.9 (0.2)	6.0 (0.1)	7.4 (0.2)	5.8 (0.1)	<b>59.9</b>
Tyumen' oblast		5.1 (0.2)	4.3 (0.1)	4.8 (0.1)	6.0 (0.2)	4.9 (0.1)	5.2 (0.2)	1.8 (0.1)	<b>32.3</b>
Khanty–Mansi AO—Yugra		7.9 (0.5)	5.5 (0.4)	4.2 (0.3)	3.2 (0.2)	4.1 (0.3)	4.1 (0.3)	2.2 (0.1)	<b>31.2</b>
Yamalo-Nenets AO	8.5 (1.6)	3.9 (0.7)	5.0 (0.9)	2.4 (0.5)	2.9 (0.5)	2.1 (0.4)	1.3 (0.2)	1.6 (0.3)	<b>27.8</b>
Novosibirsk oblast		11.2 (0.4)	5.7 (0.2)	4.8 (0.2)	4.6 (0.2)	5.0 (0.2)	4.9 (0.2)	2.7 (0.1)	<b>39.0</b>
Republic of Sakha (Yakutia)	5.3 (0.5)	4.5 (0.5)	2.7 (0.3)	2.3 (0.2)	2.5 (0.2)	1.6 (0.2)	1.9 (0.2)	1.6 (0.2)	<b>22.5</b>
<b>Total</b>	<b>49.5</b> <b>(0.2)</b>	<b>82.8</b> <b>(0.3)</b>	<b>63.8</b> <b>(0.3)</b>	<b>53.0</b> <b>(0.2)</b>	<b>51.5</b> <b>(0.2)</b>	<b>41.7</b> <b>(0.2)</b>	<b>41.8</b> <b>(0.2)</b>	<b>30.4</b> <b>(0.1)</b>	<b>414.5</b>

the population size and, accordingly, to a decrease in the deviation of the modeling results from the actual values of this indicator (see Table 3).

The data in Table 3 indicate that the greatest impact of the regional program on population growth was observed in the Yamalo-Nenets Autonomous Okrug (the difference between the deviations for options 1 and 2 in 2018 was  $-4.7$  p.p.), which is explained by the large amount of maternal capital. The least impact was observed in St. Petersburg ( $-0.6$  p.p.), which is explained by the higher cost of housing compared to other regions and, accordingly, the lower relative importance of maternal capital of  $\text{P}100000$ . Assessing the results of the experiment as a whole, we also note that, in the second option, the number of regions for which the deviation from the fact was less than 2% increased significantly: throughout the entire simulation period it was 5, while in the first option it steadily decreased and by the end of the period amounted to 1. The latter observation, in our opinion, indicates the adequacy of the algorithms developed for

simulating the reproductive behavior of people, which ensured even greater approximation of the simulation results to reality.

Note the changes in the software package, associated with the implementation of the new block of the model, which could significantly affect the efficiency of the model's supercomputer version:

- adding a new class of family agents and creating the corresponding population;
- complication of the procedures for setting the initial state of the system;
- adding new stages and respective synchronization points, i.e., possible delays during the model's operation at each step of the simulation;
- a significant increase in the number of agent connections and, accordingly, an increase in message traffic between the agents.

All this led to a change in the technical characteristics of the supercomputer versions of the model. Thus, with a comparable total number of agents, the average simulation execution time per step increased signifi-

**Table 3.** Comparison of the deviation of the results of population modeling taking into account migration from the actual values for two variants of experiments: (1) without regional projects and (2) with the implementation of regional maternal capital programs, %

Region	2012		2013		2014		2015		2016		2017		2018	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
St. Petersburg	-3.2	-3.2	-3.7	-3.6	-4.2	-4.0	-4.7	-4.5	-5.3	-4.9	-5.8	-5.4	-6.3	-5.7
Krasnodar krai	-2.1	-1.7	-2.2	-1.5	-2.4	-1.5	-2.6	-1.5	-2.7	-1.5	-2.9	-1.4	-2.9	-1.3
Stavropol' krai	-2.3	-1.7	-2.4	-1.3	-2.5	-1.1	-2.7	-1.1	-2.9	-1.0	-3.1	-1.3	-3.2	-1.4
Rostov oblast	-1.3	-1.3	-1.4	-1.4	-1.5	-1.2	-1.6	-1.1	-1.7	-1.0	-1.8	-0.9	-1.7	-0.7
Tyumen' oblast	-3.1	-2.9	-3.4	-3.1	-3.7	-3.3	-4.0	-3.5	-4.5	-3.8	-4.8	-4.0	-4.9	-3.9
Khanty–Mansi AO– Yugra	-3.9	-3.9	-4.5	-4.2	-5.1	-4.4	-5.7	-4.8	-6.1	-5.0	-6.5	-5.2	-6.8	-5.3
Yamalo–Nenets AO	-4.4	-3.0	-4.9	-2.8	-5.6	-2.7	-6.3	-2.8	-7.1	-3.0	-7.6	-3.2	-7.8	-3.1
Novosibirsk oblast	-1.5	-1.5	-1.7	-1.4	-1.8	-1.3	-2.0	-1.3	-2.2	-1.4	-2.4	-1.4	-2.4	-1.1
Republic of Sakha (Yakutia)	-0.8	-0.5	-1.0	-0.3	-1.3	-0.2	-1.7	-0.3	-2.0	-0.4	-2.1	-0.3	-2.1	0.0
<b>Maximum deviation</b>	<b>-4.4</b>	<b>-3.9</b>	<b>-4.9</b>	<b>-4.2</b>	<b>-5.6</b>	<b>-4.4</b>	<b>-6.3</b>	<b>-4.8</b>	<b>-7.1</b>	<b>-5.0</b>	<b>-7.6</b>	<b>-5.4</b>	<b>-7.8</b>	<b>-5.7</b>
<b>Minimum deviation</b>	<b>-0.8</b>	<b>-0.5</b>	<b>-1.0</b>	<b>-0.3</b>	<b>-1.3</b>	<b>-0.2</b>	<b>-1.6</b>	<b>-0.3</b>	<b>-1.7</b>	<b>-0.4</b>	<b>-1.8</b>	<b>-0.3</b>	<b>-1.7</b>	<b>0.0</b>
<b>Number of regions with deviation ≤ 2.0%</b>	<b>3</b>	<b>5</b>	<b>3</b>	<b>5</b>	<b>3</b>	<b>5</b>	<b>3</b>	<b>5</b>	<b>2</b>	<b>5</b>	<b>1</b>	<b>5</b>	<b>1</b>	<b>5</b>

cantly (more than two times) and the average number of messages sent by human agents per step doubled. Nevertheless, the total simulation time remains quite acceptable. For example, the total time of ABM operation on one processor when forecasting for 17 years in the first option (without families) was about 7.7 min with the number of agents of eight million, and in the second option (four million human agents with the addition of the family agents formed by them), 16.9 min.

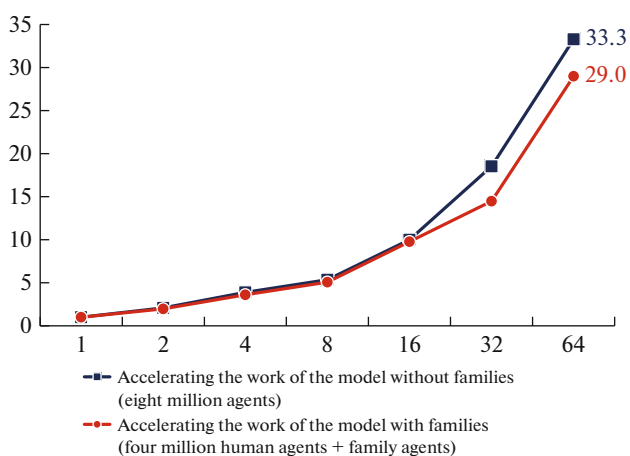
In the new option, scalability also decreased slightly (acceleration of the model, achieved by increasing the number of processors of the supercomputer), although this important indicator of the efficiency of parallel operation of the model remains at a high level (acceleration by almost 30 times for 64 processors), as is shown in Fig. 2.

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Thus, based on the experiments carried out, the following conclusions can be drawn:

- The MÖBIUS design system used to create the demographic ABM of Russia makes it possible to develop complex models that include agents of various types, maintaining social, including hierarchical, ties. It provides their automatic decomposition on a variety of computing processors for efficient parallelization of the program code on supercomputers.

- The MÖBIUS system ensures the synchronization of the reaction of individual ABM elements thanks to the mechanism of dividing its work into stages, and the subsequent aggregation of their characteristics and states along the hierarchy makes it possible to assess the impact of the planned measures on the resulting indicators, which are chosen as targets for the experimenter.



**Fig. 2.** Comparison of the acceleration of the two versions of the model, achieved by using a different number of supercomputer processors, the number of times.

- Adding such a construction as “projects” to the model makes it possible to bring the nature of the experiments closer to the usual planning methods used by practitioners, which increases the attractiveness of the model as a tool for preparing managerial decisions.

For the further development of the software package presented, in our opinion, the following is necessary:

- to introduce other types of projects into the model—monthly cash payments and additional education programs for children, which, as sociological studies show [12], are important for young families making a decision to have a child; and

- to develop mechanisms for imitation of migration as a conscious choice of agents, considering indicators of the quality of life in different regions and their significance for agents. The key subject in both cases should be the family.

#### FUNDING

This study was supported by the Russian Science Foundation, project no. 19-18-00240 “Supercomputer Technologies in the Social Sciences” using the computational resources of the RAS Joint Supercomputer Center (JSCC RAS).

#### CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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Translated by B. Alekseev