THEORETICAL AND METHODOLOGICAL APPROACHES TO THE RESEARCH INTO SOCIAL SPACE

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CONCEPTUAL SCHEME OF AN AGENT-BASED MODEL OF REGIONAL HEALTH CARE

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In the context of growing demand for medical services on the part of the population and limited available resources of regional health care, the development of tools that allow risk-free testing of management decisions in this area is of particular relevance. One of the modern approaches to solving this problem is agent-based modeling. Despite the fact that Russian and foreign studies have repeatedly proposed variants of models of individual components of the health care system, no comprehensive solution applicable at the regional level has been developed. The aim of the study is to substantiate the conceptual scheme of the agent-based model of regional health care (case study of the Vologda Region). We present the key characteristics of the model agents, its structure, assumptions and limitations, and justify the choice of input data for model construction and software environment for its realization. We outline the advantages of the proposed model, in particular, its applicability for testing management decisions in various subsystems of regional health care. The practical significance of the research results is that the output parameters of the model (indicators of population satisfaction with medical care, the level of workload on doctors, attendance of medical organizations, the mortality rate in certain classes of diseases), calculated within the framework of experiments, will be used to assess the effectiveness of the regional health care system along with the indicators of resource costs for its functioning. This will make it possible to compare the results of management decisions and choose optimal scenarios (optimizing the load on doctors, choosing a scheme of spatial location of medical infrastructure facilities, adjusting the volume of financing of medical organizations, etc.).

Agent-based modeling, medical care, medical activity of the population, efficiency of regional health care.

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Introduction

The specifics of the current stage of development of the Russian healthcare system lie in the growing contradictions between the existing approach to healthcare funding and the interests of regions' spatial development. One of the consequences of this conflict is increasing inequality in access to medical services for the population (Shabunova, Natsun, 2023). This problem is becoming especially relevant for residents of small cities and rural settlements. An additional number of problems are being formed under the influence of the modern demographic situation and the unsatisfactory state of public health in Russia's regions.

The most serious challenges facing healthcare today are as follows: demographic aging; high premature mortality of the Russian population; significant gap between life expectancy and healthy life expectancy, reflecting the burden of diseases accumulating in older cohorts of the population; the fact that people have to use paid medical services due to lack of resources to provide free medical care in the public health system (Morozova et al., 2022); lack of funding for territorial programs of state guarantees for providing free medical care to the population (Grishin et al., 2021).

These challenges lead to increased competition for limited resources between different types, forms, and profiles of medical care. In this regard, the problem of improving the effectiveness of the healthcare system comes to the fore. The possibility of meeting people's demand for medical care as fully as possible, and, consequently, to a large extent, public health indicators, depends on its successful solution.

There are various approaches to assessing the effectiveness of regional healthcare. Thus, a systems approach involves considering regional healthcare as a system that includes a number of subsystems. The immediate results that can be obtained within the framework of this approach include construction of models of the entire system and its individual subsystems, construction of information and structural and functional models, models of interaction, system management, models of system optimiza-

tion, resource allocation, creation of programs for the implementation and improvement of the system, substantiation of management decisions. Conducting a systems analysis involves using indicators characterizing public health, the activities of healthcare institutions, as well as their resource provision (Lebedev, 2007).

Assessing the effectiveness of regional healthcare using the cost – effectiveness method allows us to move from cost planning to planning specific results in the formation of regional and local budgets. When using the cost – effectiveness method, the volume indicators of medical services provided to the population, primary morbidity, morbidity, primary disability, mortality, morbidity with temporary disability, and the number of complaints from the population about the quality of medical services provided are used as the resulting indicators of healthcare (Ilyin et al., 2006). The advantages of this approach to assessing the effectiveness of regional healthcare in terms of management are its high information content and the clarity of the conclusions.

In general, to analyze the economic effect of management decisions in the healthcare sector, it is sufficient to use the abovementioned cost – effectiveness method. However, it does not allow us to directly identify the key social factors that determine morbidity and premature mortality of the population and are not amenable to regulation by the healthcare system. Therefore, the results of such an analysis should be interpreted only in conjunction with data on the prevalence of major social risks. Also, the indicators of healthcare financing used in the framework of the considered approach and statistical data on mortality and morbidity alone do not allow us to identify problematic issues in the interaction of the healthcare system with the population. Simulation models of healthcare can serve as a successful solution to fill these gaps.

The use of simulation modeling in the study of the functioning of comprehensive socio-economic systems is an actively developing field in foreign and domestic science (Makarov, 2013; Brajnik, Lines, 1998; Pyka, Werker, 2009; Edmonds, 2010). This toolkit has been successfully used to solve large-scale problems in the field of socio-economic research (Makarov, Bakhtizin, 2013; Okrepilov et al., 2015; Okrepilov et al., 2015; Makarov et al., 2018). In demography, an example of such a task is the creation of a digital twin of the region (Kalachikova et al., 2024).

The practical point of creating simulation models is to support management decisions, since they allow for risk-free testing of new management mechanisms (Rossoshanskaya et al., 2022), to assess the effect of changes in financing parameters or spatial location of infrastructure facilities (Dianov et al., 2021; Shvetsov et al., 2023). Their special case is the agent-based approach, the reliability of which is determined, among other things, by a qualitative description of characteristics of agents and rules of their interaction.

The use of agent-based models is possible at the level of the healthcare system as a whole, at the level of its individual subsystems (for example, for specialized medical services) and medical organizations (Tracy et al., 2018). The research of foreign authors presents solutions and approaches using simulation models to solve the problems of queues in the preventive healthcare sector, in hospitals and emergency departments. It has been shown that simulation modeling is applicable to solving problems of optimizing patient routing processes ("clinical pathways") and managing their treatment (Aspland et al., 2019). Thus, the use of discrete-event simulation allows identifying ways to reduce the time needed to treat patients with lung cancer. In particular, due to the high accuracy of the model's predictions, scenarios were found in which the time from the first visit to the doctor and the establishment of a preliminary diagnosis to receiving the necessary treatment was reduced to 40 days for patients with a target value of 62 days (England et al., 2021).

In Russian practice, research aimed at building regional healthcare models is relatively rare (Shaganina et al., 2023). There is not enough work aimed at solving problems related to optimizing the cost of the sector's resources and increasing the effectiveness of its functioning. Based on data from the Vologda Region, a num-

ber of publications have presented approaches and software solutions applicable to simulating individual blocks and subsystems of regional healthcare (Dianov et al., 2020; Dianov et al., 2021; Dianov et al., 2022; Shvetsov et al., 2023). At the same time, the final conceptual vision of the sector's functioning process and ways to describe it in an agent-based modeling environment has not been developed to date. This makes it important to continue research in this area.

These circumstances determined the choice of the aim and objectives of this study. The aim of the work is to substantiate the conceptual scheme of the agent-based model of regional healthcare. Research objectives are as follows:

1) to analyze the dynamics of Vologda Region healthcare development targets for the period from 2020 to 2023;

2) to conduct a review of Russian and foreign experience related to simulating the functioning of the healthcare system;

3) to look into the concept of the proposed model of regional healthcare;

4) to present the structure of the model, as well as main parameters of its software implementation (types of agents, their characteristics, model assumptions).

Materials and methods

Simulation modeling, in particular agent-based modeling, is one of the modern methods of supporting the management of complex systems, which can include the healthcare sector (Makarov et al., 2022). This trend is poised to increase in connection with the development of computing devices and the art of programming (Makarov et al., 2019; Bandini et al., 2009).

The main advantages of agent-based modeling can be characterized as follows: simplicity of constructing the logic of interaction of modeled objects, possibility of implementing a hybrid approach in modeling. However, since ABM can be fully considered a heuristic, it has the same disadvantages associated with the lack of an absolute understanding of the mechanisms of operation and design of the model. Also, due to the variety of mathematical and instrumental tools used in ABM, there arises a problem related to the correct and accessible description of the simulated structure. There are solutions to this problem, represented by the ODD protocol, DREAM and Template Software specifications, which are well discussed in the PhD thesis (computer science) by M.A.H. Niazi (Niazi, 2011), but they are not comprehensive and are not generally accepted in the scientific community. The above determines the high importance of a qualitative study of the concept of the model under construction and requires researchers to carefully interpret the obtained modeling results.

There is a wide variety of software products for building simulation models (Bragin et al., 2022; Wrona et al., 2023), a significant part of which is focused on using supercomputers (Makarov et al., 2011). In Russian practice, AnyLogic software and services can be called the main tool for implementing agent-based models. The characteristic advantages of this software are localization into Russian, extensive graphical interface, technical support and updating of software products provided by developers. The possibility of integrating the model with GIS maps is also an advantage (Khrol' et al., 2023).

In the framework of this study, data from the Federal State Statistics Service and its territorial department for the Vologda Region are used to fill the agent-based model of regional healthcare with empirical data.

When considering the effectiveness of regional healthcare, medical statistics were used, as well as official government statistics posted on the EMISS. To solve the problems of population behavior modeling, data from sociological monitoring of physical health for 2020, 2022 and 2024 have been taken into account. The monitoring method is a sociological survey of the population aged 18 years and older living in the Vologda Region. At each stage of the monitoring, the sample size was at least 1,500 people. The selection is targeted and quota-based. The survey area includes the cities of Vologda and Cherepovets, and eight municipal okrugs of the Vologda Region (Babaevsky, Velikoustyugsky, Vozhegodsky, Gryazovetsky, Kirillovsky, Nikolsky, Tarnogsky, Sheksninsky).

The representativeness of the sample is ensured by observing the proportions between urban and rural populations, the proportions of the sex and age structure of the adult population, and the proportions between residents of various types of settlements (rural settlements, small and medium cities). Sampling error is no more than 4%.

Results

Key parameters of functioning of the primary level of regional healthcare (on the example of the Vologda Region)

The task of ensuring access to medical care for citizens remains on the agenda as part of the implementation of the state social policy. Thus, the development of the primary health and social care system was one of the priorities of the national project "Healthcare"[1] being completed.

The "Vologda Region Healthcare Development" program includes, among the target indicators for improving the effectiveness of medical care, such indicators as mortality from all causes (per 1,000 people), mortality from diseases of the circulatory system (per 100 thousand people), mortality from malignant neoplasms (per 100 thousand people), mortality from road accidents, mortality from tuberculosis, maternal and infant mortality, life expectancy at birth, coverage of patients with medical rehabilitation, provision of necessary medicines to citizens who are entitled to receive medicines for free, provision of doctors working in public medical organizations, public satisfaction with the quality of medical care. Based on the available statistical data, let us look at how the values of some target indicators changed between 2020 and 2023 *(Tab. 1)*.

As of 2023, the target values have not been reached for almost all target indicators. The exception was the indicator of mortality from all causes. It is impossible to unambiguously assess the indicator "mortality from malignant neoplasms", since there is no data on this indicator in state statistics, and the most relevant regional information dates back to 2021. However, as of 2021, the level of the indicator in question was below the target value for 2023.

The statistics do not contain indicators to determine the satisfaction of the population with the quality of medical care. This gap is filled by data from sociological surveys. Thus, data from a survey of the Vologda Region pop-

Table 1. Values of the target indicators of the regional state program "Vologda Region Healthcare Development" in 2020–2023

Indicator	Year				
	2020	2021	2022	2023	2023, target
Mortality from all causes*	15,7	18,4	14,5	13,8	15,5
Mortality from diseases of the circulatory system**	808,9	860,9	773,9	786,8	694,9
Mortality from malignant neoplasms**	209,0	210,6	n/d	n/d	211,7
Mortality from road accidents**	6,5	7,9	10,2	9,4	6,8
Mortality from tuberculosis**	1,6	1,1	1,1	1,0	1,4
Life expectancy at birth	70,68	69,06	71,56	71,7	72,37
Maternal mortality, cases per 100 thousand live births	9,3	67,5	10,8	33,9	12,8
Infant mortality (per 1,000 live births)	5,5	5,3	3,6	6,0	5,3
Provision of doctors working in public medical organizations, people per 10 thousand people	30,2	31,9	29,1	31,04	34,7

* Per 1,000 people.
** Per 100 thousand people.
Sources: EMISS: State statistics. Available at: https://fedstat.ru; Key performance indicators of healthcare institutions in the Vologda Region for 2021. Department of Health of the Vologda Region. Medical Information and Analytical Center. P. 76.

[1] Federal project "Development of the primary healthcare system". Ministry of Health of the Russian Federation. Available at: https://minzdrav.gov.ru/poleznye-resursy/natsproektzdravoohranenie/pervichka

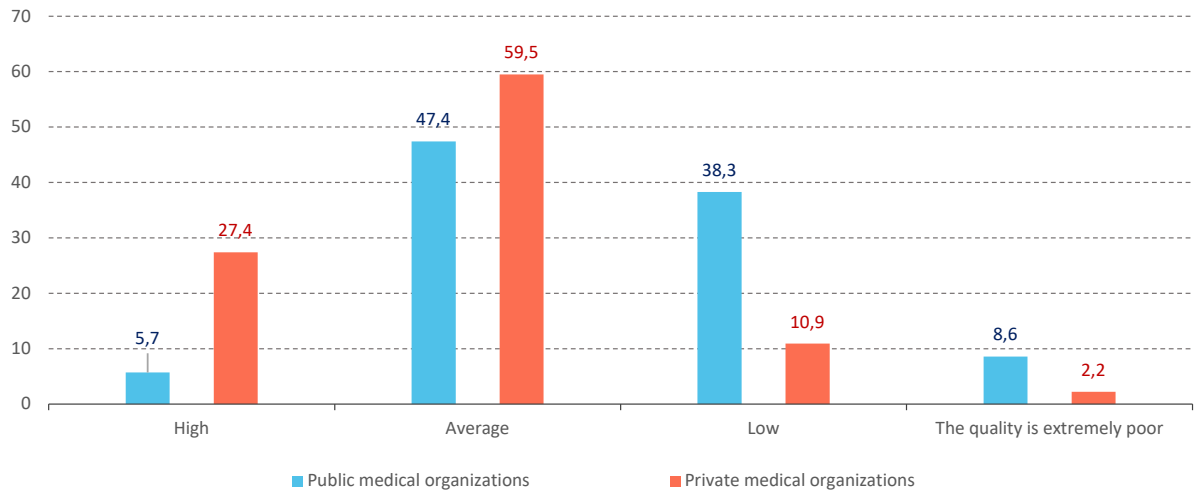

Figure 1. Distribution of responses to the question "How do you generally assess the quality of medical care provided in public institutions (polyclinics, hospitals, etc.) and private medical organizations?", % of those who sought medical help during the year

Source: sociological survey of the Vologda Region population "Studying public health and its determining factors", 2022.

ulation conducted by VolRC RAS in 2022 indicate that among respondents who applied to public medical organizations during the year preceding the survey, 6% consider the quality of medical care provided to them to be high, 47% to be average, 38% to be low, and another 9% responded that the quality of services is "very poor". In comparison, private medical organizations received higher ratings. Of the respondents who had experience contacting them during the year, 27% called the quality of medical services high, 60% average, 11% low, and only 2% noted that the quality of services was "very poor" *(Fig. 1)*.

The satisfaction of the population with the quality of medical care provided largely depends not only on the effectiveness of treatment, but also on the timeliness of receiving medical services. Thus, in a speech by O.S. Zabralova, a senator of the Russian Federation, at the SPIEF in 2022, it was noted that during the project to study satisfaction with medical care in the Moscow Region in polyclinics, patients most often complained about the difficulty of making an appointment with a doctor and the need for regular visits. In the course of this study, it was also revealed that about 10% of all visits to polyclinics are related to obtaining certificates, issuing referrals, obtaining a prescription and other information[2].

In order to improve the accessibility of medical services to the population, a number of activities are being implemented within the framework of the national project "Healthcare", among which an important role belongs to the activities of the federal project "Creation of a single digital contour in healthcare based on the unified state information system in the field of healthcare (EGISZ)". This project is aimed at ensuring accessibility of digital services for citizens through the introduction of electronic document management, telemedicine technologies, electronic doctor's appointment, electronic prescriptions, as well as improving the effectiveness of the healthcare system by creating mechanisms for interaction between medical organizations based on the EGISZ, the introduction of digital technologies and platform solutions that form a single digital health framework[3].

[2] Public satisfaction with medical care is a complex, comprehensive and subjective indicator. Available at: https://mednet.ru/novosti/udovletvorennost-naseleniya-mediczinskoj-pomoshhyu-kompleksnyij-slozhnyij-i-subektivnyij-pokazatel

[3] Federal project "Creating a single digital contour in healthcare based on the Unified State Information System in the field of healthcare (EGISZ)". Ministry of Health of the Russian Federation. Available at: https://minzdrav.gov.ru/poleznye-resursy/natsproektzdravoohranenie/tsifra

Table 2. Statistical indicators characterizing the process of digitalization of healthcare in the Vologda Region in 2021–2024, %

Indicator	2021	2022	2023	2024	Growth rate
Share of appointments with a doctor made by citizens remotely	2.0	2.9	6.3	10.6	81.1
Share of citizens who are users of the Unified Portal of State and Municipal Services (functions) who have access to electronic medical documents in the Patient Personal Account "My Health" based on the fact of medical care provided during the period	0.07	11.9	46.2	76.3	99.9
Share of medical organizations of the state and municipal healthcare systems using medical information systems to organize and provide medical care to citizens, ensuring information interaction with the EGISZ	62.8	97.0	94.8	98.96	36.5
Share of medical organizations of the state and municipal healthcare systems connected to centralized subsystems of state information systems in the field of healthcare of constituent entities of the Russian Federation	26.9	98.7	100	100	73.1
Source: EMISS. Available at: https://fedstat.ru					

In statistics, data reflecting the results of implementation of individual indicators on the digitalization of healthcare are presented starting in 2021. Thus, over the period from 2021 to 2024, the share of remote doctor appointments increased, and the share of users of the Unified Portal of Public Services increased, where electronic medical documents based on the results of requests for medical help are available in the patient's personal account. The share of medical organizations using information systems to provide medical care to citizens and interact with the EGISZ has increased. As of July 2024, all state and municipal medical organizations in the region were connected to the EGISZ *(Tab. 2)*.

The formation of a digital healthcare contour in the future will significantly simplify the routing of patients and accelerate the receipt of necessary medical care. At the same time, the use of information systems will help to increase the effectiveness of management actions only when it is accompanied by a comprehensive analysis of the parameters characterizing the response of the healthcare system itself, as well as the response of public health indicators.

Simulating medical activity of the population in the context of building an agent-based model

The problem of choosing a healthcare provider is considered in detail in review studies by foreign authors (Victoor, 2012). Based on the generalization of the conclusions of numerous studies, it has been established that the hypothesis of the rationality of the choice that the patient makes does not stand up to testing in practice. To make rational choices, patients need complete information about service providers, unlimited cognitive abilities, stable preferences, willpower, and the ability to anticipate their needs (Victoor, 2012). But in reality, these conditions are rarely fulfilled. It has been found that not all patients actively make choices; that is, they specifically search for information about service providers, analyze it, and compare the quality of services (Robertson, Burge, 2011). For example, one study showed that only 10% of patients are looking for an alternative to their local hospital during surgery; they mostly rely on the recommendations of the attending physician, their own positive experience of interacting with a particular service provider, are susceptible to social influence (reputation of the service provider, reviews and recommendations of friends and acquaintances), or choose the nearest service provider (Schwartz et al., 2005). The reasons are that not all patients consider the choice important, the degree of choice for some patients is limited, and the available information is insufficient or unsuitable for decision-making. When choosing a healthcare provider, patients primarily pay attention to the characteristics of the service delivery process, rather than the qualitative indicators of their outcome. At the same time, the authors of the review (Victoor et al., 2012) point to the lack of studies examining the choice of healthcare providers by patients in a real-life situation, rather than as part of experi-

ments, which distorts the understanding of the subject under consideration.

Studies by Russian authors have noted a link between the medical activity of the population and the availability of health services, including due to the remoteness of medical organizations from potential patients. It is also justified that the level of medical activity is higher among people of retirement age (Polyanskaya, 2024). In the work of A.V. Abramov, medical activity is proposed to be considered, on the one hand, as a criterion for the formation of patients' health, and on the other, as a criterion for the effectiveness of doctors (Abramov et al., 2018). Consequently, in this interpretation, medical activity becomes not only a characteristic of the population's health behavior, but also directly characterizes the healthcare system itself. This message fully corresponds to the above data on the existence of a link between the medical activity of the population and the availability of health services. At the same time, it is individuals who make the decision to seek medical help; that is, medical activity primarily characterizes their choice, while the availability of health services is only one of the factors that influence it.

Using the parameters of medical activity of the population as characteristics of agents in the regional healthcare model allows forming more precise rules for the interaction between them and the "medical organizations" type of agents, in particular, to more accurately assess the likelihood of citizens seeking medical care in the context of its various types (primary healthcare, specialized, including high-tech, ambulance, palliative care), forms (planned, urgent, emergency) and conditions of provision (outside the medical organization, outpatient, in a day or round-the-clock hospital).

There are many options for medical activity among the population of the region. For each individual, the parameters of behavior in this area are determined by objective reasons (place of residence, state of health, presence of dis-

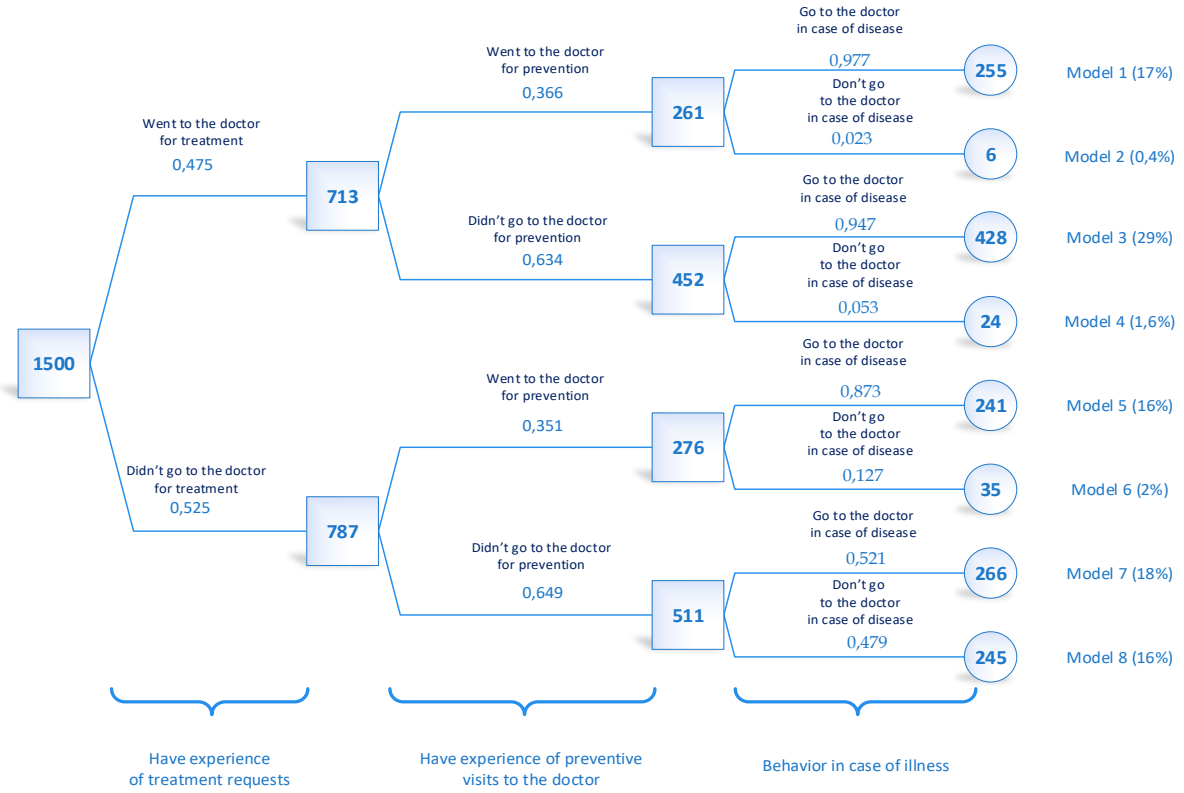

Figure 2. Models of medical activity of the Vologda Region population

Note: the number of respondents who made the appropriate decisions is indicated inside the figures in the diagram.

Source: own elaboration.

ability) and subjective characteristics (values, attitudes, preferences, habits, previous life experience). The data from a representative sociological survey of the Vologda Region population allowed identifying several of the most common typical models of medical activity. To solve this problem, three questions were used: about the experience of seeking medical help, the experience of preventive visits to a doctor, as well as about the willingness to seek medical help in case of a significant deterioration in well-being. Using the "decision tree" method, eight models were identified, but not all of them became widespread in the region *(Fig. 2)*. Based on the obtained typology, for the purposes of this study, agents of the "population" type are assigned a variable value containing the probability that they will adhere to one of the selected models of medical activity.

In the context of all the socio-demographic characteristics considered, the largest proportion of respondents accounted for the standard model of medical activity No. 3 (29% of respondents). This model is characterized by the fact that a person has consulted a doctor about treatment, but has not made preventive visits, and in case of illness usually seeks medical help. That is, such respondents do not have a habit of preventing health disorders, they come to the doctor only when they get sick.

When comparing the socio-demographic characteristics of respondents with different models of medical activity, their gender, age, place of residence, level of education, type of employment, self-reported health, presence of chronic diseases, and disability were considered. The population group with the third model of medical activity included 34% of all women surveyed, 42% of people of retirement age, 30% of all people with higher education, 64% of people with low self-reported health, 24% of all people with chronic diseases, 47% of all people with disabilities, 40% of all people low self-assessment of income, 34% of respondents living in rural areas *(Tab. 3)*.

Diagram of the states of agents of the "population" type

To solve the problem of simulating interactions between the population and medical organizations, diagrams of the states of the corresponding agents were constructed. In addition to the model of medical activity, the key characteristics of population-type agents include the territory of residence, gender, age, self-reported health, presence of chronic diseases, disability group, labor market status, marital status, children, income level, experience of hospitalization (planned or emergency) during the year, number of cases of diseases during the year. A population-type agent has several possible states, each of which has its own parameters for interaction with agents of the "medical organizations" type *(Fig. 3)*.

For agents who initially have chronic diseases, the "sick" status is set in the model. After their conditions change according to the "sick –

Table 3. Socio-demographic characteristics of respondents with different models of medical activity*

Model of medical activity	1	2	3	4	5	6	7	8
№ 1	20.6	18.9	19.0	13.5	15.3	39.2	20.3	15.3
№ 2	0.2	0.0	0.2	3.8	0.2	0.0	0.3	0.2
№ 3	33.8	42.2	30.4	64.4	23.8	47.1	40.7	33.6
№ 4	1.7	0.9	2.9	0.0	1.8	0.0	2.5	0.7
№ 5	17.0	11.5	13.3	7.7	17.0	5.9	9.6	16.7
№ 6	2.0	0.6	2.4	0.9	2.7	0.0	1.9	1.4
№ 7	14.5	17.6	17.3	6.7	20.4	3.9	13.2	16.9
№ 8	10.1	8.3	15.1	2.9	18.8	3.9	11.5	15.1

Designations: 1 – proportion of all women, %; 2 – proportion of all persons over working age; 3 – proportion of all persons with higher education, %; 4 – proportion of all persons with low self-reported health, %; 5 – proportion of all persons with chronic diseases, %; 6 – proportion of all people with disabilities, %; 7 – proportion of all people with low self-assessment of income; 8 – proportion of all people living in rural areas, %.
* 100% – by column.
Source: own compilation.

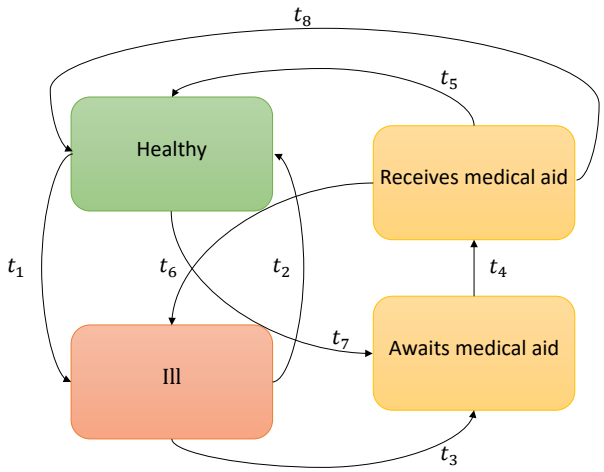

Figure 3. Diagram of states of population-type agents

Designations: t_1 – time during which the agent is healthy; t_2 – time of natural recovery; t_3 – time spent searching for and waiting for medical help; t_4 – time spent on registration, initial diagnosis and referral to a specialist (if necessary); t_5 – time of treatment before recovery; t_6 – time of treatment before the symptoms of a chronic disease are relieved; t_7 – time spent seeking and waiting for preventive medical care; t_8 – time spent receiving preventive medical care.
Source: own elaboration.

awaiting medical care – receiving medical care" scheme, they are again assigned the "sick" status, since there is no definitive cure in the presence of a chronic disease. The healthy – sick – healthy transition reflects a situation where an agent decides not to seek medical help while being sick. The situation of seeking preventive medical care is described by the transition "healthy – awaits medical aid – receives medical aid – healthy". Agents of the "population" type who have gone through a cycle of "healthy – sick – awaits medical aid – receives medical aid – healthy" acquire additional characteristics of the experience of seeking medical help for the purpose of treatment: they remember the duration of waiting for medical aid, and also acquire an opinion about its quality (the degree of satisfaction with medical care). For agents who applied to private medical organizations, the parameter of satisfaction with the price of medical services provided to them is added. In the model, agents of the "population" type can share their experience of contacting medical organizations. Based on the frequency distribution of the assessments received from them, each medical organization will be assigned an average assessment of the quality of medical care for the relevant types of medical services. Based on these values, as well as the criterion of distance from the place of residence, agents of the "population" type who are in the "sick" state will select a place to receive the necessary treatment. Studies conducted earlier on the example of the Vologda Region have shown that the availability of medical care has an impact on the medical activity of the population (Korolenko, 2021). Since the availability of medical care is largely determined by the parameters of the spatial location of healthcare facilities, the remoteness of the location of medical organizations is introduced by us as a predictor of agent behavior. In addition, there is empirical evidence of its relationship with the population's access to medical care in case of illness, as well as with adherence to prescribed treatment (Polyanskaya, 2024).

With regard to agents of the "population" type, it is also necessary to solve the problem of modeling their spatial movement from their place of residence to the place of receiving medical services. The model assumes the rational behavior of agents. Based on this, two criteria for choosing a medical organization are set – its remoteness and the average assessment of the quality of medical services provided in it. The significance of both criteria is assumed to

be equal by default. However, this parameter can be changed if the experimental conditions require it (for example, if necessary, to test the influence of public opinion on the revenue of private clinics). According to the formulated rule, the probability of contacting a medical organization is higher if it is located closer to the agent's place of residence and if it has a higher average assessment of the quality of medical services, which an agent of the "population" type is looking for.

The description of the behavior of agents of the "population" type who are looking for a place to receive medical services is supposed to be carried out using the basic formula of the ant algorithm (1), the parameters of which are adapted to solve the problem. In general terms, it models the laying of a conditionally optimal route by a colony of ants to their food source (Shtovba, 2005). The work can serve as a development of this approach (Beklaryan, Akopov, 2015).

$$P_i = \frac{{\tau_i}^{\alpha} {\eta_i}^{\beta}}{\sum_{j \ni i} {\tau_j}^{\alpha} {\eta_j}^{\beta}}, \quad (1)$$

where:

P_i – probability of choosing the i-th medical organization;

τ – average assessment of the quality of services provided by the medical organization;

η – inverse value of the distance to the medical organization;

α, β – parameters of the importance for the patient of the quality of medical services and the distance to the medical organization.

Agents of the "medical organizations" type are stationary, unlike agents of the "population" type. This type of agent will act as a location for medical services. The only exception to this rule is the "ambulance" agents, who will move through the model's space in accordance with the specified conditions.

Since the model does not aim to detail the interaction between the population and medical personnel, this type of agent is not introduced in it. The characteristics of such interaction, which are essential for the formation of the meso-level model, are sufficiently represented in the data of regional medical statistics. This circumstance allows us to somewhat abstract from the particular cases of doctor – patient interaction and focus on general patterns.

The capacity, the number of doctors by specialty, and the number of visits per 10,000 people will be used as key characteristics of "medical organization" type agents. Also, the properties of each agent of this type will indicate its form of ownership (private or public medical organization) and the range of medical services that it provides.

An agent of the "medical organization" type can have only two states: "service is available" and "service is unavailable". The first option is implemented if the service is included in the list of services provided by a medical organization, if it has spare capacity (equipment, beds, laboratory, visiting teams of medical workers), and currently available specialists (internists, specialist doctors, and nursing staff). If at least one of the essential conditions is not met, the service is unavailable until the status of such condition is reversed.

The conceptual scheme of the regional healthcare system

The regional healthcare model will include several functional modules: primary medical care; specialized outpatient medical care (profiles – cardiology, oncology, obstetrics and gynecology, geriatrics), specialized medical care in a 24-hour hospital (according to individual profiles), emergency medical care.

The software implementation is supposed to begin with simulating the functioning of the module "primary medical care in outpatient settings" based on data from one of the municipal okrugs of the Vologda Region.

In the agent-based model of regional healthcare, the agents of the first level are the population and medical organizations of state, municipal and private ownership. The second-level agent is the Regional Health Department and the Territorial Compulsory Health Insurance Fund. The third-level agent is the region. The behavior of agents is influenced by environmental conditions, factors of various nature, as well as the nature of agents' interactions with each other *(Fig. 4)*.

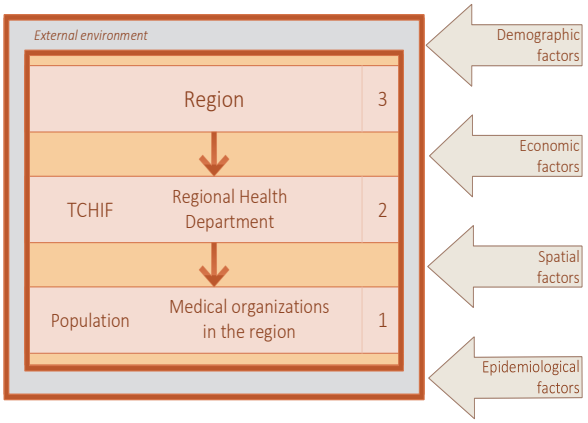

Figure 4. Structural diagram of the agent-based model of regional healthcare

Source: own compilation.

The parameters that will be used to characterize agents of the "population" type are presented in *Table 4*. Initially, a population of agents of this type will be created in accordance with the frequency of occurrence of these characteristics among the population of the Vologda Region. The initial data will be the results of representative sociological surveys conducted in the region by Vologda Research Center of the Russian Academy of Sciences. Agents of the "population" type appear in the model as part of the initial population formation, and are removed as a result of death. When a year passes in the model, the population of agents of the "population" type is completely updated: new parameters are set in accordance with statistical data and representative sample observations.

The parameters that will be used to characterize agents of the "medical organizations" type are presented in *Table 5*. The initial data for characterizing agents of this type will be open statistical data, as well as information provided on the official websites of medical organizations in the region.

As noted above, the spatial location of healthcare facilities affects the medical activity of the population; therefore, when creating a model of a regional healthcare system, its integration with GIS maps will be implemented. All medical organizations will have their own spatial coordinates and will be displayed on the map of the region. Using the capabilities of GIS technologies, calculations of the time of the patient's arrival at the place of receiving medical care, as well as the time of the ambulance's arrival to the patient (when simulating the work of emergency medical care) will be carried out.

The inclusion of both the Territorial Compulsory Health Insurance Fund and the Department of Health as second-level agents in the model is due to the fact that such a solution will allow for more accurate computational experiments according to the "what if" scenario for cases of differentiated changes in the amount of funding for medical organizations in the region from these sources.

The time in the model is measured in calendar days, the modeling step is 1 hour. The following assumptions are accepted in the developed agent-based model of regional healthcare. First, the model does not take into account the impact of migration of "population" type agents on the capacity utilization of medical organizations, since we do not reliably know the quantitative characteristics of the referral of patients from other regions to medical organizations in the Vologda Region. Second, the model assumes that the "population" agents in the "sick" state request and receive the necessary medical care within a period of time calculated taking into account the distance to the medical organization, the workload of internists in this organization, as well as the duration of the appointment itself. The model initially does not take into account possible delays in receiving medical care related to the situation on the roads, queues, as well as exceeding the regulated duration of doctor's appointments. However, these corrections can be introduced during the implementation of computational experiments according to the "what if" scenario. Third, the incidence rate of each agent of the "population" type is set based on a calculated risk function, the arguments of which are the health characteristics of the agent, its gender, age and occupation. Since this function is probabilistic, its individual values will not match the actual characteristics of the patients. At the same time, the result of its calculation for the entire existing population of agents will re-

Table 4. Characteristics of "population" type agents in the agent-based model of regional healthcare

Characteristic	Range of values
Individual number	From 1 to 1500
Gender	male – 1, female – 2
Age	18 – 100
Income level	high – 3, median – 2, low – 3
Education level	higher and postgraduate – 4, secondary vocational – 3, secondary full or general secondary – 2, no secondary education – 1
Employment status	employed – 1, school student/higher school student – 2, retired – 3, unemployed for health reasons – 4, voluntarily unemployed – 5
Marital status	in a registered marriage – 1, in an unregistered union – 2, single – 3
Has/doesn't have minor children	has children – 1, doesn't have children – 2
Has/doesn't have adult dependents in the family	has – 1, doesn't have – 2
Self-reported health	very good – 5, good – 4, satisfactory – 3, poor – 2, very poor – 1
Chronic diseases	no – 0, there is – from 1 to 17 (according to the list*)
Disability	group 1, group 2, group 3, in the process of registration, none
Health limitations	vision limitations – 1, hearing limitations – 2, mobility limitations – 3, self-care limitations – 4, none – 5
Place of residence	Vologda – 1, Cherepovets – 2, municipal okrugs of the region: 3 – Babaevsky, 4 – Velikoustyugsky, 5 – Vozhegodsky, 6– Gryazovetsky, 7 – Kirillovsky, 8 – Nikolsky, 9 – Tarnogsky, 10 – Sheksninsky
Polyclinic / outpatient clinic at the place of residence	the value will be indicated for each agent individually
Usual way to get to the doctor / paramedic (polyclinic, central district hospital, rural health post)	individual motor transport – 3, public transport – 2, on foot – 1
Time it usually takes to get to the doctor	up to 30 minutes –1, from 30 minutes to 1 hour – 2, from 1 to 2 hours – 3, more than 2 hours – 4
Preventive treatment during the last 12 months	yes – 1, no – 2
Treatment requests during the last 12 months	yes – 1, no – 2
Requests for information, statements, and prescriptions during the last 12 months	yes – 1, no – 2
Seeking emergency medical care during the last 12 months	yes – 1, no – 2
Assessment of the quality of medical care provided in public health organizations	high – 3, medium –2, low –1
Assessment of the quality of medical care provided in private medical organizations	high – 3, medium – 2, low –1
Assessment of the level of accessibility of medical care in public health organizations	high – 3, medium – 2, low –1
Assessment of the level of accessibility of medical care in private medical organizations	high – 3, medium – 2, low –1
Model of medical activity	from 1 to 8
Adherence to the rules of healthy lifestyle	high – 3, medium – 2, low – 1
Smoking	smokes – 1, does not smoke – 2
Alcohol consumption	yes – 1, no – 2
Spends more than 8 hours a day in a sitting position	yes – 1, no – 2
Makes an appointment with a doctor via the Internet	yes – 2, no – 1

* Chronic diseases: 1 – hypertension and/or coronary heart disease, 2 – frequent headaches, 3 – joint damage (arthritis), 4 – osteoporosis and/or osteochondrosis, 5 – allergies, 6 – diabetes, 7 – stroke, cerebral hemorrhage, 8 – thyroid pathology, 9 – gastric ulcer and/or duodenal ulcer, 10 - asthma, 11 – chronic bronchitis, emphysema, 12 – chronic anxiety or depression, 13 – urolithiasis, 14 – cataracts, 15 – cholecystitis, 16 – malignant neoplasms, 17 – other diseases.
Source: own compilation.

Table 5. Characteristics of outpatient health facilities in the region

Characteristic	Value
Form of ownership	State/municipal/private
Location	Vologda – 1, Cherepovets – 2, municipal okrugs of the region – from 3 to 11*
Type of institution	Polyclinic Central district hospital Rural health post Clinic
Number of visits per shift per 10,000 people	Number of visits
Number of general practitioners	People
Number of primary physicians	People
* Designations of municipal okrugs: 3 – Babaevsky, 4 – Velikoustyugsky, 5 – Vozhegodsky, 6 – Gryazovetsky, 7 – Kirillovsky, 8 – Nikolsky, 9 – Tarnogsky, 10 – Sheksninsky. Source: own compilation.	

flect the intensity of the population's requests for medical care at a particular time. The fourth assumption of the model concerns the modeling of the number of "population" agents According to Rosstat's forecast, in the medium term, the birth rate will not be able to compensate for the death rate of the population[4]; therefore, in the model, the number of agents of the "population" type is gradually decreasing. The probability of death of agents is determined by the survival parameters. The data source for the calculation is the mortality statistics of the region's population (mortality by age). Since the result of the model is the performance indicators of the regional healthcare system for a certain year, in order to increase the accuracy of calculations, the population of agents of the "population" type is fully updated every time one year passes according to the model time.

Conclusion

The proposed model of regional healthcare will allow conducting computational experiments aimed at solving problems related to optimizing the location of healthcare facilities, financing the industry, increasing the availability of medical care for the population, as well as public satisfaction with medical services. The advantages of the proposed model are related to its modular organization, which makes it possible to detail the experiments conducted for different subsystems of regional healthcare. In addition to the outpatient medical care module, the model is supposed to create modules reflecting the functioning of emergency medical care, as well as the work of hospitals (in several specializations – cardiology, oncology, obstetrics and gynecology). The output parameters of the model will be the indicators of public satisfaction with medical care calculated as part of the experiments, the level of workload for doctors, attendance at medical organizations, and the death rate of the population for certain classes of diseases. Taken together, these parameters, when compared with resource costs, will make it possible to assess the effectiveness of the regional healthcare system. The reliability of the calculation results is ensured by the fact that the initial data for the operation of the model are statistical data characterizing the state of medical organizations in the region, as well as data from sociological monitoring of the physical health of the Vologda Region population. Linking the location of medical organizations in the model to the geographical coordinates of real medical infrastructure facilities in the region will provide more accurate calculations of the time that patients spend on their way to medical organizations, as well as the time that emergency medical teams spend on their way to patients.

At the next stages of the scientific project, work will continue on the software implementation of the model; its graphical description, debugging, correction of calculations, and vari-

[4] Demographic forecast. Demography. Federal State Statistics Service. Available at: https://rosstat.gov.ru/folder/12781

ous types of computational experiments will be carried out. The practical significance of developing an agent-based model lies in creating a management decision support tool that correctly reflects, on the one hand, the existing healthcare parameters of the Vologda Region, and, on the other, the real behavioral practices of the region's population.

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