Research article
DOI: https://doi.org/10.48554/SDEE.2022.3.3

AGENT-BASED MODELLING OF SUSTAINABLE DEVELOPMENT OF REGIONAL HEALTHCARE INFRASTRUCTURE

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Abstract

This study examines the problems of providing support to decision-making in the field of sustainable development of a regional healthcare infrastructure. To tackle these problems, there is a need to fund healthcare systems more efficiently, improve sanitation and hygiene, and provide access to medical services for a wide strata of the population. A network of healthcare organisations should be developed based on the structure and level of morbidity, mortality, gender and age composition of the population, climate and geography of territories, and transport accessibility of healthcare organisations. An important scientific challenge we face today is how the spatial allocation of healthcare infrastructure facilities can be enhanced. The paper presents the authors' concept of building agent-based models that safeguard decision-making on the best spatial allocation of healthcare infrastructure facilities. It includes a formal description of the objective of selecting the best location for healthcare infrastructure facilities, as well as the final description of the models, using a protocol for standardising the description of agent-based models. Relying on this concept, the paper presents a prototype of an agent-based model, built for a real-world system. The concept can potentially be used to solve a wider range of problems related to spatial allocation of social infrastructure facilities, which could ensure sustainable development of the regional social infrastructure.

Keywords: sustainable development, regional infrastructure, healthcare system, spatial allocation, agent-based modelling

Citation: Rodionov, D., Dianov, D., Dianov, S., 2022. Agent-based modelling of sustainable development of regional healthcare infrastructure. Sustainable Development and Engineering Economics 3, 3. https://doi.org/10.48554/SDEE.2022.3.3

Научная статья
УДК 336.645.1
DOI: https://doi.org/10.48554/SDEE.2022.3.3

АГЕНТ-ОРИЕНТИРОВАННОЕ МОДЕЛИРОВАНИЕ УСТОЙЧИВОГО РАЗВИТИЯ РЕГИОНАЛЬНОЙ ИНФРАСТРУКТУРЫ ЗДРАВООХРАНЕНИЯ

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Аннотация

Статья посвящена вопросам обеспечения поддержки принятия решений по устойчивому развитию региональной инфраструктуры здравоохранения. Решение этих задач требует более эффективного финансирования систем здравоохранения, улучшении санитарии и гигиены и обеспечения доступности медицинских услуг для широких слоев населения. Развитие сети медицинских организаций происходит и базируется на основе структуры и уровня заболеваемости, смертности населения, его половозрастного состава, климатических, географических особенностей территорий и транспортной доступности медицинских организаций. Актуальной научной задачей на сегодняшний день является оптимизация пространственного размещение объектов инфраструктуры здравоохранения. В статье представлена авторская концепция построения агент-ориентированных моделей, обеспечивающих процесс принятия решений по оптимальному пространственному размещению объектов инфраструктуры здравоохранения. Она включает формальное описание задачи по оптимальному пространственному размещению объектов инфраструктуры здравоохранения, а также конечное описание моделей с использованием протокола, предназначенного для стандартизации описаний агент-ориентированных моделей. Представлен прототип агент-ориентированной модели для реально существующей системы, созданный на основе данной концепции. Разработанная концепция в перспективе может быть использована для решения более широкого круга задач, связанных с пространственным размещением объектов социальной инфраструктуры. Это послужит обеспечению устойчивого развития региональной социальной инфраструктуры.

Ключевые слова: устойчивое развитие, региональная инфраструктура, система здравоохранения, пространственное размещение, агент-ориентированное моделирование

Цитирование: Родионов, Д., Дианов, Д., Дианов, С., 2022. Агент-ориентированное моделирование устойчивого развития региональной инфраструктуры здравоохранения. Sustainable Development and Engineering Economics 3, 3. https://doi.org/10.48554/SDEE.2022.3.3

1. Introduction

In 2015, the United Nations member states officially adopted a plan of action for sustainable development called "Transforming our world: The 2030 Agenda for Sustainable Development," which includes 17 goals and 169 targets. One of the goals is to "Ensure healthy lives and promote well-being for all at all ages"[1]. Since the Agenda was adopted, considerable success has been achieved in increasing life expectancy and reducing some of the most common causes of death, especially those related to child and maternal mortality. However, the situation was aggravated by the crisis that arose due to the coronavirus pandemic, with many of the current targets being pushed into the background. The crisis also highlighted the need to make additional efforts to completely eliminate a wide range of diseases and resolve many common and new healthcare problems. To address these problems, we must fund healthcare systems more efficiently, improve sanitation and hygiene, and safeguard access to medical services for a wide strata of society.

In August 2020, the Pan-European Commission on Health and Sustainable Development was established. It aims to put forward comprehensive proposals to transform healthcare systems for future challenges. Acting on behalf of the WHO Regional Office for Europe, the commission made the following appeal[2] to its member states:

- Based on the national context, commit to ensuring timely, fair, and equal access to good quality and safe services on testing, treating, and vaccinating against COVID-19 while providing the population with unrestricted access to the main medical services;

- Develop the potential of the country in the context of readiness for emergencies, plan the recovery stage, and get ready for any potential healthcare emergencies in the future.

The 2021 survey "What Worries the World"[3], conducted by Ipsos in 28 countries, showed that every fifth respondent (21%) believed that the ineffectiveness of the healthcare system was a big problem faced by their country. The main barriers to adequate response of the healthcare system to the expectations of people are the lack of resources or non-use of many reserves for increasing the efficiency of the material, labour, and financial resources that are already being used. An interesting finding regarding the efficiency of the healthcare sector in some countries (a sample of 120 countries) with low and average incomes during 1997–2014 (Petitfour, 2017) was the decreasing efficiency of financial investment in the healthcare system as the country became more mature.

Efficient use requires planning. Planning a healthcare system refers to striking a certain balance between the population's needs for medical help, pharmacological support, sanitary-antiepidemic services, and the ability to meet these needs (Gaidarov and Gashenko, 2016). It is essential to introduce methods for evaluating health status and loss of health, and priorities for the efficient use of resources should be determined. Thus, better efficiency and stability of medical services is seen as a must for the sustainable development of a country. To eliminate drawbacks in the healthcare sector and fight new threats, we need a realistic and operative plan of action for the benefit of people, based on the needs, priorities, scientific data, and best practices.

The process of planning a network of healthcare organisations can be divided into several stages: defining a reasonable need for medical care; gauging the required network capacity by type of medical care; forming a rational network structure by type of medical care; analysing the current network of medical organisations; identifying deviations from the rational structure by type of medical care; and developing measures for eliminating deviations. An accurate picture of the current situation can be gained by sound statistical investigation, that is, scientific, accurate, and reliable information. This approach is the basis of management decision-making in healthcare and public discourse on medicine. The net-

1 UN Sustainable Development Goals. Available at: https://www.un.org/sustainabledevelopment/ru/health/

2 Statement Covid-19 a continued call for international solidarity and equity. WHO. Available at: https://www.euro.who.int/ru/health-topics/health-emergencies/coronavirus-covid-19/statements/statement-covid-19-a-continued-call-for-international-solidarity-and-equity

3 What Worries the World - November 2021. Ipsos. Available at: https://www.ipsos.com/en/what-worries-world-november-2021

work of medical organisations must be set up according to their nomenclature. The development of the network should be based on the structure and level of morbidity, mortality of the population, its gender and age composition, climate and geography of territories, and transport accessibility of healthcare organisations.

We are currently witnessing a wider use of simulation modelling for solving problems related to finding the best location for healthcare infrastructure facilities. Unlike other approaches, modelling can be used for detailed description of a system and for analysing dynamic effects, offering a powerful tool for decision-making when problems of spatial allocation of objects are being handled.

One of the advanced methods of simulation modelling is agent-based modelling. Due to their applicability to describing the individual behaviour of system elements, agent-based models can be used to solve a wider range of problems than traditional approaches. They also consider certain aspects of the operation of a complex system in a more sophisticated way (Nianogo and Arah, 2015). When solving the problems of spatial allocation of healthcare infrastructure facilities, agent-based modelling can take into account the specific needs of the population as well as the behavioural attitudes of various social groups. A significant advantage of agent-based modelling is that it considers the changing dynamics in the characteristics of the entities under study over time and the dynamics of spatial allocations of the entities, as well as the possibility of capturing the structure of relationships between these entities (El-Sayed et al., 2012).

Agent-based models can logically incorporate optimisation mechanisms with medical services capable of acting as agents, that is, having their own behaviour model, including territorial allocation. The models can search for the best options for providing services while simultaneously allowing users to cooperate or compete for services. Thus, a model built as close to reality as possible and reflecting a set of basic and principle transactions between the agents within a regional healthcare system can be helpful for making good management decisions related to resource distribution and rational spatial allocation of the infrastructure facilities of the sector.

Despite all the advantages of using agent-based models in healthcare, there are also some constraints caused by the nature of their development and parameterisation. A major problem is the tangible contradiction between the simplicity of the model and its realism. Finding a balance between the wish for a simplified representation of reality and the need to embrace quite complex elements for a new insight is a true art (Hupert et al., 2008), which is developed through trial and error. Therefore, knowing the specifics of the agent-based model, most authors focus on the development of its conceptual structure (Chekmareva, 2017). To build an agent-based model, developers need to overcome the difficulties associated with determining the types of agents, their number, and their characteristics, as well as understand the mechanism by which the agents interact with each other and the external environment (Makoveev, 2016).

The main aim of this study is to develop a concept of agent-based models, safeguarding decision-making on the best spatial allocation of healthcare infrastructure facilities. This paper contributes to the development of the theoretical and applied aspects of building agent-based models related to providing services for social systems.

2. Literature Review

Agent-based modelling is becoming an increasingly popular method for the visualisation, analysis, and evaluation of complex dynamic healthcare systems (Cassidy et al., 2019). These models can be used in virtual experiments designed to manage regional health systems. Due to the complexity of such systems, it is common to create models that embrace individual aspects of their operations. Traditionally, they have been used to predict the development of epidemic crises (Lee et al., 2010). There are agent-based models of emergency care (Brenner et al., 2010; Rohleder et al., 2011; Liu et al., 2014), distribution of the population in a certain territory by medical organisations (Jones and Evans, 2008; Bonabeau, 2002), analysis of patient flows in healthcare institutions (Hutzschenreuter et al., 2008), use of beds in hospitals (Vasilakis and El-Darzi, 2008), and networks of medical services provided for groups of people with a specific disease (Charfeddine and Montreuil, 2010).

Patients act as prototypes of the main agents in the models. They are attributed to domain-relevant characteristics and behaviours. Paulussen et al. (2006) examined agent-based models in the field of medical research and management of medical services and concluded that the characteristics of the agents correlated with the patients' socio-demographic characteristics significant to the problem considered. Thus, Tracy et al. (2018) presented a scheme for a hypothetical healthcare agent-based model (Figure 1). People may have various characteristics at the individual level—ranging from endogenous factors to socio-economic status (blue table at the top)—as well as at the community level (green table at the top), which overlap to form individual behaviour in relation to health and the use of medical services.

As shown in the figure, the creation of a conceptual basis for an agent-based model involves various stakeholders and allows clear assumptions about the aspects of a specific system and how they work together to achieve positive public health results.

Alibrahim and Wu (2018) considered an agent-based model of patient selection by healthcare providers in accountable healthcare organisations. The structure shows the various levels of the modelling system, as well as its various agents—the payer, provider, and patient—and their key components. This model can evaluate the process of choosing a service organisation by the patient. The patient agent has seven variables: three health status variables (diabetes, hypertension, and chronic heart failure) and four demographic variables (age, race, gender, and income). The demographic variables are the predictors of the patient's preferences in relation to the service providers and their activity in searching for a service organisation. Further, the same seven patient-specific variables predict the likelihood of the patient developing chronic heart failure and the various phases of the condition and treatment. The model assumes that hospitals and clinics provide identical services and have identical carrying capacity. Thus, it calculates the number of occasions on which the patient seeks help from alternative providers. The agent behaviour models use a distance parameter, defined as the travel time between suppliers. A higher distance parameter indicates less dense, more dispersed service points, which reduces the probability that the patient will visit all the nearest service providers. A lower distance parameter means there is a more compact distribution of service points; hypothetically, the patient in this scenario is more likely to visit all local providers. The model assumes that the distance between any pair of preferred and alternative providers is the same (60 minutes) to simulate typical rural or urban conditions. In other words, if patients decide to get help from an alternative provider, they have to travel for 60 minutes. In fact, this model determines the degree of influence that distance has on the behaviour of service consumers. The service provider agents are either hospitals or primary care clinics. A key aspect of a provider agent is its ability to decide whether to participate in disease treatment programmes. The payer agent evaluates the quality of the services that have been provided and influences the distribution of investments. The decision-making process of the patient agent who chooses a service provider consists of three phases: perception, intention, and implementation. The decisions that are made affect the reimbursement of expenses for the services, as well as the patients' mortality and hospitalisation rates.

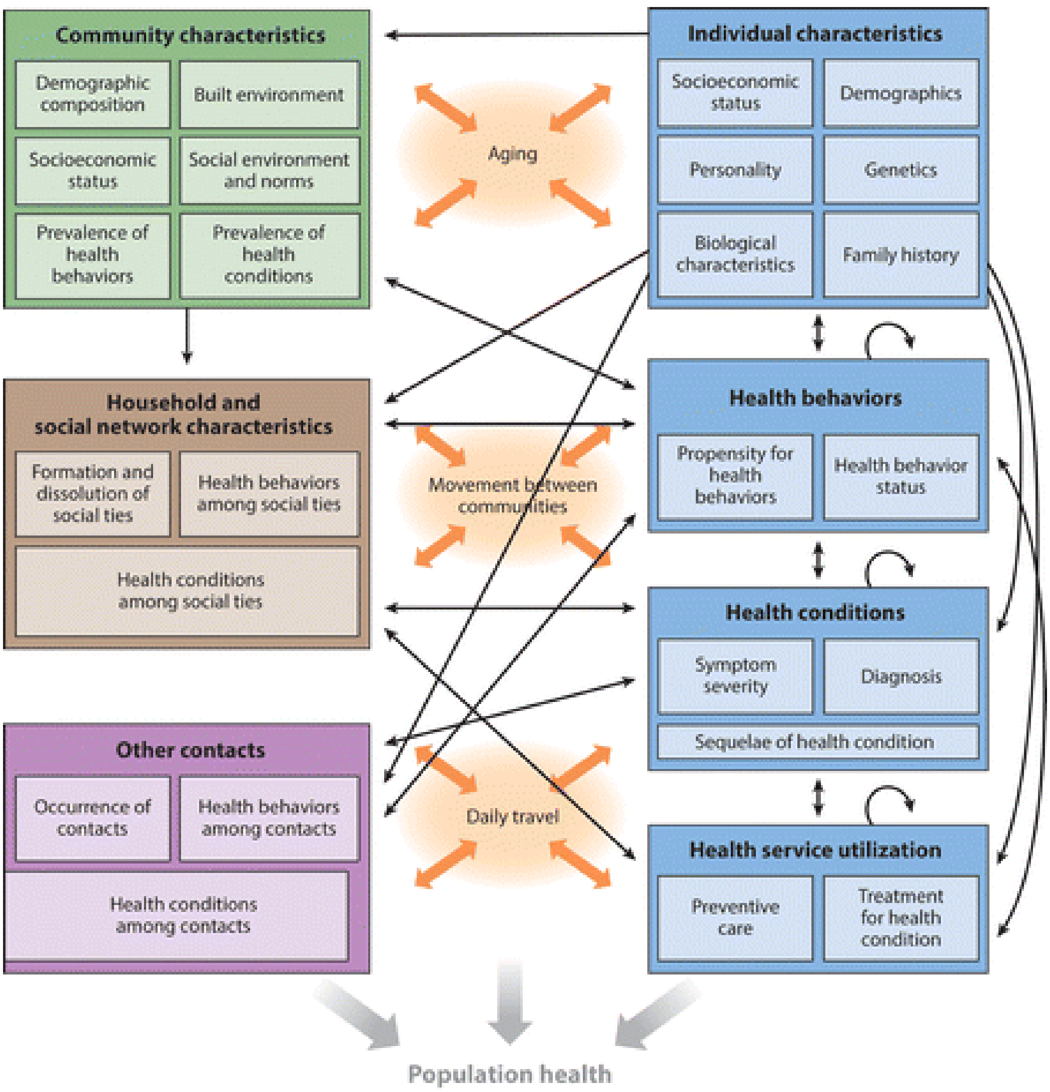

Figure 1. Scheme of a hypothetical agent-based healthcare model

Einzinger et al. (2013) presented a GAP-DRG agent model that is suitable for comparing reimbursement schemes for outpatient treatment. It simulates patients and medical staff as agents. In the simulation, patients with health problems (diseases) and medical service needs are led to healthcare providers. The behaviour of agents in the model is divided into five modules: epidemiology, need for service, use of a provider, provision of services, and reimbursement. The structure of the model allows each patient to have several health problems at a time. Each health problem creates a need for services for each quarter of the year in the form of a list of medical services and their corresponding frequencies. Patients then try to get these services in full scope from healthcare providers (the use of a provider). After they are provided with the services included in their portfolios (provision of services), the provider addresses the social insurance fund for reimbursement. Reimbursement takes place once every quarter of a year, when the reimbursement system imposes these claims and updates its statistics.

Paulussen et al. (2004) described an agent-based approach to the planning of patient placement in hospitals. In the agent-based model, patients and hospitals are seen as autonomous agents. Hospital agents consider patient agent objects to be treated. Agent patients turn to hospital agents for services. The distribution of patients in hospitals is achieved through a market mechanism. Patient agents compete with each other for services in hospitals. Their behaviour is influenced by their health status and the price of services. The modelling concept takes into account the time characteristics of the services provided and movements to the places where services are provided.

As noted earlier, there is considerable experience in agent-based modelling of the operation of emergency departments. The model presented in Yousefi and Ferreira's (2017) study was used to investigate the possibility of redistributing the resources available in the department. Apart from patients, registry employees, nurses, and doctors act as agents here. All agents participate in the decision-making process on resource redistribution in the department based on their own observations. All available human resources are redistributed using this method during the working day. Patients can decide whether to continue treatment or leave the department at any stage of treatment. To evaluate the efficiency of this approach, six different scenarios are presented. The simulation results are the number of deaths, the number of patients who left the emergency department, the length of stay, the waiting time, and the total number of patients discharged from the emergency department.

Yousefi et al. (2018) discussed the modelling of the behaviour of patients who leave the emergency department of a public hospital without being serviced, which is mainly due to long waiting times or queues. Patient agents decide whether they should keep waiting or leave, among other things, based on the results of their communication with each other.

The agent-based model presented in Silverman et al.'s (2015) study aims to provide support in making decisions about searching for measures that would improve public health and quality of medical aid while decreasing costs. Citizen agents exist within the social structures of a higher level (organisations and society), which influence them and can also be influenced by them. These are the conditions under which their social health determinants are shaped.

Our review shows that individual elements necessary for reaching the targets of medical resource distribution are present in agent-based models. They include identification of a class of patient agents with a number of socio-demographic characteristics; determination of social, spatial, and economic factors in the behaviour of patient agents; identification of the classes of healthcare infrastructure agents (healthcare institutions, personnel, etc.), whose behaviour models consider the mechanisms of coordinated actions; formation of the spatial environment where the agents exist; formation of the processes according to which the agents interact within the framework of the medical services that are provided; and determination of the medical efficiency criteria for evaluating services. Nevertheless, there are currently no holistic universal concepts for building agent-based models that would ensure the decision-making process for the best spatial allocation of healthcare infrastructure facilities. Hence, our research aims to fill this gap by creating a variant of this concept.

3. Materials and Methods

The problem of the spatial allocation of healthcare infrastructure facilities can be described as the distribution of partially mobile services for mobile users (Dianov, 2021). The mobility of services is related to the fact that they move to users to provide services. The mobility of users is related to their ability to choose certain services and move to places where they can use them. In general, the model can be presented as follows:

$$M = (U, R, S, C) \tag{1}$$

where U is the location nodes of services and clients, R are the connections between the nodes, S is the services, C is the users.

The services and users can be in a limited number of locations. For this reason, model M can have a certain quantity of nodes where services and users are located:

$$U = \{U_1, \ldots, U_{UN}\} \tag{2}$$

Many connections can exist between the nodes–movement routes of services and clients:

$$R = \{R_1, \ldots, R_{RN}\} \tag{3}$$

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The nodes and connections have a set of attributes of various natures that characterise them:

$$U : A^U = \left\{ A_1^U, \dots, A_{AUN}^U \right\},\ R : A^R = \left\{ A_1^R, \dots, A_{ARN}^R \right\} \tag{4}$$

The model has many services and clients:

$$S = \left\{ S_1, \dots, S_{SN} \right\},\ C = \left\{ C_1, \dots, C_{CN} \right\} \tag{5}$$

As for the problem described, they demonstrate active behaviour and belong to the category of agents. The Service Agent can be described as follows:

$$S = U_i, A^S, Bh^S \tag{6}$$

where U_i is the node of permanent dislocation of the service, A^s is the population of service attributes ($A^S = \left\{ A_1^S, \dots, A_{ASN}^S \right\}$), and Bh^s is the model of service behaviour. The Client Agent has a similar description:

$$C = U_i, A^C, Bh^C \tag{7}$$

where U_i is the node of permanent dislocation of the service, A^c is the population of service attributes ($A^C = \left\{ A_1^C, \dots, A_{ACN}^C \right\}$), and Bh^c is the model of service behaviour.

The behaviour models contain modules in which the behaviour scenarios of agents are defined. The modules consist of a set of rules that allow an agent to select a particular scenario, depending on the current values of the parameters of the model elements. Two modules are defined in the Service Agent's behaviour model:

$$Bh^S = \left\{ Md_s^S, Md_d^S \right\} \tag{8}$$

where Md_s^S is the service provision scenario module, Md_d^S is the movement scenario module.

There can be two types of Service Agents: stationary, firmly attached to a certain node, and mobile. No movement scenario module is defined for stationary agents:

$$Md_d^S = \varnothing \tag{9}$$

Whether a service is possible and what the procedure would be for providing the service to a particular user are defined at the level of the service provision scenario module. On that basis, the values of the user and service attributes are used in the following rules:

$$Md_s^S = \left\{ Pr_1^{MdSs}\left(A^S, A^C \right), \dots, Pr_{PrMdSsN}^{MdSs}\left(A^S, A^C \right) \right\} \tag{10}$$

where $Pr_i^{Md\dots}\left(X_1, \dots, X_{XN} \right)$ is the i-th rule of the module containing parameters $X_1, \dots, X_{XN}$.

At the level of the movement scenario module, the user's needs, possibility, parameters, and movement route are defined:

$$Md_d^S = \left\{ Pr_1^{MdSd}\left(A^S, A^C, A^U, A^R \right), \dots, Pr_{PrMdSdN}^{MdSd}\left(A^S, A^C, A^U, A^R \right) \right\} \tag{11}$$

In the behaviour model of the User Agent, there are also two modules:

$$Bh^{\tilde{N}} = \left\{ Md_{gu}^C, Md_{pu}^C \right\} \tag{12}$$

where Md_{GU}^C is the scenario module of service generation, Md_{PU}^C is the scenario module of service use.

The scenario module of service generation provides the ability of the User Agent to initiate the need and wish to use a specific service. The module depends on the personal characteristics of the agent and the factors of the environment in which they exist:

$$Md_{gu}^{C} = \left\{ Pr_{1}^{MdCgu}\left(A^{C}, A^{U}\right), \ldots, Pr_{PrMdCguN}^{MdCgu}\left(A^{C}, A^{U}\right) \right\} \tag{13}$$

According to the rules of the service use scenario module, the User Agent is defined with the possibility and method of using the service, as well as with their actions:

$$Md_{pu}^{C} = \left\{ Pr_{1}^{MdCpu}\left(A^{S}, A^{C}, A^{U}, A^{R}\right), \ldots, Pr_{PrMdCpuN}^{MdCpu}\left(A^{S}, A^{C}, A^{U}, A^{R}\right) \right\} \tag{14}$$

The module should define the optimality criterion, connected to evaluating the dynamics of change in the properties of the Service and User Agents:

$$K = f\left(d\left(A^{S}\right), d\left(A^{C}\right)\right) \tag{15}$$

where *d (X)* is the function characterising the dynamics of change in parameter X.

The solution to the problem is connected with multiple modelling of situations with different combinations of the location of Service Agents in the nodes. Based on the results of each iteration, the value of the optimality criterion is calculated. The values of the criteria are compared. According to the results of the comparison, the model with the best, in a certain sense, criterion value is selected.

For the final description of the model, we used the ODD protocol (Overview, Design Concepts, and Details), aimed at standardising the descriptions of agent-based models (Grimm et al., 2020). The protocol consists of seven elements conceptually divided into three categories: Overview, Design Concepts, and Details. Each of these categories serves its purpose: to provide an overview, explain how design concepts that are important for the model have been used, and explain all the details of the model concept.

The Overview category is aimed at reflecting the general architecture of the model. It has three sections: Purpose and Patterns, Entities, State Variables and Scales, Process Overview, and Scheduling. The Purpose and Patterns section explains the purpose of the model. The Entities, State Variables, and Scales sections describe the structure of the model with specifications of all types of entities in the model. The Process Overview and Scheduling sections describe the processes occurring in the model and their schedules.

The Design Concepts category includes only one section with the same name, which contains a description of the concepts that build the model. The following structure of the section has been defined:

- Basic Principles. This provides a description of general concepts, theories, hypotheses, or approaches to modelling underlying the structure of the model.

- Emergence. This describes the systemic phenomena caused by the interactions between agents.

- Adaptation. This provides a description of the decision-making procedure followed by agents in response to changes in their own parameters or the parameters of elements of the surrounding environment.

- Objectives. This outlines the objectives pursued by the agents.

- Learning. This provides a description of the possibility of agents' adaptive behaviour (if any).

- Prediction. This describes the procedure according to which agents evaluate the possible consequences of their decisions.

- Sensing. This describes the mechanisms of agents' perceptions of their own parameters and the parameters of the elements of their surrounding environment, as well as the range of the parameters they perceive.

- Interaction. This provides the possible types of interactions between agents.

- Stochasticity. This describes the processes of the model, in which there are elements of a random nature.

- Collectives. This describes the possibility of forming individual elements of the model or changes in the nature of agents' behaviour related to their grouping.

- Observation. This displays a mass of data collected with a certain frequency in the course of data modelling, aimed at testing, understanding, and analysing the model.

The Details category is aimed at describing the mechanisms of implementation of the model. It includes three sections: Initialisation, Input Data, and Submodels. The Initialisation section describes the initial state of the model world—which entities are in existence and the exact values of their state variables. The Input Data section describes the sources of data that arrive in the model from external sources. The Submodels section specifies the processes described in Process Overview and Scheduling.

4. Results

We present the concept of the proposed agent-based model developed in the form of a template for describing models in the ODD protocol format, corresponding to the formal description of the problem of the spatial allocation of healthcare facilities presented earlier.

1. Purpose. The model is designed to search for the best parameters of the healthcare infrastructure in a territory: spatial allocation, number, and performance parameters of elements. The optimality criteria are the maximum possible satisfaction of the needs the population in a territory has for medical services with time characteristics to ensure their good quality, given the limited resources available.

2. Entities, State Variables and Scales. Table 1 presents the model entities, while Table 2 contains their parameters.

Table 1. Entities of the model

Name	Type	Reflection
Client	Agent	Person who needs a certain medical service
Service	Agent	Service providing medical help
Node	Environment element	Location nodes of clients and services
Route	Environment element	Route, connecting the location nodes of services with those of clients

Table 2. Parameters of model entities

Entity name		
Parameter	Scale	Range
Client		
Identifier	Names	Arbitrary identifier (letter, numeric, alphanumeric)
Time of occurrence	Date/Time	
Diagnosis	Names	Population of the names of diagnoses
State	Actual number	0..1 (0 is a mild form, 1 is an extremely severe form)
Human characteristics	Structures	Population of pairs of the form: characteristic – characteristic value

Selected service	Names	Population of service identifiers
Status	Names	{ready to move to the service, moves to the service, waiting to use the service, uses the service}
Service		
Identifier	Names	Arbitrary identifier (letter, numeric, alphanumeric)
Medical service	Names	Population of the names of medical services
Mobility type	Names	{mobile, stationary}
Provision cost	Figure (monetary)	>=0
Provision time	Integer (minutes)	>=0
Current client	Names	Population of client identifiers
Location	Names	Population of node identifiers
Schedule	Structure	Population of triples: day of the week – start of work – end of work
Node		
Name	Names	Population of the names of residential areas in a territory
Type	Names	{city, village }
Population characteristics	Structure	Population of pairs: characteristic – characteristic value
Route		
Identifier	Names	Arbitrary identifier (letter, numeric, alphanumeric)
Beginning node	Names	Population of node names
End node	Names	Population of node names
Duration	Integer (minutes)	>0
Cost	Figure (monetary)	>0
Schedule	Structure	Population of pairs: day of the week – starting time of movement

3. Process Overview and Scheduling. The model time is set in minutes. Depending on the type of medical service considered in the model, the modelling period can be chosen in different ways, which must be determined based on the frequency of the need for medical services and the duration of their provision. Table 3 presents a list of the processes.

Table 3. Typical Model Processes

Process name	Executed by	Execution period	Execution order
Generation of the Client Agent	At the model level	One-time after a certain period of model time	Based on the analysis of the parameter values of every “Node” entity, Client Agents with certain parameter values are generated.
Change in the state of the Client Agent	Client Agent	Many times from the moment the Client Agent is created till their removal after a certain period of model time	Based on the analysis of the parameter values of the Client Agent, the value of its “State” parameter is calculated and corrected. If the value of the “State” parameter of the Client Agent is equal to 0 or 1, this agent is removed.

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Getting access to the service	Client Agent	The moment of creation of the Client Agent	1. According to the value of the "Diagnosis" parameter of the Client Agent, the medical service is determined, and then a set of Service Agents with respective values of the "Medical Service" parameter is found. 2. Based on the analysis of the parameters of the routes, connecting the location nodes of Client Agents with the location nodes of the Agent Services, the current workload of the Service Agents, and the values of their own parameters, the Client Agent determines the Service Agent, which will provide the respective service, and includes it in the identifier as the value of their own "Selected Service" parameter. 3. If the selected Service Agent has the value of the "Mobility Type" parameter as mobile, the value of the "Status" parameter is set as "waiting to use a service." Otherwise, the value of the "Status" parameter is set as "ready to move to the service."
	The Client Agent with the "ready to move to the service" value of the "Status" parameter	The onset of the schedule item of any route to the location node of the Service Agent	The Client Agent determines the possibility of moving along the route. If the result is positive, they move along the route, and the value of the "Status" parameter is set as "moves to the service."
	The Client Agent with the "moving to the service" value of the "Status" parameter	The Client Agent's reach of the location node of the Service	The value of the "Status" parameter is set as "waiting to use the service"
Providing the service	The Service Agent with a non-filled value of the "Current Client" parameter and the "mobile" value of the "Mobility Type" parameter within the limits of the schedule drawn up for the Service Agent	Every cycle of model time	1. The Service Agent selects a Client Agent from among those who are waiting to use the service. 2. If there is a choice: - The identifier of the selected Client Agent is put in the "Current Client" parameter. - The Service Agent moves to the location node of the Client Agent. - The value of the "Status Parameter" of the Client Agent is set as "uses a service." - The Service Agent provides the service. - The Client Agent is removed. - The value of the "Current Client" parameter is removed. If there is no choice: If they are not in the permanent location node, he moves to it. 3. Schedule analysis: In case they go out of the range, they return to the location node.
	The Service Agent with a non-filled value of the Current Client parameter and the "stationary" value of the "Mobility Type" parameter within the limits of the schedule drawn up for the Service Agent	Every cycle of model time	1. The Service Agent selects a Client Agent from among those who are waiting to use the service. 2. If there is a choice: - The identifier of the selected Client Agent is put in the "Current Client" parameter. - The value of the "Status" parameter of the Client Agent is set as "uses a service." - The Service Agent provides the service. - The Client Agent is removed. -The value of the "Current Client" parameter is removed.

4.1. Design Concepts

4.1.1. Basic Principles

- Since medical resources are limited, the most important objective is their optimal distribution in a territory. Optimal distribution is understood as the possibility of providing medical services to the largest number of people who need them. Accessibility of medical services is an important factor for everyone. Accessibility largely depends on the infrastructure that provides access to the service and the ability of the population to bear access and service costs. The initial data of the simulation should be the parameters of the distribution dynamics of those in need of the medical services in a territory, as well as their ability to use medical services. The closest to reality in this regard would be agent-based models, which see all people living in the territory as agents. However, due to the objective difficulty in collecting real data (given their dynamic nature), and the need to use large computing resources, doing this does not seem realistic. That is why the presented model relies on an approach in which qualitative and quantitative analyses of the population composition and its spatial location in a territory are used to generate agents whose quantity and characteristics would reflect the dynamics of the appearance of people in need of medical care (Client Agents). Client Agents are associated with permanent residences of people in the territory (nodes). According to the concept, when such agents are generated, the mobility factor of the population is neutralised (an urgent need for medical service may arise at work, when staying out of town, or during visits to relatives, etc.). This point can be taken into account as the model is further developed. To make the generation of Client Agents possible, information about the parameters of the population living in the territory should be associated with nodes. A set of such parameters can be different: distribution by gender, age, social status, education, etc. Based on these data, we determine the probability of the appearance of a Client Agent with certain needs for obtaining medical services in a particular node. Thus, the Client Agent created does not characterise a specific person with a set of inherent health characteristics but a person who needs a specific medical service at a given time, in a certain place. Beyond that, it is necessary to generate an agent with a specific set of characteristics (age, gender, social status, etc.) on the basis of which we determine other behaviours related to choosing a specific medical service and methods of accessing it. To obtain an objective picture of what is happening in reality, the model must consider the dynamics of the degree of need for medical services. The state of human health can change, both for the better and for the worse. As a result, the need for medical intervention in both cases may fade away. Based on this, agents whose state parameters have changed to a critical level, as well as agents who have been provided with a service in order to optimise the computational process, are removed from the model.

- Medical services in the concept presented are interpreted quite broadly. They can be the service of a specific medical worker, medical examination, hospital treatment, etc. In accordance with the aim of modelling, there is no need to display real processes related to the organisation and the quality of medical services provided. Providing the service is important. Many potential customers may be interested in the service at any given time. The agent displaying the service (Service Agent) can serve only one client at any given time. In this case, the agent is in the “Busy” state. Everyone else should wait for the end of this process. After the Service Agent becomes free, it selects a client from a queue of Client Agents. We can form various strategies for choosing the next client in the agent behaviour model. To obtain a realistic picture, it is necessary to provide the possibility of servicing within the schedule.

- Medical services are located in certain nodes. They can be stationary and mobile (emergency medical care, a district doctor visiting patients, etc.). In the case of mobile services, the service process includes the movement of Service Agents to the location of the recipient of the service. Movement occurs by route. The routes have no direct association with the transport infrastructure of the region. They relate more to the way of travel: bus route, air travel, going by taxi, private transport, on foot, etc. The route can be complex; that is, combine different ways of movement. Each route connects two nodes of the territory. There may be several different routes between the two nodes. At the model level, the time of travel along a route is a significant parameter. Movement along routes can occur according to schedule (for example, a route is followed by public transport). Client Agents move to stationary medical services also using routes.

- Medical services and routes have their own costs. Along with the current workload of Service Agents and the travel time along the route, it is used by the Client Agent as a parameter when choosing a service.

- The modelling process involves running the model many times by placing a different number of Service Agents in different nodes. The number of services can act as a limiting criterion. The target is to find such a location structure of Service Agents that minimises the number of unserved Client Agents within the simulation period.

4.1.2. Emergence

In our concept, Client Agents, on the one hand, are generated based on the parameters of the population of a territory, that is, a real situation, associated with the emergence of the need for medical services in a certain territory, is shown. On the other hand, agents appear with a certain degree of probability. It is impossible to know in advance the exact number of Client Agents, the values of their parameters, and their locations at any time during the operation of the model. The behaviour of Client Agents aimed at choosing a Service Agent and using the service depends on the parameters of the agent itself and the current structure of the interaction between Client Agents and Service Agents. As a result, a scheme of servicing and movement of agents along routes cannot be predicted in advance, which ultimately determines the analysed characteristics of the model. Changing any parameters of the model (creating new routes, their schedules, reducing the cost, speeding up movement along them, changing the locations of Service Agents, their number, service time, schedules, as well as the characteristics of the population in the territory) significantly changes the result, which, at the same time, cannot be calculated in advance.

4.1.3. Adaptation

The adaptive ability of the model is demonstrated at the level of Client Agents' behaviour when they select the Service Agent. The assessment of the possibility of choice is related to the assessment of the agent's own capabilities (determined by the parameters of the agent) and state. If there are alternative options, the cheapest, fastest, a certain combination of these characteristics, or none at all, can be selected. In the latter case, repeated iterations of the choice are possible if conditions become different, there are new alternatives, and the state of the agent changes.

4.1.4. Objectives

The main goal of Client Agents when choosing a Service Agent is to receive services at minimal cost and avoid a decrease in the state to some critical point. At the same time, they must remember that their states may improve.

4.1.5. Learning

The model does not envisage agents' learning.

4.1.6. Prediction

The Client Agent can predict the situation by analysing the dynamic of change in the workload of Service Agents and evaluating their own state, given the experience in the development of the state among people with similar characteristics.

4.1.7. Sensing

Agents in the model can sense the parameters of any other agent and the elements of the environment.

4.1.8. Interaction

The model does not envisage the direct communication of agents with each other. There is a synchronisation between the Service Agent and the Client Agent during the process of servicing. There is an indirect interaction between Client Agents during the choice of the Service Agent for servicing.

4.1.9. Stochasticity

Stochasticity is present in the model in the following processes:

- Generation of Client Agents;
- Change in the state of the Client Agent;
- Selection of the Service Agent by the Client Agent for servicing;
- Selection of the route by the Client to move to the location node of the Service Agent;
- Determination of the time of servicing of the Client Agent by the Service Agent;
- Determination of the time of movement along the route.

4.1.10. Collectives

The model does not envisage the formation of collectives.

4.1.11. Observation

Table 4 presents the data from the model collected for testing, comprehension, and analysis.

Table 4. Collected data from the test model

Collected	Collection Parameters
Number of generated Client Agents	During generation of an agent, the value of the respective variable-counter increases by one
Number of serviced Client Agents	After the operation of servicing, the value of the respective variable-counter increases by one
Number of Client Agents removed from the model as the “State” parameter is equal to one	When the corresponding condition is checked during the operation of change in the state of the Client Agent, the value of the respective variable-counter increases by one
Busy time of the Service Agent	The time of execution of the next process “Providing the service by the Service Agent” is registered, and the corresponding value is introduced in the relevant table
Time within which Client Agents are in the state of searching for the service	The time between the moment of generation of the Client Agent and the moment of assigning the value “waiting to use the service” to their “Status” parameter is registered, and the corresponding value is introduced in the relevant table
Time within which Client Agents are in the state of expectation of the service	The time between the moments of assigning the values “waiting to use the service” and “uses the service” to the “Status” parameter of the Client Agent is registered, and the corresponding value is introduced in the relevant table

4.2. Initialisation

The initial state of the model is characterised by:

- The set values of the environment elements “Node” and “Route,” which correspond to the current situation for the simulated territory.

- Based on the established criteria (they can be grounded on the results of some analysis, reflect the current situation, or be set arbitrarily), a certain number of Service Agents is created and located in the nodes.

- Further research of the model implies the possibility of changing the number of Service Agents, their locations, and parameters.

4.3. Input data

This model does not use input data from external sources, which are intended to represent the processes that change over time.

4.4 Submodels

This section has to describe in detail the submodels representing the processes listed in the “Process Overview and Scheduling” section. In its essence, the model is a template for building specific models related to the objective of spatial allocation of healthcare facilities. Therefore, subprocesses are described in detail, based on the context.

Using this approach, we are currently creating a prototype of an agent-based model of the best locations of rural health posts (RHPs) in the Babushkinsky Municipal District of the Vologda Region. The agents in the model are RHPs, which provide medical services to the population, and the population itself, which takes the form of people who need these services. The model is implemented in the AnyLogic modelling environment. Figure 2 shows the implementation level of the model at which the formation and interaction of agents occur.

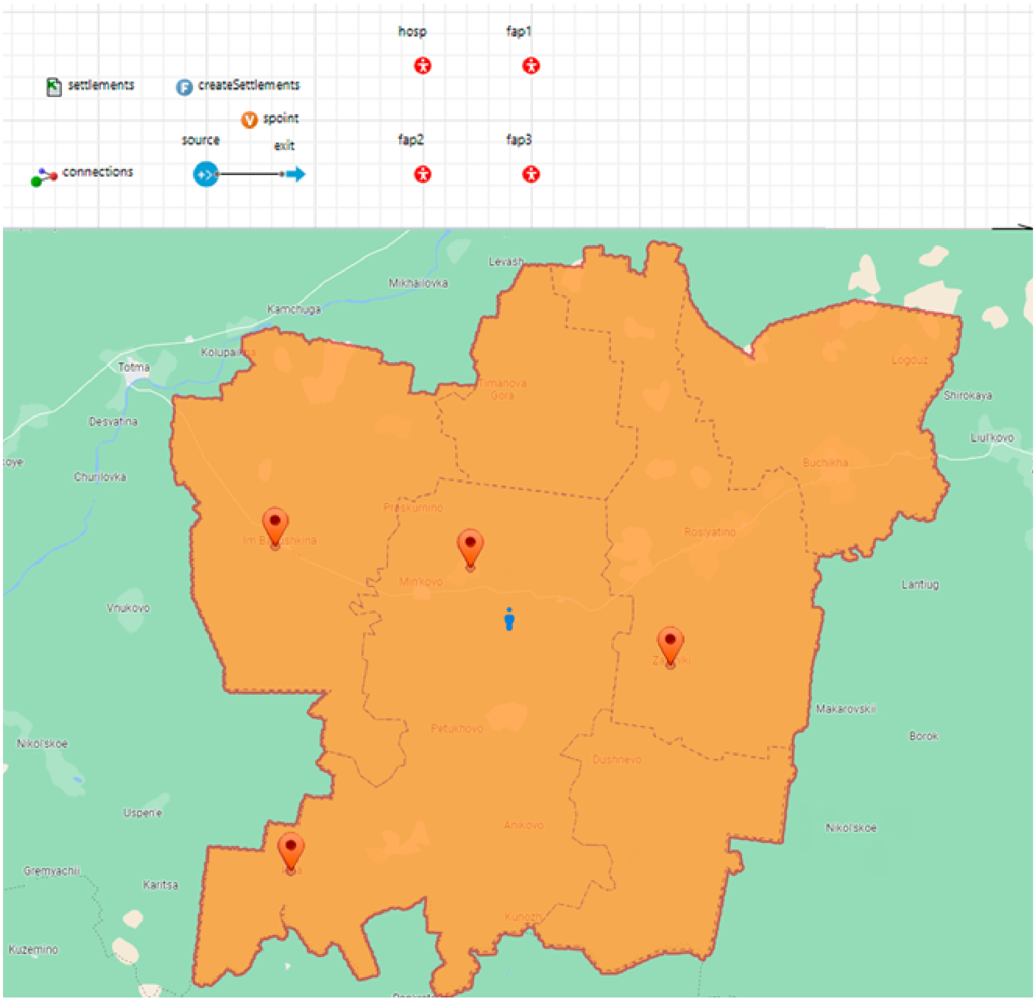

Figure 2. The level of implementation of the model at which the formation of agents and their interaction takes place

The model uses data on the location of settlements and RHPs of the Babushkinsky District, obtained from the geoinformation system incorporated into AnyLogic, as well as Rosstat data on the population of the settlements. The data on the number of appeals were obtained from Resolution N 1483 of December 14, 2020 “On the Approval of the Regional Program of the Vologda Region “Modernization of the Primary Health Care of the Vologda Region” for 2021-2025.” The model implements the processes of interaction between RHPs and people concerning the possibility of using services, the choice of the location where services are provided to the public, the movement of people to the location of services, and servicing itself. Currently, the model is being filled with real data.

5. Discussion

The problem of the best spatial allocation of healthcare infrastructure facilities is important and has been considered in many studies. There is an apparatus of mathematical methods designed for solving such problems in the theory of decision-making that can also be used for tackling the problems related to finding the best location for objects. Today, the most commonly used are the methods of discrete optimisation, geoinformatics, and simulation modelling. Further, particular problems concerning the placement of specific elements of the healthcare infrastructure are resolved, which, in many ways, reduces the adequacy of the results obtained. In this regard, it is essential to choose methods that will allow us to find complex solutions. Such solutions must be adaptive to most situations related to resource allocation. Simulation modelling ensures a detailed description of the system suitable for the analysis of its dynamic characteristics. A significant advantage of agent-based modelling is the ability to consider the dynamics of change in the characteristics of the entities that are being studied over time and the dynamics of the spatial allocation of these entities, as well as the ability to take into account the structure of relationships between the entities. The analysis of agent-based models designed to support decision-making in the healthcare sector shows that some of them solve individual problems of spatial allocation of healthcare facilities. However, there is no holistic, spatial optimisation-oriented concept for building these models. In our work, we attempted to address the problem of the spatial allocation of healthcare infrastructure facilities based on the socio-demographic parameters of the territory, that is, the distribution of partially mobile services for mobile users. The problem was formally captured from the perspective of an agent-based approach, taking into account the spatial component. Using the well-known method of specifying agent-based models, we elaborated on the conceptual structure of the proposed model. This allowed us to demonstrate the approach we used in a visual form. Currently, agent-based models grounded on the developed concept are being practically implemented. The full-fledged implementation of several models of existing territorial healthcare systems will allow us to verify our approach. Creating accessible, user-friendly interfaces through which public healthcare and policy specialists can adapt the specifications of agent-based models to their specific conditions will contribute to the further introduction of these methods, increase the utility of the results of the model, and open up opportunities for independent assessments of their reliability (Badland et al., 2013). The concept can be used in the future to resolve a wider range of problems related to the spatial allocation of social infrastructure facilities. This will facilitate the sustainable development of the regional social infrastructure.

6. Conclusion

The main purpose of this study is to develop a concept of agent-based models that would ensure the decision-making process for the best spatial allocation of healthcare infrastructure facilities. To accomplish this purpose, the following problems have been resolved:

- We analysed existing approaches to building agent-based models that provide solutions to problems in the healthcare sector. The results show that agent-based models have some individual elements necessary for handling the problems of allocating healthcare resources. Currently, there are no holistic universal concepts for building agent-based models that would ensure the decision-making process for the best spatial allocation of healthcare infrastructure facilities.

- We proposed a formal description of the problem of the best spatial allocation of healthcare infrastructure facilities. It includes the general architecture of agents and the environment within which they exist, agent behaviour models, optimality criteria, and the order of solving the problem.

- We fulfilled the final description of models using the ODD protocol (Overview, Design Concepts, and Details) aimed at standardising the descriptions of agent-based models. Our concept of an agent-based model is presented in the form of a template for describing models in the ODD protocol format, which corresponds to the formal description of the problem of the spatial allocation of healthcare facilities. The description matches all seven elements of the ODD protocol.

- We presented a prototype of an agent-based model for the best allocation of rural health posts in the Babushkinsky Municipal District of the Vologda Region. It is expected to be used as an element of verification of the approaches that have been developed. The model can be further used as a tool for planning the development of a network of RHPs in the Babushkinsky Municipal District of the Vologda Region. It can also act as a basis for the formation of similar networks in other territorial entities.

In general, this work contributes to the theoretical and applied aspects of creating agent-based models for the provision of services in social systems. Its further development would primarily involve the formation of behavioural models of health care infrastructure agents involved in an independent active search for the best locations for themselves.

Acknowledgements

This study was financially supported by the Russian Foundation for Basic Research (scientific project No. 20-010-00852 A)

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Россошанская Е.А. Концептуальная модель воспроизводства трудового потенциала на муниципальном уровне: агент-ориентированный подход. Социальное пространство 4, 11.

The article was submitted 17.05.2022, approved after reviewing 21.07.2022, accepted for publication 07.08.2022.

Статья поступила в редакцию 17.05.2022, одобрена после рецензирования 21.07.2022, принята к публикации 07.08.2022.

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