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Agent-Based Modeling Methodology for the Development of Territorial Logging Systems

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Abstract. The paper examines methodological and practical aspects of designing agent-based models that support decision-making on the development of territorial logging systems. The aim of the study is to design an agent-based modeling methodology to create models for a territorial logging system. Scientific novelty and significance of the research consist in the creation of specialized approaches to designing logging systems models, in which we elaborate on creating a spatial network, possibilities of its integration with geoinformation systems, ensuring the possibility of adaptation to a service-based approach in the formation of elements, enabling the formation of agents' behavior in terms of using spatial elements of the model. We consider tasks related to the development of territorial logging systems in Russia, including the creation of an effective transport and logistics network. We analyze the toolkit used to solve the abovementioned tasks. Most studies have formulated the same goal – to reduce the total operating costs of harvesting wood. In this regard, agent-based modeling can claim to be a significant tool for solving this task. The main problem is lack of a methodological basis for building models; therefore, so far it is premature to talk about the possibility of creating a unified methodology, the list of tasks to be addressed is often endless. At the same time, it is possible to narrow the range of issues at hand by focusing on individual subject areas. Thus, we analyze existing approaches to the creation of agent-based systems and formulate our own approach to the creation of agent-based models of territorial logging systems. We put forward an algorithm of specific steps and stages to design and implement agent-based models. It includes creating a contextual diagram of the simulated system, a methodology to form a conceptual and functional structure of the model that is invariant to the tools of agent-based modeling. We consider constructing a spatial environment for models by integrating them with geoinformation systems. At the moment, the concept of an agent-based logging model has been created for the territory of Babushkinsky Municipal District of the Vologda Region, the main aspects of its implementation have been worked out in AnyLogic modeling environment. In order to desing a full-fledged model, there must be interest on the part of those who can provide actual data.

Key words: logging system, transport accessibility of forest resources, transport and logistics network, agent-based modeling methodology, service-based approach.

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Introduction

The key strategic documents on the development of the Russian forestry complex envisage its transition to a sustainable development model, which ensures the satisfaction of public needs in wood raw materials and other forest resources, preservation of the ecological and socio-economic role of forests based on the use of modern scientific and technical achievements, radical renewal of all areas of activity and break-even forestry[1]. Intensification of the use and reproduction of forests is defined

[1] Strategy for the Development of the Forest Complex of the Russian Federation until 2030: Government Order 312-r, dated February 11, 2021. *SPS ConsultantPlus*.

as the most important direction of long-term state policy in the Russian Federation[2].

The intensive model reflects sustainable forestry, ensuring sustainable forest management, increasing economic returns, and preserving the biological functions of forests. Its application is associated with the need to solve the problems of creating a sustainable raw material base in accessible areas for processing, to form a balanced internal and external markets of demand for forest products, to provide conditions for long-term investment in the forest fund and processing, to implement the economic model of intensive forest reproduction, to create a system of long-term planning at all levels of forestry (Rusetskaya, Sanina, 2023).

The Russian Federation is the world leader in terms of forest area, with over 20% of the planet's forests[3]. According to the expert assessment of Roslesinforg, the total value of all forest resources in Russia was equal to 73.3 trillion rubles at the end of 2022. The total value of timber reserves that can be used for commercial purposes (export and trade of timber and timber products, use of forests as fuel) amounted to 2.2 trillion rubles[4]. In 2022, the supply of raw materials increased by 1 million m^3, and from 2023, the volume of forest wood resources annually put into economic turnover is planned to increase by 30 times, which will lead to an increase in the number of logging sites available for new leases[5].

However, the full-fledged, but at the same time rational development of these reserves is a significant problem. While Russia ranks first in the world in terms of forest reserves, it ranks only fifth in terms of timber harvesting. For instance, in 2020, 429.7 million m^3 of forest was harvested in the United States (11.0% of the global volume), 351.8 million m^3 (9.0%) in India, 341.7 million m^3 (8.7%) in China, 266.3 million m^3 (6.8%) in Brazil, and 217.0 (5.5%) in Russia (Rusetskaya, Sanina, 2023). Finland, neighboring Russia, with only 0.5% of the planet's forest resources, carries out 1.5% of the total volume of logging (Rusetskaya, 2022).

In Russia as a whole, the ratio of the actual volume of timber harvested to the established permissible volume of timber removal (estimated cutting area[6]) in the period from 2019 to 2021 averaged 30.1%[7]. In some regions of the country this indicator is even lower. For example, in the Komi Republic in 2022 the estimated cutting area was utilized by 28.3%[8]. In the Tomsk Region this indicator was 18%[9] in 2020. In the Arctic zone of the Russian Federation, the estimated cutting area was utilized by 19.9%[10] in 2021. In the Far Eastern Federal District, the level of utilization of the estimated cutting area is only 10.7%[11].

This situation is largely due to the fact that the volume of economically accessible cutting area is

[2] Fundamentals of the State Policy in the field of use, protection, conservation and reproduction of forests in the Russian Federation for the period up to 2030: Government Order 1724-R, dated October 26, 2013. *SPS ConsultantPlus.*; Strategy for the development of forestry complex of the Russian Federation until 2030: Government Order 312-r, dated February 11, 2021. *SPS ConsultantPlus.*

[3] The area of forests in Russia increased by 458.5 thousand hectares over the year. Available at: https://roslesinforg.ru/news/all/ploshchad-lesov-v-rossii-za-god-uvelichilas-na-458-5-tys-ga/

[4] Roslesinforg estimates the value of Russian forests. Available at: https://roslesinforg.ru/news/all/v-roslesinforge-otsenili-stoimost-rossiyskikh-lesov-/

[5] The available volume of timber increased by 1 million "cubes". Available at: https://roslesinforg.ru/news/all/dostupnyy-obem-drevesiny-uvelichilsya-na-1-mln-kubov-/

[6] Allowable annual volume of harvesting that does not harm the self-reproduction process of forest resources.

[7] On the State and Environmental Protection of the Russian Federation in 2021: State Report. Moscow: Ministry of Natural Resources of Russia; Lomonosov Moscow State University, 2022. P. 187.

[8] There is less deforestation in Komi. Available at: https://www.bnkomi.ru/data/news/159906/

[9] Knorr: Loggers logged 18% of the allowable forest in the region in 2020. Available at: https://www.riatomsk.ru/article/20210204/tomsk-lesozagotovka-2020-objem/

[10] On the state and protection of the environment of the Russian Federation in 2021: State report. Moscow: Ministry of Natural Resources and Environment of Russia; Lomonosov Moscow State University., 2022. P. 251.

[11] Trails and roads of the Far East timber industry. Available at: https://www.eastrussia.ru/material/lesnymi-tropami-chem-zhivyet-lesprom-dalnego-vostoka/

much lower compared to that defined as the estimated one (Orlov et al., 2022). According to rough estimates, the area of economically accessible forests, in which it is possible to obtain profit from forest use, does not exceed 1/5 of the country's forest area[12]. One of the main factors determining the economic accessibility of forest resources is transportation, which forms a significant share of costs associated with the production of forest products (Pryadilina, Petrov, 2020, p. 152).

The insufficiently high degree of transport infrastructure development and transport development of forests restrains the growth of the forest industry and reduces the level of its investment attractiveness. For example, in the Northwestern Federal District, the existing forest transportation highways account for only 29% of the required number in terms of length, and in general, the technological network of branches in terms of length is 36% of the value required for the full transport development of forests in the NWFD (Bzhelenko et al., 2021). In this regard, the development of forest transportation infrastructure, and the construction of forest roads in particular, is the most important task for the Russian timber industry complex (Bzhelenko et al., 2021).

Traditional methods of designing transportation networks are focused on the design of forest roads of the extensive model of forest management and do not pay due attention to transportation support of the intensive model tasks. According to some estimates, the total required length of public roads, forest highways, branches and whiskers per unit area under the intensive model (20.5 km / 1,000 ha) is almost twice as high as under the extensive model (11.8 km / 1,000 ha) (Larin et al., 2022).

Optimization of the transportation and logistics network is an important aspect of supply chain planning. In the forest industry, since transportation is the major cost of raw wood supply, transportation planning should allocate the distribution in such a way as to minimize the total movement of wood. Reducing transportation costs through advanced planning and improved efficiency has motivated researchers. Much of the research has focused on developing planning methodologies and decision support systems for large and complex vehicle routing problems in timber or roundwood transportation (Audy et al., 2022).

Various methods have been used to optimize logistics in the forest industry, including decision support system (DSS) and network analysis techniques (Parsakhoo et al., 2017); ant colony optimization (ACO) algorithms (Chung, Contreras, 2011; Lin et al., 2014; Lin et al., 2016; Lin et al., 2017); artificial bee colony optimization (ABC) algorithm (Jamhuri et al., 2020; Jamhuri et al., 2021; Jamaluddin et al., 2023); algebraic modeling (Peyroy et al, 2021); column generation optimization (Palmgren et al., 2003; Palmgren et al., 2004; Rey et al., 2009; Rix et al., 2015); linear programming approach – transport simplex algorithm (Devlin, Talbot, 2014; Lotfalian et al, 2022); integer programming model combined with column generation (Bordón et al., 2021); mixed integer programming model MIP + GIS (Najafi, Richards, 2013); MILP mixed integer linear programming model (Aydinel et al., 2008; Van Dyken et al., 2010; Moad et al., 2016; Bordón, 2018; Balaman, 2018); mixed integer nonlinear programming model (Shabani, Sovlati, 2013); fuzzy ε-constraint method (Balaman et al, 2018); linear programming model (Acuna, 2017; Boukherroub et al., 2017, Flisberg et al., 2015; Frisk et al., 2010; Forsberg et al., 2005); simulated annealing algorithm (Han, Mirphy, 2012); geographic information systems (Dean, 2011; Danilović et al., 2013; Olsson et al., 2017; Đuka, et al. 2020); computer learning (Almeida et al., 2022).

[12] Интенсивное устойчивое лесное хозяйство: барьеры и перспективы развития: сб. статей / под общ. ред. Н. Шматкова Всемирный фонд дикой природы (WWF). М.: WWF России, 2013. С. 5.

Russian researchers also apply modeling tools in solving problems of scientific support for the logging industry development. The article (Antonova, 2011) presents a mathematical model of optimal transport development of leased forest areas taking into account the timing of adjacency and the possibility to minimize the costs of logging and construction of logging roads; its implementation by the method of dynamic programming will raise the volume of the logging stock development and increase the enterprise's profitability. Based on the system approach, mathematical and cartographic modeling, geoanalysis and computational machine experiment by means of GIS, the paper (Antonova et al., 2015) developed a methodology, mathematical model, algorithm and PTOL software package based on MapInfo GIS to solve the problem of logging site location and forest transport development. The article (Goncharova, 2018) worked out a scheme of forest roads using graph theory. The research (Bzhelenko et al., 2021) carried out the calculation of the optimal parameters of the width of load-collection zones of forest roads and their required length per unit area for the conditions of the NWFD by developing an optimization model in MS Excel environment using the subsystem "Solution Search" and GIS-project of the transport infrastructure of the NWFD by methods of geoanalysis. The study (Motovilov et al., 2023) proposed a mathematical model for determining the optimal location of pellet production facilities in the region and an algorithm for its implementation based on the theory of optimal decision methods.

In recent years, simulation models have been increasingly used to solve logistical problems in the forestry industry. They provide advantages for management contingency planning in non-stationary systems under uncertainty compared to mental, conceptual, physical or mathematical models. Simulation modeling techniques such as discrete event simulation (DES), agent-based simulation (ABS), and system dynamics (SD) are common frameworks for representing a real-world system (Borshchev, 2014).

Timber supply chain encompasses a set of processes and operations for harvesting, extraction, transportation, storage, pre-treatment, utilization, and processing of timber. Timber supply chain management is concerned with the related decisions to plan, design, operate, control and monitor the flow of materials, services, finance and information within and between different actors (Kogler, Rauch, 2018). In this regard, studies based on the application of discrete event modeling methodology and tools have become quite widespread (Asikainen, 2001; Saranen, Hilmola, 2007; Puodžiunas, Field, 2008; Mobini et al, 2011; Beaudoin et al., 2013; Berg et al., 2014; Marques et al., 2014; Wolfsmayr et al., 2016; Gronalt, Rauch, 2018; She et al., 2018; Akhtari et al., 2019; Kogler, Rauch, 2019; Kons et al., 2020; Lundbäck et al., 2022, etc.).

In addition to discrete event simulation, agent-based simulation (ABS) has been used in forestry research in recent years and has been widely applied to solve various problems of modeling logistics production in geographically distributed production systems in various industries, such as electricity (Divényi, Dán, 2013), oil industry (Sinha et al., 2011), metallurgy (Azar et al., 2021), agro-industrial production (Naghavi et al., 2020), etc. Instead of defining the behavior of a global system, the ABS model defines the behavior of actors that exist together in the environment and communicate with each other and with their environment. The factors affecting each other at the aggregate level need not be known, but if the behavior of individual actors is known, then ABS can model global behavior (Borshchev, Filippov, 2004). This is the advantage of ABS over other modeling techniques such as system dynamics (SD) or DES, which have limitations in this regard. In particular, in the forestry sector there are often different people and objects such as operators, operational managers, machines, etc. that interact with each other and the environment.

The research (Karttunen et al., 2013) performs simulation modeling of an economically efficient intermodal containerized forest chip supply chain through a combination of agent-based and discrete event simulation.

The study (Holzfeind et al., 2021) uses an agent-based approach to analyze and model a system of logging and transportation operations in the forestry sector in a mountainous environment with limited space. The set of agents placed in the spatial model environment and acting as top-level agents were rope skidders, trucks and individual sorting lines. The impact on system behavior and performance of parameters such as weather conditions, storage capacity, the number of trucks involved and the timing of their orders was evaluated. The functionality of the model was evaluated using assumed logging data based on assumptions, personal knowledge, general information and data from published literature. The model can be applied to support operational planning of rope skidder harvesting and transportation of harvested timber to industrial plants.

The paper (Helo, Rouzafzoon, 2023) carries out a simulation to minimize transportation costs when logs are collected from several regions and delivered to the nearest collection point. An agent-based model is given, comprehensively covering the key elements of the timber supply chain and representing the units as interacting autonomous agents. The modeling combines components such as geographic information system (GIS) routing, potential facility locations, log collection locations, fleet size, and distance of timber transported by trucks and trains. The simulation results are presented in the form of time series charts such as number of trucks used, facility inventory, and trip distance. In addition, various simulation scenarios are applied to investigate potential facility locations and number of trucks, and to determine the optimal facility location and fleet size.

The results of the analysis of models, methods and algorithms for the construction of logging systems allow arguing that agent-based simulation, despite all the existing difficulties in its use, is the most promising and most adequate approach for solving the problem of reducing the total operating costs of timber harvesting. To a certain extent, evolutionary algorithms and discrete event simulation can be used to model such systems. But their possibilities are limited by the description of rather primitive behavior of the system elements, which is determined at the general model level. Territorial systems of logging production belong to the systems in which the elements have their own inherent behavior associated with the situational factors at certain points in time. And it is agent-based simulation that allows the use of various mechanisms of behavior implementation both at the level of behavior models of particular agents and at the general model level. But the key problem is the lack of a methodological basis for building agent-based models. At the same time, it is impossible to speak about the possibility of creating a single methodology at the moment, since the list of problems to be solved here is substantial and often immense. The issues of adequate representation of agent behavior, adaptation methods, and inference under uncertainty are particularly difficult. Therefore, agent-based modeling will develop together with the development of other areas of mathematics and computer science. However, there is a possibility to narrow the range of solved questions by focusing on separate subject areas. In this regard, the main objective of the presented research is the development of agent-based simulation methodology aimed at developing models of the territorial logging system. The scientific novelty and significance of the research lies in the creation of specialized approaches to the development of models of logging systems, in which the issues of creating a spatial network, the possibility of its integration with geographic information systems, providing the possibility of adaptation to the service-oriented approach in the formation of elements, providing the possibility of forming the agents' behavior in terms of using spatial elements of the model are worked out. As a result, a consistent and complete cycle of stages is provided, starting from the analysis of the subject area and ending with the practical implementation and use of models.

Methods

The existing methods of ABS development have been investigated in the works (Alfimtsev et al., 2013; Aksenov et al., 2016; Zubareva et al., 2016). They are described in the most detail by A.N. Shvetsov, who divided the existing methodologies into four classes: those based on object-oriented methods and technologies using appropriate extensions (Agent UML, P2P Agent Platform, ADELFE, INGENIAS, O-MASE); those using traditional knowledge engineering methods (MAS CommonKADS); based on organization-oriented representations (Gaia, PV-networks, M-architecture, SODA, ANEMONA, ASPECS, GORMAS, ROMAS); combining to varying degrees the methods of the first three classes (Tropos, PASSI, Prometeus) (Shvetsov, 2016).

Each of the methodologies outlined above offers its own set of basic elements and instructions and, in some cases, software tools for creating agent-based systems. All this diversity of approaches, in turn, leads to the need to combine and generalize design methodologies within model implementation projects. In practice, a specific implementation of a multi-agent system can be considered as a program with specific behavior and functioning in a heterogeneous environment (Nikolaychuk et al., 2019). In this regard, the general concept underlying the formation of agent-based systems, which allows having a unified view on the formation of the role model, is of particular importance. Here, we note two approaches developed by Russian researchers: the concept of needs and capabilities networks (NCNs) and the meta-methodology of designing multi-agent intelligent systems (MAIS).

According to the concept of NC-networks, each requisition, order, and other needs and capabilities (production resources, machines, equipment, vehicles, personnel) are assigned to program agents that negotiate with other agents and schedule orders to be completed "just-in-time" or "as early as possible," thus providing support for real-time collective coordination and decision-making at various stages of planning and execution of the production plan in different departments working together on the solution to the problem. The constant search for matches between competing and cooperating agents' needs and capabilities in the virtual market of the system allows building a solution to any complex problem as a dynamic network of links, flexibly changing in real time (Skobelev, 2015).

The metamethodology of MAIS design (Shvetsov, 2016) is based on the reflection of the selected subspace of the real or virtual world in the entire possible completeness of its empirically manifested and not manifested properties. For this purpose, we used the concept of model world space (MWS) as a high-level epistemological concept covering the part of reality that is modeled by MAIS and the components of the external environment that exist in ontological unity with MAIS. The features of metamethodology are the inclusion of both real and virtual worlds, which are already informational representations of other worlds (possibly also virtual), into the field of changeable reality. Thus, a multilevel nested representation of the world in which physical and informational entities exist and operate emerges. This approach makes it possible to consider the analysis, modeling and design of MAIS proper as a single multilevel iterative process, which allows obtaining models of MWS with different degree of reality detailing.

Regarding the issues of methodology of designing agent-based models, it is impossible to ignore the available specifications for describing this type of models. The most commonly used specifications are DREAM (descriptive agent-based modeling) and ODD (Overview, Design concepts and Details) protocol.

In accordance with the DREAM specification, the initial stage involves the creation of a complex network model that graphically depicts the main elements of the model. The complex network model can be transformed into a specification model, which contains a set of specification constructs reflecting direct unambiguous correspondence with the constructs of the agent-based model. In accordance with the specification, an agent-based model is created. Thus, the end result is a construct of consistent elements of the DREAM specification. From the complex network model, it is possible to move to the specifications, and from them to the agent-based model. The reverse transition is also possible (Niazi, 2011).

The key idea behind the development of the ODD protocol is to create a common format and standard structure by which all model elements can be documented. This ensures simplicity and completeness of model description, and increases the efficiency of model creation and perception. This simplifies the process of reproducing the model, hence the possibility to speak more consciously about its adequacy (Grimm et al., 2020).

Specifications cannot be positioned as methodologies (they are not intended to be). But they can certainly be incorporated as components of methodologies, especially in the analysis and validation phases.

Results and discussion

We develop our own concept of creating agent-based models. Its ideological basis is the meta-methodology of MAIS construction, and the role and functional models are based on the object-oriented approach and the concept of NC-networks. In our interpretation, it is a service-oriented approach (Gulin et al., 2023). The concept defines the basic rules for creating the agent-based forest management system under development: determination of target indicators and criteria for assessing the effectiveness of the system's functioning under the conditions of the existence of mobile elements; formation of a spatial graph of the system's functioning, taking into account the existing infrastructure, capable of reflecting the mobility of the system's elements; determination of the composition and parameters of the system's objects in accordance with the service-oriented paradigm; determination of behavioral models; determination of the system's parameters in accordance with the service-oriented paradigm.

The concept is the basis for the methodology of agent-based model development, some aspects of which are presented in the article (Shvetsov, Dianov, 2019). The concept was used to create the concept of the logging model in the territory of Babushkinsky Municipal District of the Vologda Region (hereinafter referred to as the model concept).

The process of model space formation is provided by using the context diagram. The context diagram visualizes external objects and their interactions with the system. It clearly and understandably shows the necessary external interfaces with a brief explanation of what is passed in and out. In this way, we have a visual representation of the inputs and outputs of the system. In this case, for the considered type of spatially distributed systems, we proposed to identify separately two circuits of interaction between external objects and the system: the control circuit of target settings at the intrasystem level and the control circuit of the rules of organization of the system functioning. These two contours interact with the system through external objects-mediators. Influencing the system constantly, they shape its behavior. In contrast to the interactions carried out directly between external objects and the system, the types of interactions of these circuits are mediated, i.e., carried out through intermediaries. In this case, the intermediaries are external objects that have both interactions with other external objects and interactions with the system. *Figure 1* presents the context diagram of the regional logging system.

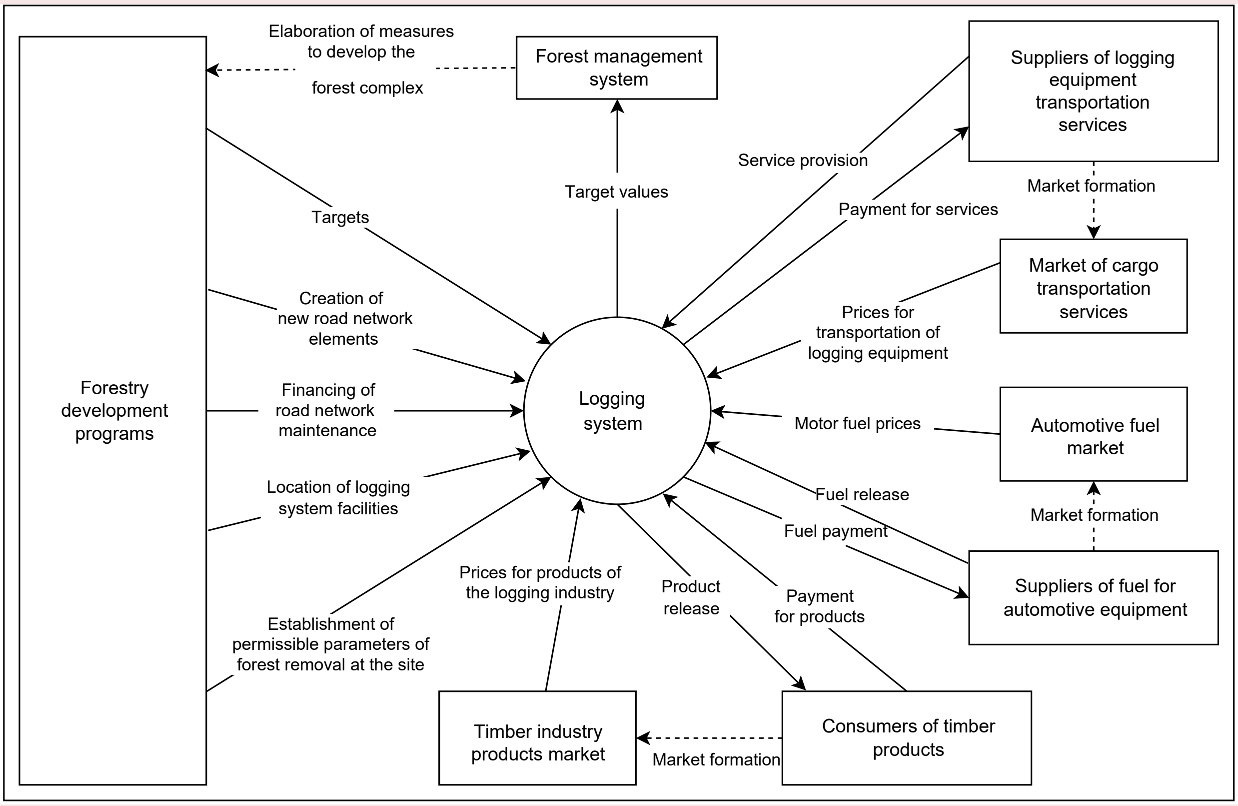
Using the context diagram and the formed conceptual space, we formed a part of the initial data set for modeling, controlled parameters of the model and modeling indicators. For instance, based on the context diagram presented in Figure 1, we can identify the following parameters:

– input data for modeling: prices for transportation of logging equipment, prices for motor fuel, prices for products of the logging industry;

– managed parameters: targets, new road network elements, financing of road network maintenance, location of logging system facilities, parameters of forest removal at the site;

– modeling indicators: values of target indicators, the amount of payment for transportation of logging equipment, the amount of payment for fueling the equipment, the volume of products supplied by the logging system.

Figure 1. Context diagram of the regional logging system



Source: own compilation.

The context diagram also allows clearly defining the parameters for working with the system model, which are the starting point for the formation of its conceptual space.

At the first step of forming the conceptual structure of the model, we identify the objects containing the attributes that directly form its studied indicators. Further for all pairs "object – attribute" of each identified at the first step object, we determine the list of processes, with which the change of values of the corresponding attributes is connected. For all processes the subjects of realization are defined, which, in essence, represent the following set of identified objects of the model. At the next step, we defined three blocks of attributes for each "subject–process" bundle: goal-setting, initializing and forming. The goal-setting attributes form the motivational component of the process launch. Initializing attributes participate in the description of the situation that makes it possible to start the process. Formative attributes determine the degree of influence of the process on the attribute to be changed. The process of identification of the components of the conceptual structure of the model is completed at the step at which no new "object-attribute" mappings appear. Then the structure of model objects is formalized. *Table 1* shows the structure of Harvester object.

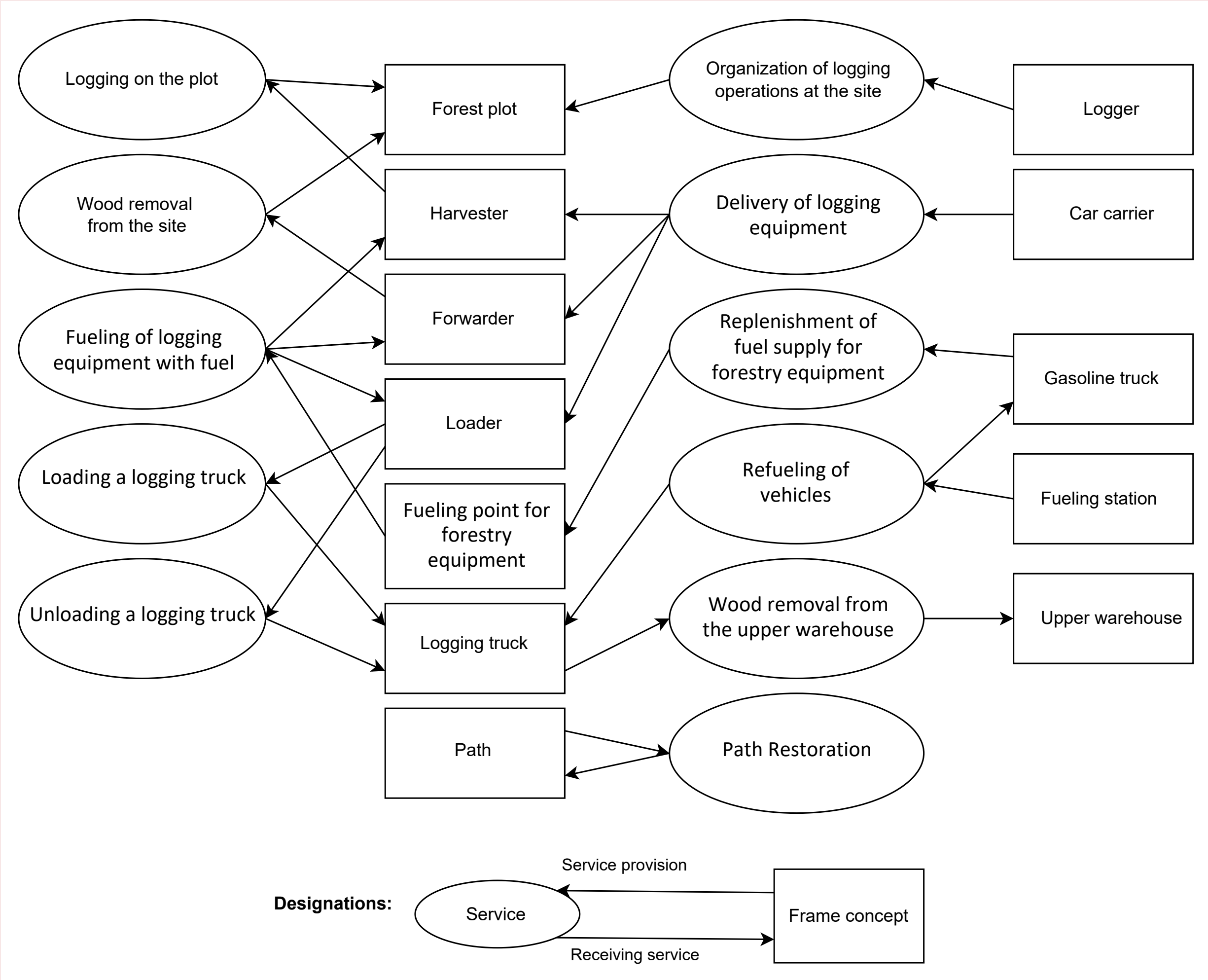
The further stage of the model formalization is connected with the formation of the structure of services in the relationship with the model objects. The processes identified in the conceptual structure of the model are positioned as services. Each service has two sides of relations with objects: providing service and consuming service. These relations are displayed using OS-projection (*Fig. 2)*.

Motivation modules are associated with each "Receive service" relation. These modules have a single output parameter with the values "motivated" or "not motivated". For example, for the relationship between the object "Harvester"

Table1. Harvester object structure

Harvester			H(N_h)
Attribute	Value range	Unit	Designation
Identifier	Alphanumeric designation		H_id
Place of permanent deployment	Item ID Node		H_loc
Current location	Item ID Node		H_cloc
Workplace	Item ID Node		H_rloc
Affiliation	Logger element identifier		H_vlad
Weight	Numerical value	kg	H_mass
Productivity	Numerical value	m3/hour	H_eff
Fuel tank capacity	Numerical value	liter	H_vbak
Current fuel level	Numerical value	liter	H_cbak
Current fuel level	Numerical value	ltr/hour	H_rt
Cost of maintenance in the operation phase	Numerical value	rub. / hour	H_stobe
Cost of maintenance in the idle phase	Numerical value	rub. / hour	H_stobp
Travel speed	Numerical value	km / hour	H_spped
Operating time	Numerical value	hour	H_te
Own compilation.			

Figure 2. OS model projection



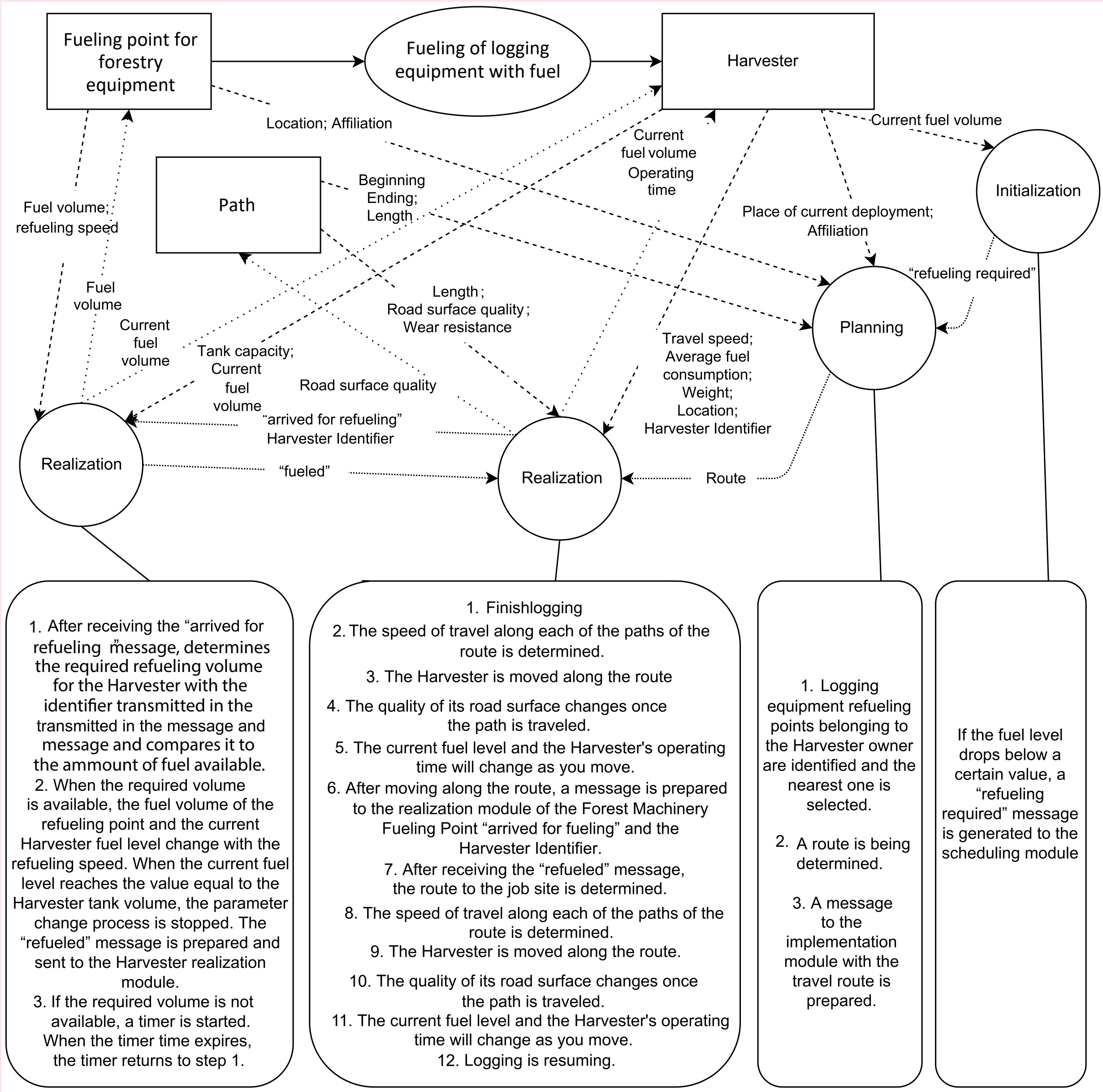
Source: own compilation.

and the service "Refueling of logging equipment" the motivation module "in demand" is defined. The logic of its content is that if the object "Harvester" has an owner (the target attribute "Ownership" is filled in), then the output parameter of the motivation module has the value "motivated".

To realize services, we form modules of service identification, planning and realization in their structure at the level of service-related objects. Between the modules, it can be established links that ensure the transfer of parameters. At the input, they have a certain set of values of attributes of model objects. We give the description of algorithms of its realization for each module.

The identification module operates with the current values of the output parameter of the motivation module and the initiating parameter "Current fuel level" of the object "Harvester". If the first one has the value "motivated" and the second one has the value below a certain value, the identification module is started.

Figure 3. Projection of modules of the service "Fueling of forestry equipment"



Source: own compilation.

Figure 3 presents an example of a module description.

OS projection and service module projection are further implemented in agent-based modeling environments.

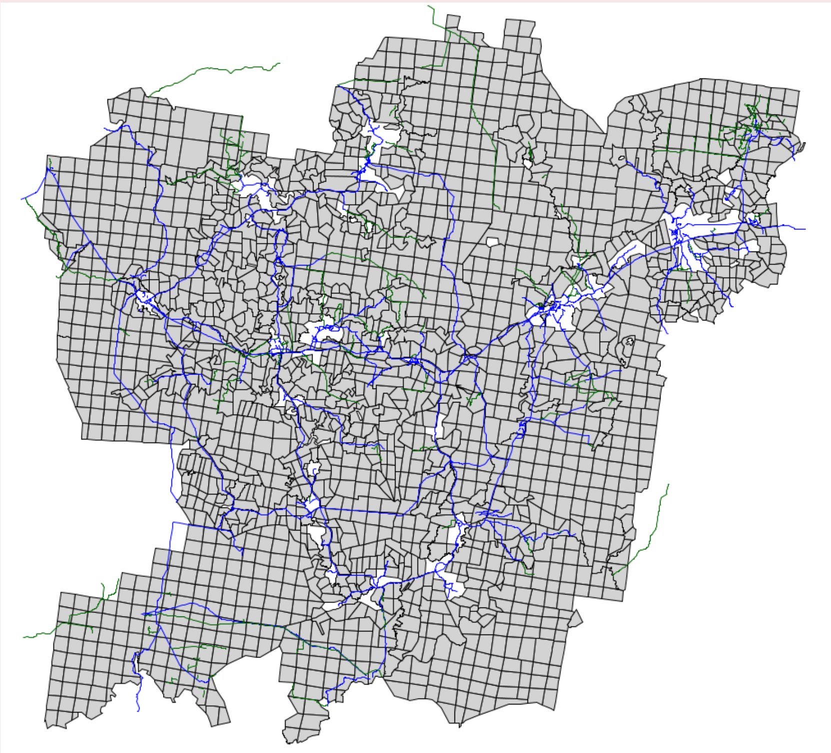
The next stage forms the spatial structure of model elements. Here a set of nodes of model objects placement is defined, a coordinate system is specified and in accordance with it the placement of nodes and interaction network between nodes is determined. Then the identified model objects are placed in the nodes.

Qualitative representation of transportation networks in the models is important. On the one hand, they should represent the existing road network, on the other hand, they should provide an opportunity to form a network of forest roads to be built. In addition, it is necessary to link the parameters of road network objects with the elements of agent-based models. At the same time, it is necessary to formulate and implement mechanisms for simulating the functioning of the road network used in forest management processes, based on the existing mechanisms for implementing spatial networks in agent-based modeling systems.

Many of the existing agent-based environments (e.g. AnyLogic, NetLogo, GAMA) provide the ability to generate spatial networks through integration with geographic information systems (GIS). Thus, agent-based models can utilize information about the existing road network, which is contained in geographic information systems. In doing so, the models are more realistic and visualized. Integration is provided by the services provided by modern Web-GIS. These include tile services and shapefile provisioning services. In addition to appearance, from geographical data agents get the exact dimensions of the modeled objects, which allows to develop more adequate models. In the concept we have developed, the road network is divided into separate sections – paths. Each path is associated with a separate agent, which contains the characteristics of the path.

Figure 4 presents the obtained road network for logging in the territory of Babushkinsky Municipal District of the Vologda Region. The OSM (OpenStreetMap) portal was used as a source of cartographic data, where individual shapefiles of highways, forest roads and forest blocks can be obtained. The maps required for the model were created using the QGIS GIS toolkit, which allows downloading, editing and viewing of geographic data. The QGIS QuickOSM plug-in was used to search and select the required data.

Figure 4. Road network for logging on the territory of Babushkinsky Municipal District of the Vologda Region



Source: own compilation.

A road network derived from a GIS can be augmented using specialized elements available in agent-based environments. These typically include elements that allow point and polygonal objects to be created and connected.

In accordance with the developed concept of creating agent-based models, we defined the management decision-making scheme. It uses the results recorded in the processes of interaction of model objects in the provision of services. The interaction is carried out in the configuration of the territorial transportation network, which determines the characteristics of interaction. In the process of rendering services, the values of a given set of parameters are formed within the framework of assessing the success of the model functioning – target indicators. The main purpose of modeling is to find the most optimal architecture of functioning of the modeled system (structure of the transport network, number, characteristics and places of permanent dislocation of objects) based on the values of target indicators with available resources (constraints). In the process of modeling various architectural compositions of the modeled system are formed. The number of possible variants is limited by the specifics of the subject area and available resource constraints. Modeling is performed for each of the variants during a certain modeling time. According to the results, the values of the model performance indicators are calculated, which are derived from the values of the parameters of the model objects fixed during modeling. The set of obtained indicators for each model is compared with the set of target indicators. According to the results, we determine the most optimal variant of the architecture of the modeled system.

Conclusion

As a result of the study, we have developed an algorithm of specific steps and stages necessary for the design and implementation of agent-based models that provide decision support for the formation of effective infrastructure for the use of forest resources. It is based on the service-oriented approach to the design of agent-based models and includes a consistent and complete cycle of stages, starting from the analysis of the subject area and ending with the practical implementation and operation of models. Its distinctive feature is the use of the developed schemes of functioning of the modeled agent-based system and its objects at the stage of conceptual design. At the first stage, the verbal model development is carried out: formal description of the modeled system, modeling objectives, targets and criteria for model evaluation are defined. At the stage of conceptual design of the objects’ functioning environment, the elements of the spatial graph (nodes and paths) and their attributes are defined. This process, on the one hand, is carried out taking into account the environment of the real subject area, on the other hand, may contain elements of its expected development.

Then follows the stage of conceptual design of model objects. Based on the analysis of the verbal model, model objects are identified in accordance with the service-oriented approach. As a result, a set of objects with needs and services assigned to them, mobility parameters, attributes and structure of modules of behavioral models is obtained. At the stage of model formalization, the content of modules of object behavior models is elaborated. In the course of realization of steps of this stage the conceptual model of the environment of functioning of objects and conceptual model of objects are refined. The next stage is the formation of the agent-based model architecture. Based on the analysis of the results obtained at the conceptualization and formalization stages, the composition and structure of model agents are determined. Here the sets of controllable parameters and parameters of modeling results estimation, as well as the mechanisms of formation of parameters of modeling results estimation are determined.

Then follows the stage of model realization, which is carried out using software tools. The initial set of model elements is formed, their initial parameters and spatial placement are set. At the stage of model operation, experimental studies related to changes in the controlled parameters are carried out. For separate purposes of system modeling (if it is necessary to evaluate its various configurations), the stage of model reconfiguration can be defined. In this case, two options are possible: first, repetition of the stages of implementation (formation of a new configuration of the initial set of model elements, their initial parameters and spatial placement) and experimental studies; second, repetition of the stage of conceptual design of the object functioning environment (reconfiguration of the agents' functioning environment) with subsequent repetition of the stages of implementation and experimental studies. The final stage is associated with the evaluation of the obtained results.

The algorithm of specific steps and stages necessary for the design and implementation of agent-based models was tested in the framework of creating the concept of an agent-based model of logging infrastructure on the territory of Babushkinsky Municipal District of the Vologda Region.

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