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CONCEPT OF THE AGENT-BASED MODEL "DIGITAL DEMOGRAPHIC TWIN OF THE VOLOGDA REGION"

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Studies, aimed at creating realistic models of society to forecast scenarios of demographic development and testing various options of controlling influences on it, is becoming particularly relevant in the context of demographic challenges (depopulation, population ageing, declining birth rate, decreasing contribution of migration to compensate for natural population loss) and the need to achieve strategic national priorities in the demographic sphere. Such an opportunity is provided by digital demographic twins – agent-based models, which are laid the foundations for simulation of individual behavior of separate agents – members of society. Such models serve as a platform for conducting experiments in the sphere of demographic processes management and, consequently, as a tool to support managerial *decision-making. The aim of the paper is to substantiate the concept and program implementation of the agent-based model simulating the region's demographic development (the Vologda Region), designed to test the managerial impact on it. The article considers examples of foreign and Russian agent-based models. Despite the existing developments, it is still relevant the construction of digital demographic twins for individual constituent entities of the Russian Federation, especially for the regions of demographic disadvantage. We present the concept of the agent-based model "Digital Demographic Twin of the Vologda Region": its structural blocks (simulation of population reproduction and migration behavior, simulation of external influences – immigration), types of agents (agents-people and agents-territories) and their properties, characteristics of the external environment, list the main assumptions and limitations of the model, methods of simulation of demographic processes, pay special attention to the scheme of agent-human behavior. We describe the design of the model, and disclose the main parameters of its software implementation. The advantages of the model include the following: taking into account their demographic states and transitions between them when simulating the behavior of agents-people; using data from sociological monitoring surveys; using the new software environment GamaPlatform for modeling; taking into account the territorial factor in modeling and the possibility of detailing the model at different levels.*

Agent-based modeling, digital twin, demographic development, demographic processes, Vologda Region.

Introduction

It is becoming particularly relevant to conduct the research aimed at creating realistic social models to forecast scenarios of demographic development and testing various options of controlling influence on it in the context of demographic challenges (depopulation, population aging, falling birth rate, decreasing contribution of migration to compensate for natural population loss) and the necessity to achieve strategic national priorities in the demographic sphere.

Demographic processes are classic examples of bottom-up processes, as decisions are made at the level of individuals, and overall indicators are formed as a result of aggregation of the actions of these individuals. Therefore, demography is one of the areas of application of the agent-based approach, which is widely presented in the scientific literature (Makarov et al., 2019).

The main idea of agent-based models (ABM) is to build a computational tool that represents a set of agents, an artificial society, which consists of independent agents interacting with each other with a certain set of properties. In this case, the operation of the ABM is based on the simulation of individual behavior of each of the agents – members of this society, and changes in the overall state of the entire system are the integral result of the actions of individual agents (Makarov et al., 2015).

British researcher E. Silverman and his colleagues identified three key problems in demography that agent-based modeling can help to solve: the need to analyze demographic phenomena at three levels – from individuals through households and geographic regions to the society's level as a whole; the need to link statistical data with other useful sources of information to obtain meaningful results about the possible trajectories of demographic processes in the future; addressing the level of sophistication of demographic models and the extent to which empirical data from cross-sectional and longitudinal studies are used in their construction. As the authors note, agent-based models differ significantly from statistical approaches because they can consider phenomena for which there is no explicit analytical representation, thus they can provide explanatory power in the case of nonlinear phenomena or complex interactions (social behavior) and include elements that are difficult to formalize (embedding in social context, networks of relationships and related spatial elements) (Silverman et al., 2013). Digital demographic twins (artificial societies) developed using the agent-based approach act as a platform for conducting experiments in the field of demographic process management (Makarov et al., 2022), hence, serve as a tool to support managerial decision-making.

The aim of the paper is to substantiate the concept and program implementation of an agent-based model simulating the demographic development of the region (Vologda Region), including the main demographic processes, designed to test the managerial impact on it. We set the following tasks to achieve the stated goal:

– review of the experience of developing agent-based demographic models in foreign and Russian studies;

– presentation and substantiation of the concept of the agent-based model "Digital Demographic Twin of the Vologda Region";

– description of the model design, in particular the main parameters of its software implementation.

Theoretical and methodological aspects of the research

The development of computer science contributed to working out a computational approach to the study of human behavior, which began to be applied within the social sciences in the 1990s and was actively developed in the 2000s (Billari et al., 2003), including within the framework of demographic science. Both foreign and Russian researchers are engaged in the development of agent-based demographic models. Among foreign demographic models it is worth mentioning the ***agent-based marriage model, or the so-called the "Wedding Ring" model,*** developed by the pioneers of agent-based computational demography F.C. Billari and colleagues (Billari et al., 2007). It is based on the assumption that the formation of a marriage partnership is the result of social interaction between heterogeneous individuals, with social pressure recognized as the key force driving the process of first marriage. Partner availability and marriage desirability were the main factors in the model for the likelihood of marriage. Partner availability in the human agent population was modeled by considering the set of potential partners both in the immediate environment and within an age group. Marriage desirability was modeled by taking into account the dynamics of social pressure expressed in the share of married people in the corresponding social network. According to the results, the proposed the ABM can reproduce the shape of marriage probability observed at the population level (i.e., the probability function emerges from the bottom-up) (Billari et al., 2007). The level of social pressure determines how far an agent is willing to look in search of an available partner. Thus, agents under more social pressure will expand their search area. Partner search in the model is reciprocal: marriage occurs only when both the agent and a suitable partner are within an acceptable age range. Once an agent is able to find a spouse, he or she will be able to have children, and these children will be added to the population of the Wedding Ring (Silverman et al., 2013).

E. Silverman and colleagues improved ***the "Wedding Ring" model by proposing the "Wedding Donut" model, which describes the formation of partnerships taking into account changes in the health status of people throughout life*** (Silverman et al., 2013). The model offers several extensions at once: instead of a one-dimensional space of agents' habitat (ring), it is used a two-dimensional one (torus); mortality is not limited by a 100-year interval; mortality and fertility are determined by observed (empirical) and projected indicators in England and Wales; the indicators were projected using a variant of the standard Lee-Carter bilinear demographic model; the initial structure of the population by age, sex, and marital status corresponds to the 1951 census data. The authors outline the following advantages of the model: the ability to study the connected lives of simulated people in different scenarios; the ease of embedding the simulation in appropriate social or physical spaces; the integrated approach overcomes some data limitations, as it supplements available statistical information with assumptions about the rules of agent behavior; statistical emulators for sensitivity analysis help to explore the parameter space of basic agent models (Silverman et al., 2013).

A group of American researchers (B. Aparicio-Diaz et al.) developed a ***model of the transition to parenthood that reflects the impact of social interaction on fertility*** (Aparicio-Diaz et al., 2011). The authors did the simulation for women only and took into account different stages of their life cycle, but did not include partnerships. Agents in the model are endowed with three characteristics: age, perceived education, and number (multiplicity) of births. Agents endogenously form their network based on social proximity (an agent's social network is represented by friends, siblings and mother). An agent's social network influences individual birth probabilities and birth multiplicity. The study shows that the developed model, which takes into account the influence of social interactions and social pressure, captures to a high degree the changes in the timing and number of births in Austria over three decades (from 1984 to 2004). The model was also used to project age-specific fertility rates up to 2016 (Aparicio-Diaz et al., 2011).

The researchers from the UK (D. Kniveton, Ch. Smith, Sh. Wood) designed the ***model of changes in migration flows (Ecological Migration Model)*** to reproduce climate migration in 1970–2000 in Burkina Faso and simulated migration flows up to 2060 (Kniveton et al., 2011). Human agents in the model interact with each other and the environment to develop intentions to adapt to changes in rainfall through migration. Agents' migration probabilities are influenced by both individual characteristics and their placement in the social network within which rainfall changes are discussed. Each individual considers adaptation options based on three components: their attitudes toward adaptive behavior, their subjective norm (or assessment of others' expectations), and their perceived behavioral control (or perceived adaptive capacity). Taking into account the characteristics of the individual, migration probability values are used to reflect the normative probability that such an individual will undertake each adaptation option. The model shows that shifts to drier climates lead to the largest overall and international migration flows, coupled with changes in inclusive and interconnected social and political governance. While the lowest international migration flows occur in wetter climates with exceptional and diverse governance scenarios (Kniveton et al., 2011).

Russia is also developing agent-based demographic models. For example, a team of researchers from the CEMI RAS (V.L. Makarov, A.R. Bakhtizin, E.D. Sushko) developed a ***demographic model of the Russian region,*** based on which the reproductive behavior of the population was simulated (Makarov et al., 2015). The agents in the model were divided into two groups with different reproductive strategies: the agents of the first group adhere to the traditional strategy, characterized by high fertility, and the agents of the second group adhere to the modern strategy, with significantly lower fertility. At the same time, both types are represented on the same territory, although in different proportions for representatives of different ethnic and social groups (for example, there is a noticeable difference between urban and rural populations). In the model, based on the use of probabilistic mechanisms, the processes of natural population movement in the region – mortality and fertility – are simulated. The extinction of agents occurs in accordance with sex-age mortality rates, but the same for the entire population. The creation of new agents (birth of children) in the model is the result of the choice of female agents of reproductive age and depends on their internal attitudes related to belonging to one or another group. The age and social structure of the region as a whole is formed as a result of aggregation of the actions of individual agents. In the course of experiments, the authors found that the developed agent-based model, despite the obvious simplification of reality, faithfully reproduces both the initial state of the population of a conditional region, including its sex-age and social structure, and the dynamics of the main characteristics of this population (Makarov et al., 2015).

Later, the same group of researchers developed an ***agent-based demographic model "Russia"*** that recreates in an artificial environment the structure and features of the functioning of real socio-economic systems, as well as technologies for implementing such ABMs in a supercomputer environment (Makarov et al., 2018; Makarov et al., 2019; Makarov et al., 2022). The basic block of the model is the block simulating the processes of mortality, fertility, and migration. Mortality in the model is simulated based on the use of statistical data on the age-sex structure of the deceased for the modeled region, while the simulation of fertility and migration is based on the individual behavior of agents, depending on both the internal properties of agents and environmental factors. Each human agent chooses a partner, creates a family and "gives birth" to a child (creates a new human agent) in accordance with the reproductive strategy peculiar to him/her, depending, in turn, on the agent's commitment to a certain type of reproduction. The agent has the following properties: age, sex, maximum desired number of children in the family and number of children already born. In addition, the agent "remembers" its family ties. For this purpose, the model uses its individual collections (lists) – collections of parents, children, siblings, and other relatives (Makarov et al., 2018; Makarov et al., 2022). Agents in the model are induced to migrate by the difference in the level of average per capita income between different regions, as well as the availability of attractive jobs in other regions or their absence in the region of residence. The social ties of agents (e.g., kinship ties), on which the level of agents' awareness of labor market conditions largely depends, play a major role in migration decisions (Makarov et al., 2018).

The team of researchers from the Federal Autonomous Scientific Institution "Eastern State Planning Center" (E.A. Rossoshanskaya, T.A. Doroshenko, N.A. Samsonova, etc.) developed an ***agent-based model of the Far Eastern Federal District*** with a detailed description of 11 constituent entities of the Russian Federation, including 230 municipalities, and implementation on a real scale (1:1) (Rossoshanskaya et al., 2022). The structure of the model reflects the components of population change and includes natural (the ratio of births and deaths) and migration (the ratio of arrivals and departures) growth. The relationship between the components of population change is modeled in the framework of the conditional life trajectory of an agent, which includes educational, labor, family and migration trajectories. Transition between life cycle stages and trajectories is described by system parameters and constraints, external environment characteristics, functional dependencies both for individual elements and processes and for their totality. The main element of the model is a human agent (persona), which has individual properties and belongs to a family and household. Persons in the model can be aggregated into the total population of a municipality, subject or macro-region. The element "region" has a number of characteristics reflecting the attractiveness of the territory for residence/migration inflow of population, which is required to assess the integral and regional levels of attractiveness of regions in the Far Eastern Federal District, including taking into account the implementation of experimental calculations on the implementation of measures of state migration and social policy. The element contains summary population statistics at the level of macro-region, regions and municipalities. In the course of the model's operation, the probabilities of transitions between states are calculated for a human agent on the basis of behavioral strategies, and his/her decisions are determined using a multiplier of values of certain factors or algorithms based on the comparison of alternatives (Rossoshanskaya et al., 2022).

Agent-based models simulating individual demographic processes are also being developed. For example, T.A. Doroshenko created the ***ABM of educational migration in the region*** (case study of the Vologda Region), simulating the process of population movements in connection with studies, taking into account the migration attitudes of individual people agents, the behavior of educational organizations and the policy of regional authorities (Doroshenko, 2019). The model identifies three types of agents: agent "person", agent "educational organization", agent "power", each of which is endowed with characteristics represented in the form of parameters. Agents-people (entrants) are divided into three groups: graduates who entered medical universities (and, therefore, left the region), graduates who entered specialties other than medical; graduates who did not enter anywhere (no educational migration). In the course of the decision on the place of education, human agents are categorized into subgroups: "low-income", "in pursuit of prestige", "close family ties", "concern for the future" and "just to get in and go". The agent "managers" is present in an implicit form, its behavior is set by changing the controlled parameters of the model (setting the number of budget places; introduction of additional regional scholarships). The impact on the behavior of other agents occurs by regulating the parameters of the agent "educational organization" (setting passing scores; enrollment/denial of enrollment; opening new specialties; setting the number of paid places; determining the cost of education). The model environment is the territory of the region with its educational environment. In the course of the model operation, during each step of the model time, a population of agents with the number equal to the number of graduates of general education organizations is created, then they are endowed with characteristics (parameters). Based on the empirical distribution, agents are subdivided into three groups, acquiring the corresponding states. Depending on the given parameters of the agents of each group and in accordance with the parameters of the agent "educational organization", the conditions of the conceptual model the whole population is divided into those who left the region and those who remained. At the end of each model time step, all agents of the population are removed. Numerical data on the distribution of graduates by groups allow us to estimate the process of educational migration in the future. The developed ABM showed correspondence to the real system, and computational experiments in the model of educational migration allowed identifying the best scenarios of action of agents of all types (Doroshenko, 2019).

In the considered agent-based models, either individual demographic processes or the demographic situation as a whole is simulated by modeling its individual components (natural movement and migration). Some of the above models take into account the behavioral factor in the simulation of demographic processes by using data from sociological surveys, for example, by introducing reproductive (desired number of children) and migration attitudes as characteristics of agents.

Despite the existing developments, it seems promising to build "digital demographic twins" for separate constituent entities of the Russian Federation, which is largely due to the significant regional differentiation of demographic development in Russia and the need of regional authorities in effective tools for its management, taking into account territorial specifics. The demand for the development of the agent-based demographic models is especially great for regions in the group of demographic disadvantage, which is important for finding mechanisms to overcome depopulation. In addition, the consideration of the behavioral factor in modeling all processes – fertility, mortality and migration – is of great importance. This becomes possible thanks to the data of sociological surveys, which contain information about individual attitudes to family formation, childbearing and change of place of residence, as well as about their motives and factors.

Concept of the agent-based model "Digital Demographic Twin of the Vologda Region"

We chose the Vologda Region as a model region within the framework of the study. The region is stably included in the group of the RF constituent entities with a declining population due to the double effect of natural and migration attrition (Shabunova et al., 2021). In the post-Soviet period depopulation in the region did not stop for a single year (Rybakovskii, 2023). This fact emphasizes the demand for the development of an agent-based demographic model of the Vologda Region to find management tools and mechanisms for the region's exit from depopulation. When reflecting both the concept of the model and its program implementation, we will adhere to the logic of the Russian-language adapted form of the ODD-protocol proposed by a team of researchers (V.L. Makarov, A.R. Bakhtizin, E.A. Rossoshanskaya et al.) (Makarov et al., 2023).

The purpose of modeling is to develop a realistic computer model simulating the demographic development of the region (Vologda Region), including the main demographic processes, which is designed to test the management impact on them. The model allows forecasting the number of the region's population (including gender and age groups), key demographic processes, conducting experiments to substantiate the effectiveness of regional socio-demographic and migration policy measures.

The model distinguishes the following structural blocks to adequately reflect the modeled processes.

1. Block of population reproduction and migration behavior simulation (internal migration, emigration)

This block simulates the processes of creation and destruction of couples (families), fertility (birth of children), mortality, as well as the movement of agents within the region (arrival and departure within the region) and departure outside the region. Mortality is simulated on the basis of the age and sex structure of mortality in the region (mortality rates by gender and age) and the corresponding probabilities of death for individual sex-age groups. Creation of couples (families) is modeled on the basis of sex-age probabilities of marriage unions (for nonfamily agents aged 16 years and older). Simulation of fertility is realized on the basis of the decision of female agents of reproductive age to procreate, depending both on their reproductive attitudes (desired number of children) and the availability of a partner, and on external conditions (socio-economic situation, socio-demographic policy). Migration within the region is simulated on the basis of migration attitudes (attitudes to move) and external environmental conditions reflecting the attractiveness of a particular territory.

2. Block of external simulation unit (immigration)

Immigration simulation is carried out through modeling the arrival of new agents in the region under the influence of the parameters of the territory's attractiveness.

The model assumes the following types of agents: human agents and agents-territories (administrative-territorial units). The top-level agent is the model itself (macro-agent-region). Human agents are the main type of agents, territorial agents are an auxiliary type of agents that create a habitat for human agents. The agents of the model are endowed with a number of characteristics or properties *(Tab.)*. Human agents appear in the model during the initial formation of the population, the birth of children, and entry into the territory of the region (immigration). The removal of human agents occurs in the event of their death and departure from the region. Agents-territories are set during the initial formation of the model, their number is constant and corresponds to the number of administrative-territorial units (municipalities) in the region.

Table. Model agents and their characteristics

Type of agent	Characteristics
Human agents	- Individual number, belonging to a settlement/ municipality (place of residence); - gender, age (birth data); - marriage status; - duration and frequency of marriage; - presence and actual number of children; - level of education; - employment status; - type of job - income rate; - family affiliation and kinship; - household membership; - reproductive attitudes; - attitudes toward marriage; - self-preservation attitudes; - migration attitudes; - health status
Agents-territories (administrative-territorial units)	- Territorial location; - number of permanent population (including urban and rural population); - number of enterprises; - corporate wages; - indicators of social infrastructure development (number of educational organizations of pre-school, school, vocational education, education coverage, number of health care institutions, provision of medical personnel and beds, housing conditions (provision of the population with housing)
Source: own compilation.	

The external environment reflects the features of spatial location, demographic, biomedical, socio-economic and political parameters. Its characteristics include, respectively, spatial (location of settlements; population distribution by localities), demographic (total population, including rural and urban, age and sex structure of the population, age and sex mortality rates, life expectancy, age-related fertility rates, total fertility rates, age and sex marriage and divorce rates, distribution of the population by marital status, distribution by number of children, etc.), biomedical (characteristics of population health), socio-economic (indicators labor market and employment structure, finance, health and education, income and expenses of the population, housing conditions, etc.), political (indicators of socio-demographic and migration policy) indicators.

We involve the data of the Federal State Statistics Service and its territorial department in the Vologda Region (current statistical records and the All-Russian population census) to fill the model with real data and determine the characteristics of agents; and the data of representative monitoring sociological surveys of the Vologda Region population (monitoring of reproductive potential, physical health of the population, etc.) – to determine the behavior of human agents.

The theoretical basis for the model was the provisions of the concepts of demographic and epidemiological transition, demographic behavior (including the need for children), and mobile transition (stages of the migration process).

The model utilizes a number of assumptions and constraints:

– the agents in the model are persons permanently residing in the territory (i.e., the permanent population); the temporary population is not taken into account;

– demographic situation in the model is formed as a result of the actions of human agents, agents-territories form the environment (space) of their habitat, other agents do not influence demographic processes;

– when simulating the processes of fertility and family formation, the model did not take into account the types of marriage partnerships and families (polygamous, same-sex), which are rare and not enshrined in legislation;

– births in the model occur within partnerships (unregistered and registered marriages), births outside partnerships are not considered due to the difficulty of their statistical recording (non-marital births reported by the mother include births within unofficial marital unions);

– death in the model occurs independently of the agents (set by the parameters of survival), i.e. voluntary resignation is not taken into account (suicides account for less than 1% of deaths in the region according to data for 2022), while childbirth and moving are largely determined by the agent's decision;

– an agent's departure outside the region (emigration) is by default recognized as irretrievable, as there are no statistical data on return migrations;

– place of residence of minor human agents is determined by the place of residence of both their parents (in case of cohabitation) or one of their parents.

Figure 1 shows the conceptual scheme of the ABM "Digital Demographic Twin of the Vologda Region", reflecting the components of population formation, as well as their factors. Population formation is based on the demographic balance equation, which describes the contribution of natural movement (the ratio of mortality and fertility) and migration (the ratio of arrivals and departures). Separately, the processes of marriage and divorce are reflected, which do not directly affect the population, but affect the reproduction process, namely the birth rate. The factors indicated in the diagram contain both the characteristics of the external environment and the parameters of individual behavior.

We used the following methods to simulate demographic processes.

1. Calculation of probability indicators of mortality, fertility, marriage, divorce and migration, including from demographic tables.

2. Age-movement projection method, which assumes that the initial population size and structure are "moved" into the future,

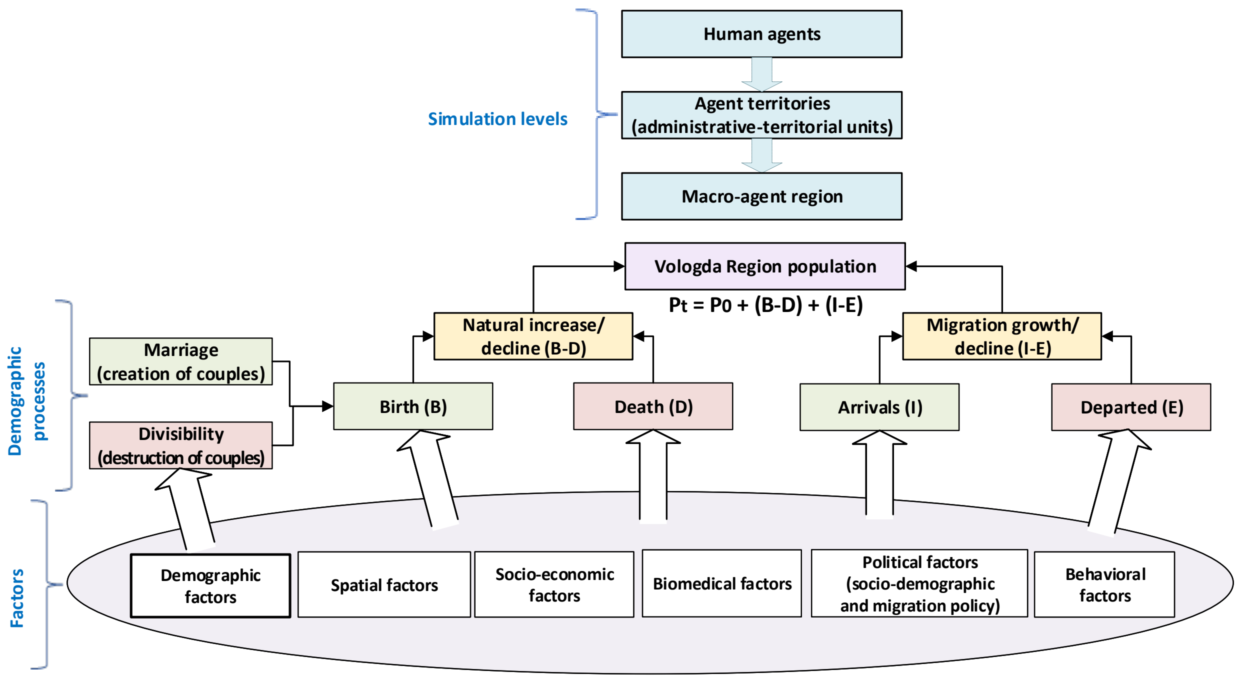

Figure 1. Conceptual (logical) scheme of the ABM "Digital Demographic Twin of the Vologda Region"

Note: Pt – permanent population at the end of the year; P0 – permanent population at the beginning of the year; B – number of births; D – number of deaths; I – number of arrivals; E – number of departures.

Source: own compilation.

decreasing at the expense of the dead (and departed) and increasing at the expense of the born (and arrived). The initial data for the projection are the size and structure of the population (usually based on the population census) and hypotheses about the trends in population reproduction and migration in the projection period.

3. Component-by-component method based on taking into account the dynamics of key demographic indicators, namely, the rates of change in fertility and mortality rates over the previous several years. On their basis, indices are constructed, which are used in modeling for changes in demographic indicators of each forecast year in the method of moving ages (Makarov et al., 2015; Sushko, 2012).

4. The method of typology of demographic behavior (allocation of types of reproductive, matrimonial, self-preservation and migration behavior on the basis of sociological data).

The main elements of the model are human agents, since their behavior and interaction with each other and the external environment determine the integral state of the entire system. The behavior of a human agent consists of a change in demographic conditions during the onset of both recurring and non-recurring events *(Fig. 2)*. States change based on the set decision-making rules governing the behavior of agents depending on the internal properties and characteristics of the environment (Makarov et al., 2015). A new human agent appears in the case of the initial formation of a population of agents, the birth of children, entry into the territory from outside (from outside the model region). An agent is removed from the model in the event of their death and migration outside the region.

The parameters of the model, controlled exogenously (user settings), are the duration of the forecasting period, the average desired number of children in a family, the average age of a woman at birth, indicators of the migration attractiveness of the territory (availability of educational institutions of secondary and higher education, unemployment rate, wages, housing provision), premature mortality (from preventable causes of death).

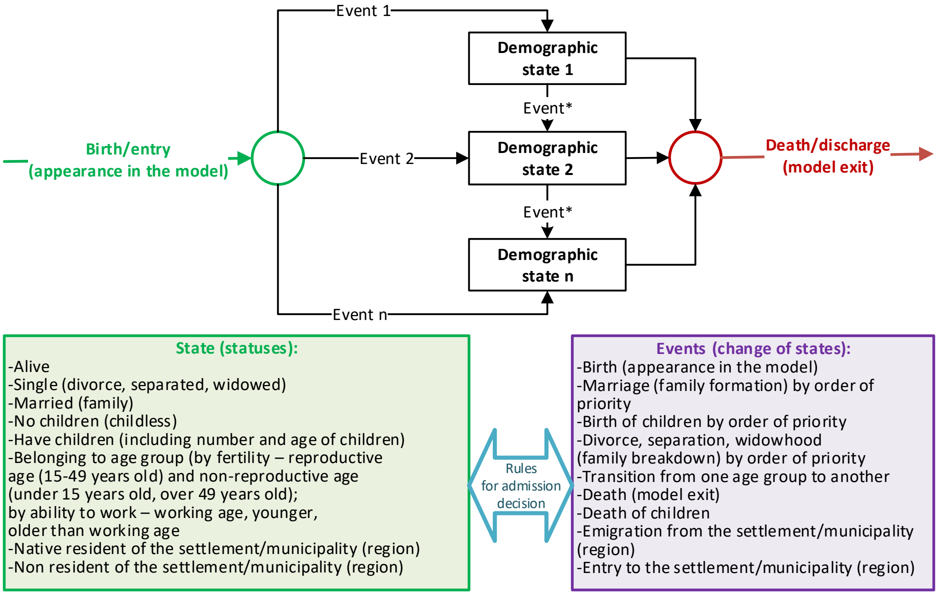

Figure 2. Behavior pattern of a human agent

* In the case of non-recurring events (for example, the birth of an agent, the transition from one age group to another, the conclusion and dissolution of marriage in order, the birth of children in order, the death of an agent), the transition between demographic states (statuses) is unilateral (→). In the case of recurring events (for example, a change of residence), a two-way transition is possible the transition (↔).

Source: own compilation.

Software implementation of modeling

At this stage of the study, we test the realization of the above aspects of the model at the technical level. To this end, the research implements an extensible prototype of the model, reflecting its basic components. The prototype of the model is made in the agent-based simulation environment of the GAME Platform[1], which we have chosen as a development toolkit based on the following considerations:

– the development environment is based on RCP (Rich Client Platform), which provides ease of use and flexibility of interface settings;

– GAML is an agent-based language designed to simplify the process of model development;

– support for a variety of data types, including GIS, images, tables and 3D models, enabling the development of complex and diverse models;

– availability of Unit-testing facilitates debugging and improves code quality;

– wide functionality, comparable to general-purpose object-oriented languages, makes GAML suitable for creating complex and detailed models;

– Java affinity opens up opportunities for integration with other tools and extending functionality;

– the openness and accessibility of the platform make it attractive to researchers and developers who want to create their own tools and push the boundaries of agent-based modeling.

We chose the Vologda Region municipalities as the human agent settlement regions for the prototype model. The regions are filled with the population according to Rosstat data. Time in the model is measured in calendar years, the modeling step is equal to 1 year. The scale of model realization is 1:1. At each step human agents are checked for the state of reproductivity, which consists, within the framework of the developed prototype, in comparing the age of the agent with the given reproductive interval (for women, it is 15–49 years, for men – 15–60 years). Male human agents in a reproductive state with no partner-form couples with females of reproductive age. Subsequently,

[1] The source code of the project is available here. Available at: https://github.com/mrDianov/VologdaDemographyABM

these couples either have offspring or, if they refuse to procreate, remain childless. When couples are formed, potential partners are screened to ensure that they are unmarried as well as closely related. These processes occur in isolation in different regions of residence, which models the dependence of demographic dynamics on population size (for greater adequacy, population density can be taken into account in the future). Within the formed pairs new human agents are created, thus modeling the childbirth process. The child birth occurs with a given probability (formed from statistical data) and depends on the number of children already born to a given couple. The final stage of a human agent's life cycle is its death. The probability of death is calculated at each step and depends on the age and gender of an agent.

Further detailing and expansion of the model to use it as a management decision support tool is envisaged at subsequent stages of the project.

Conclusion

On the one hand, the agent-based model "Digital Demographic Twin of the Vologda Region" is based on the existing developments of the demographic ABM, in particular, it takes into account the basic principles and algorithms of their construction, methods embedded in modeling, implementation schemes, approaches to selecting agents and defining their key properties; on the other hand, it develops the modeling methodology by using new tools (new software environment GamaPlatform), new types of agents (agents-territories), expanding the list of behavioral characteristics of the Vologda Region, as well as by using new tools (new software environment GamaPlatform). The digital demographic twin of the region will allow not only forecasting the number and age and gender composition of the Vologda Region population, as well as the main demographic processes, but also assessing the impact of management decisions on different parameters of the region's demographic development using scenario computer experiments.

The advantages of the model include taking into account in simulating the behavior of human agents of their life cycle, namely demographic states and transitions between them in the course of repeated and non-repeated demographic events; the use of data from sociological monitoring surveys reflecting the parameters of demographic behavior; the use of the new software environment GamaPlatform for modeling; taking into account the territorial factor (by introducing agents-territories) and the possibility of detailing the model at different levels (both municipalities (districts and okrugs) and certain settlements).

At the next stages of the project, we are planning to continue the implementation of the model in the programming environment, its graphical representation, testing and verification of correctness of work, and computational experiments. In the future, by analogy with the simulation of pair (family) formation, fertility and migration in the simulation of mortality, we intended to adjust the model by the characteristics of self-preservation behavior (in particular, behavioral risk factors). In addition, a promising direction of the model development is to take into account the spatial factor in it through the GIS-technologies. The successful implementation of the agent-based model for the Vologda Region in the future will help to develop digital twins for other regions with similar demographic development parameters on the analogy.

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