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# Architecture of the agent-based model for the region's industrial complex digital transformation

*Abstract.* The study of the transformation of the industrial complex and industrial products markets, due to its complexity, involves the use of tools that can adequately simulate elaborate systems of interconnections. The paper aims at developing an agent-based model of digital transformation of the regional industrial complex. The research methodology relies on regional economics, game and contract theories, the network approach, as well as the concepts of new industrialisation and the fourth industrial revolution. The author uses simulation modelling to study the individual behaviour of agents. As one of its outcomes, the article provides a methodological rationale for modelling industrial development processes by simulating the behaviour of interacting agents. The structural elements of the proposed model include an interaction environment, four classes of agents with individual parameters, strategies and rules of behaviour, a complex of external stimulating factors and a set of indicators of a phased digital transformation of an industrial complex. The model development algorithm consists of three parts: setting the initial state; determining the specific number of model runs corresponding to the time horizon of calculations; making final calculations and visually presenting simulation outcomes. The author proposes one of the possible methods to formalise behaviour rules of heterogeneous agents that includes the choice of the digitalisation strategy and operational decision-making. The results of the study can offer support for the practical implementation of the simulation model within a specific computer environment and lay the foundations for the control system of a region's industry digitalisation.

*Keywords:* agent-based modelling; industrial policy; digitalisation; industry transformation.

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## Introduction

Transformation of the industrial complex and its product markets should accommodate conflicting interests, strategies, and rules of behaviour of the entities subject to industrial development. One of the approaches to studying the topic is the agent-based modelling which is quite powerful and has acquired additional effective tools with the advent of computer technologies.

Agent-based models belong to the class of models that study individual behaviour of agents, usually by means of computer simulations. The main idea of these models is to make a set of agents with a set of properties and behaviours close to the real-world ones typical for the particular area of activity. At the same time, by means of simple rules of agent behaviours such models can demonstrate the dynamics of a system as a whole and produce the results that cannot be obtained by other methods.

At the current stage, the purpose of the study is to develop the architecture of the agent-based model for the digital transformation of the region's industrial complex, determine its features, and identify its main modules, interrelations, and other parameters. The practical outcome of the study consists in specifying simulation entities and interactions between them, developing the structure of the model to be implemented within the AnyLogic simulation environment, and describing the algorithm of its operation. The next stages of research will add further details to the parameters, verify the model against historical data, and perform predictive calculations based on scenarios for the regions' industrial development.

## Theoretical and methodological basis of agent-based modelling

The theoretical and methodological basis of the research rests on regional economics to explore the local industrial systems, game theory and contract theory to formalise the interactions between businesses, as well as platform and network approaches describing the modern nature of interactions between economic agents in the industry. When modelling digital transformation of industrial activities, the study also relies on the concepts of new industrialisation and the fourth industrial revolution.

Simulation modelling was used as a methodological tool to investigate the industrial complex. It has been successfully applied to research complex dynamic systems where the object and problem under study are hard to formalise and model by analytical and numerical methods. Traditionally, simulation modelling involves the following approaches: discrete-event (main tools: entities, resources, flow charts, and services); agent-based (autonomous agents, their characteristics, rules of behaviour, state charts); and system dynamics (stock and flow diagrams).

The approach to be applied is selected based on the set objectives. The real-life systems, especially socioeconomic ones, often include many elements and interactions, and may require the use of various approaches. In this case, the agent-based approach appears to be the most versatile as it focuses on modelling an agent and allows to preset a wide range of parameters, methods, behaviour rules, and other characteristics.

At the same time, local behaviours of agents following their own rules make up the global behaviour of the system as a whole making it possible to observe new systemic effects and reveal emergent properties. This effect is usually exemplified by the cellular automata theory [Macal, North, 2009] where the agents with two-three simplest rules of interaction generate rather complex structures. In addition, adding complexity to the agents' behaviour rules in the model makes it possible to predict actions of the real-world agents (by processing their statistical data, for example) that independently determine their behaviours (people, households, communities, large economic entities, etc.).

The methodology of agent-based modelling first took shape in the study of social problems by Schelling [1971]. This approach was applied to various domains such as defence [Hill, Champagne, Price, 2004; Sokolowski, Banks, Morrow, 2012], land use [Polhill et al., 2008], marketing [Duffy, Unver, 2008; Rand, Rust, 2011; Ivashkin, 2017], social studies [Patel, Crooks, Koizumi, 2012; Gangel, Seiler, Collins, 2013], logistics [Wijermans et al., 2013; Pluchino et al., 2014], inventory management, supply chains [Zamyatina, Karimov, Mitrakov, 2014], establishment of the region's economic area and information space [Zhuk, Buresh, 2010], modelling sustainable industrial development [Romero, Ruiz, 2014; Fraccascia et al., 2020], etc.

It is worth mentioning agent-based models created by researchers of the Central Economic Mathematical Institute of RAS [Bakhtizin, 2007, 2008; Makarov, Bakhtizin, 2009; Makarov, Bakhtizin, Sushko, 2013]. Such models of regions and municipalities usually include industrial enterprises as an agent class [Chirkunov, 2011; Fattakhov 2013]. A number of publications address the modelling of industrial systems, for example: the evolution of the coal industry in the competitive market [Markov, Markova, Kotelkin, 2013], operation of emission control systems in the industrial enterprises [Makarov, Bakhtizin, Sushko, 2017], high-technology and industrial cluster management [Ramzaev et al., 2017; Abramov, 2019], interaction between the state and enterprises in monopolistic markets [Panyukov, Konovalova, 2012], building predictive models for the regional timber complex development [Dianov, Rigin, 2020], free market in the electric power industry [Rashidova, 2017], etc.

From the author's point of view, it is natural that the growing popularity of agent-based modelling is associated with, among other things, increased computer performance and relevant software availability that eased conducting research [Heath, Hill, 2010]. Currently, the world's largest research centers use this approach to study socioeconomic and political processes. A whole new branch has appeared in economics, agent-based computational economics [Bakhtizin, 2008; Chen, 2011]. Agent-based modelling is described as the "correct" mathematics for the social studies [Borrill, Tesfatsion, 2010], since the state of society and its development laws are generally extremely difficult to describe mathematically. At the same time, the approach to agent-based modelling itself has constantly evolved from creating the simplest automata to studying the learning agents affected by culture with regard to their psychology and peculiarities of knowledge transfer [Serrano et al., 2014; Anzola, 2019; Antinyan, Horváth, Jia, 2019; Chen, 2020].

There is a number of scientific journals dedicated to the aspects of agent-based modelling of social systems, namely the Journal of Artificial Societies and Social Simulation (issued since 1998), and the Russian quarterly online journal Artificial Societies. In addition, there is a significant amount of reference resources on the practical issues and methods for creating agent-based models and related software which indicate the applicability and effectiveness of this approach.

The literature review suggests that agent-based models have a number of advantages for the socioeconomic research such as:

- system modelling is as close to reality as possible, interaction between economic agents is modelled directly, almost any algorithms can be introduced into the model;
- the ability to build models without exact knowledge of global interactions in the system's operation;
- the most flexible toolkit offering the ability to modify separate parts of the model with a wide range of visual presentation and scaling capabilities allowing to apply specific modelling methods to individual modules;
- the ability to calculate scenario simulations with adjustable conditions;
- configured models help identify and visually present new so-called emergent properties of the simulated systems.

The author believes that the main feature of the agent-based approach is the ability to study the changes in the system's macro-parameters by setting the correct rules for micro-interactions between agents. At the same time, the structure of the system is not rigid but gradually takes its final shape as the entities interact. By interacting with other agents based on the pre-set behaviour rules, an agent gradually changes the structure of the system, since the agent and structure are interdependent and are dynamically changing in the process of their interaction.

The agent's nature and its key qualities (proactivity, reactivity, location, ability to learn and communicate) are still debated. Some examples of agents include people (as well as other living beings), robots, cars, and other mobile units; immobile objects; sets of homogeneous objects. Generally, any object seen in real life can act as an agent in agent-based models provided that they have correct specification [Makarov, Bakhtizin, 2009]. Besides, real models may include auxiliary agents performing special functions in the studied system. The agent shall be generally defined as an autonomous structure affected by the outside world, the one that decides on and effects its response based on the rules of any complexity including the accumulation of knowledge, the choice of special strategies, random behaviour, etc.

Agent-based modelling is now widely used to address many socioeconomic and technological issues [Makarov, Bakhtizin, 2009] such as:

- supplier network optimisation and logistics planning;
- business planning;
- product demand and sales forecasting;
- optimisation of the number of employees;
- forecasting certain aspects of the socioeconomic system (e.g. a city, a region) development;
- modelling migration processes;
- pedestrian traffic simulation and optimisation;
- transport system simulations;
- environmental forecasting, etc.

At the same time, the modelling of a socioeconomic system is complicated by many direct and inverse relationships, mutual effects, and a large number of active agents with bounded rationality learning and uniting into groups, all within a changing environment. Such systems tend to have no single centre that would unambiguously determine their overall dynamics, which emerge from the actions of a large number of heterogeneous agents. All these features can be fully accommodated within the agent-based models. For this type of systems, agent-based modelling is a universal tool capable of accommodating complex structures and rules of agent behaviour. A model can be created even without any knowledge of global interactions, just by understanding the individual logic behind the actors' behaviour [Borshchev, 2014].

The distinctive features of an agent-based model involve agent autonomy, agent heterogeneity, bounded rationality of agents, availability of room for agents' activities, large number of interacting agents. In the author's view, these features allow reliably modelling the processes occurring in the industrial complex with the agent-based approach. The approach based on formalisation of interactions between entities appears to be one of the most suitable for modelling the processes and mechanisms of industrial development. This assumption is supported by the current shift in the management of industrial development from the state-run (dirigiste) model to the multi-subject one typical of developed countries. At a regional level, the industrial complex is managed through a set of mechanisms of vertical and horizontal industrial policy which include various formal and informal interactions typical for the network structures in the industry. The approach to industrial policy as a system of interactions among multiple entities and its applicability to creating competitive industry was discussed in the previous studies [Akberdina et al., 2018b].

This approach is especially useful when you need to determine the future state of a system which results from established new rules, changes in the existing ones, and effects from external factors. In this regard, the agent-based modelling seems to be best suited for the given area of study, namely the process of industrial complex transformation.

The author's approach involves the development of a methodology to explore the technological, structural, and institutional transformation of the industrial complex and industrial markets in the context of Industry 4.0 development. The agent-based model being created belongs to a group of economic and mathematical models that describe various aspects of regional industry transformation together with their objects, subjects, and characteristics of interactions. The main goal at this stage of research is to develop the architecture of the agent-based model for the digital transformation in the industrial complex of a region. In this regard, the objectives are to:

- develop and justify the structure of the model with respect to its further implementation in the AnyLogic simulation environment;

- identify the main agents, their properties, rules of behaviour, and interaction features;
- establish environmental parameters with respect to existing digitalisation trends.

## Description of the industry's digital transformation process

The digital transformation of the manufacturing industry, or digitalisation in production, involves improvement across technological and organisational areas. The Digital Economy programme lists the following end-to-end digital technologies: big data, new production technologies, industrial Internet, artificial intelligence, wireless technologies, components of robotics and sensorics, quantum technologies, blockchain systems, technologies of the virtual and augmented realities.

In Russia, digitalisation in manufacturing often focuses primarily on resource management processes, while digitalisation in the areas of product design, fabrication, and servicing lags much behind. In this sense, a more important process in line with the fourth industrial revolution would be to introduce information technologies in production.

Establishing a set of indicators to measure the processes of digitalisation in industrial production poses a certain challenge. For example, the Information and Communication Technology section of the OECD Statistics website[1] lists several dozens of indicators reflecting various digitalisation processes such as the usage of broadband Internet and various technologies and networks by different sectors of business. To assess the level of digitalisation in a model, one can use a modified index for measuring manufacturing enterprises' digitalisation which comprises the following indicators [Tolkachev, 2019]:

- broadband Internet access (with the speed of at least 100 MBit/sec);
- use of EDI (electronic data interchange);
- use of radio frequency identification (RFID) technologies;
- use of cloud services;
- use of ERP;
- use of big data;
- availability of a website allowing for online ordering;
- use of CRM;
- sharing of electronic information with suppliers and customers;
- receipt of orders over computer networks;
- placement of orders over computer networks;
- use of social media.

The set of indicators included in the index allows for a comprehensive assessment of how well a business is equipped and organisationally developed in the digital sphere.

To monitor individual digitalisation stages, the author will adopt the approach described by Akberdina [2018] who suggests the discrete qualitative changes in the industry leading to significant structural and institutional transformation. The paper will also identify the stages of the industrial complex transformation and the irreversible nature of transition to a new state with higher socioeconomic indicators. In this sense, the term "transformation" is understood as a result of prior conversions. Akberdina [2018] suggests identifying the industrial complex's transformation stages, each with a certain "digitalisation gene" and a relevant set of specific indicators. The added value of this approach lies in the set of specific indicators available from regional statistics. At the same time, it should be noted that in this approach, the main indicator at the final stages of digitalisation is the development of high-technology sectors, i.e. mechanical engineering producing specialised sensors, precision drives, and other robotisation tools and appropriate software. This may require a separate class of agents to be included in the model under development.

[1] URL: https://stats.oecd.org

## Features of the agent-based model structure

Considering the purpose and objectives of the study, the author believes that the architecture of the model being created should make it possible to:

- adjust the model, change the set of agents, their parameters, environmental conditions;
- provide aggregated indicators for a group (target cut) of agents and for the system as a whole;
- show the structure of agents' interaction, their behaviours, information exchange;
- acquire and visually present the received statistical data, to process it automatically;
- verify the simulation model, increase its reliability based on historical data;
- optimise the simulation experiment in terms of its duration and reliability;
- implement smart rules of agents' behaviour with the functions of reactive behaviour, learning, strategy selection, etc.
- import agent parameters, i.e. real-life businesses, from external databases, as well as to export the data for its further analysis.

The overall structure of the model includes a number of elements such as an interaction environment, specified external parameters, important factors affecting the transformation process, a set of agents of various classes, and aggregated macro-indicators (Fig. 1).

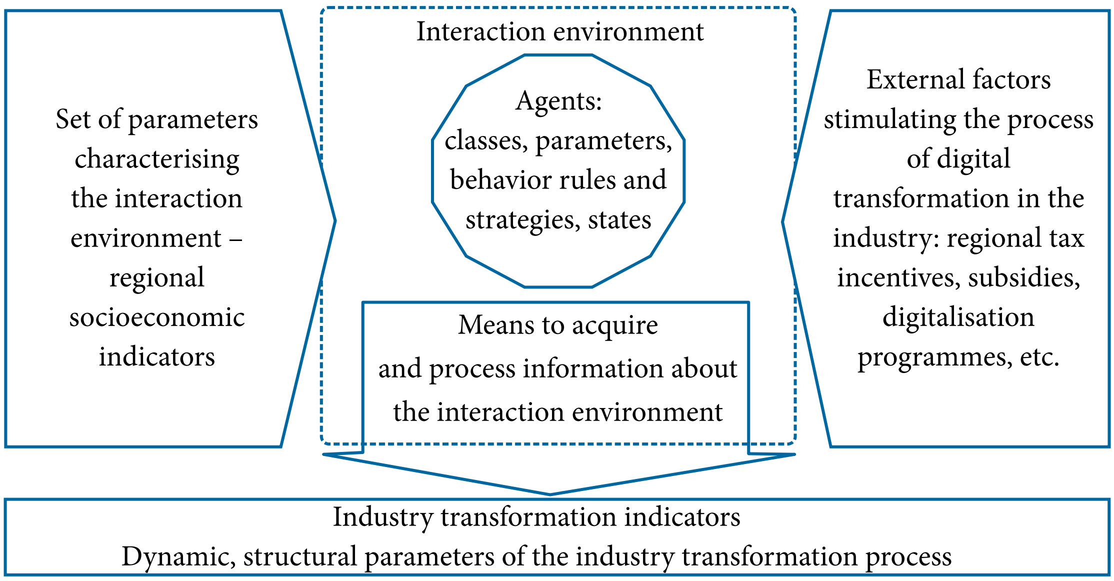


Fig. 1. The structure of the agent-based model for industrial complex transformation

Рис. 1. Структура агент-ориентированной модели трансформации промышленного комплекса

The types of agents for the model will be determined with regard to its subsequent implementation in the Anylogic simulation environment. The idea to study the region's industry as a multi-subject system with relatively independent stakeholders has already gained some traction. The author has identified the main subjects of industrial development [Korovin, 2017]. Akberdina et al. [2018a] have proposed the approach to analyse interaction between industrial entities based on the game theory, and outlined mathematical parameters for the cost-benefit ratio of their interaction. In this study the model under development will use characteristics calculated on the basis of statistical observations, surveys, and other data treated as agent parameters.

The agent-based approach will use the following tools to formalise each type of agents and interactions between them: parameters and variables, events, various functions, and state charts. Most parameters of the influence that businesses have on each other and that the environment has on businesses will be determined by regression analysis. Individual parameters of the extent to which the businesses are aware of and participate in the support system are evaluated by means of a questionnaire survey among businesses (including the one conducted by the Union of Industrialists and Entrepreneurs for the Sverdlovsk oblast).

The model includes both large and small businesses as economic agents. A separate class of agents consists of manufacturers of digital technologies, robotics, and software. The elements of industrial infrastructure, including specialist training, IT infrastructure, transport, etc., are counted as aspects of the environment and at this stage are not singled out as a separate entity. Regional government that changes individual parameters of the environment and affects the enterprises and manufacturers of digitalisation elements by interacting with them also constitutes an individual agent. Since all economics agents, except for the government, are represented by multiple entities, it is possible to monitor and modify their number as the agents can be added or removed during simulations (see table).

Each of the selected enterprise agents has its own geographical and sectoral profile, follows specific competitive strategies and business models, and shows distinguishable resource capabilities. For the purpose of the study, only key financial and selected technological indicators will be used.

**Model agents' main characteristics**

Основные характеристики агентов модели

| Agent type | Parameters (variables) | Strategies | States |
|---|---|---|---|
| **Large industrial enterprises** | Digitalisation indicators<br>Sales<br>Profit<br>Costs of particular digital technologies | 1. Reactive<br>2. Proactive | Pre-transformation state<br>Ongoing transformation period<br>Transformed state |
| **Small and medium-sized industrial enterprises** | Digitalisation indicators<br>Sales<br>Profit<br>IT expenditures<br>Level of digitalisation | 1. Reactive<br>2. Proactive | Pre-transformation state<br>Ongoing transformation period<br>Transformed state |
| **Producers of means of digitalisation and software** | Sales<br>Profit<br>R&D expenditures | 1. Proactive | – |
| **Regional government** | Costs of industrial modernisation promotion (subsidies)<br>State's benefit from industry transformation (taxes) | 1. Proactive (digitalisation promotion)<br>2. Reactive | – |

The list of large enterprise agents with appropriate parameters will be imported from the external database and identical small and medium-sized enterprise agents will be created to ensure the model reflects real-life experiences. With further elaboration, the model could be supplemented with additional agents such as scientific/educational institutions, population/households, as well as research and innovation centres, industrial parks, etc. There may also be an option to group companies by their sectoral profile (by the key industries such as aviation, automotive, electronic, radio-electronic, and pharmaceutical industries, medicine, mechanical engineering, etc.), as well as single out high-technology companies; export-oriented enterprises; emergent high-technology businesses (start-ups); companies with a high share of R&D spending;

company networks; companies engaged in creating and developing new technology, etc. Sectoral profile may be introduced as an optional parameter to adjust agents' behaviour rules.

Each agent in the model has its own behaviour strategy. Its parameters can be deduced from statistical evidence and other materials, by analysing opinions given by industrial companies' management. A study carried out by Strategy Partners, a Russian member company of the Sberbank Group, provides an estimate of the Russian companies' digital transformation readiness index. Of main interest here is the attitude of enterprise management to the possibility of digitalisation. The survey revealed that the overwhelming majority of Russian enterprises (91 %) not only keep using an outdated business model but generally have no digitalisation strategy for their business (the strategy was developed in 4 % of companies). In the next 3–5 years, only 30 % of respondents consider digitalisation as their priority, while 78 % declare their intent to use digital technologies to improve certain production processes, and 35 % are going to offer new digital products and services. 80 % of companies use digital design technologies in one form or another; over 60 % use novel materials, big data, and cloud technologies. Lack of financial resources was named as one of the main obstacles hindering digital transformation by 22 % of survey participants, while only 17 % of managers cited staffing issues as a barrier.

35 % of the managers expect the government to develop specialised educational programmes, support corporate R&D, and promote technology adoption initiatives, while 22 % expect the incentives for technological entrepreneurship (grants, acceleration programmes). At the same time, analysts suggest that digitalisation can provide the business with new competitive advantages: a several-fold increase in productivity and a drop in operating costs by a third.

The findings of the survey will help specify digitalisation strategies and estimate the likelihood of each one of them being adopted by a company.

The model at this stage will not be tied to a specific pre-set (physical) space and will not require setting rules or other attributes of agent movement or any concomitant graphical presentation. An enterprise agent will be assumed to have a full "field of vision" when it sees all its potential contractors irrespective of their actual geographical location and is aware of digital technologies. In real life, this is ensured through communication means, the Internet, a fairly effective data exchange as well as the advanced logistics network.

Parameters of the external environment are limited to the full availability of technologies, personnel, production capacities, high-potential external and internal markets, etc. At the same time, the support measures from the federal government will also be modelled as external parameters. When simulating the external environment, the regulatory impact from various measures (mostly financial) will be taken into account, namely guarantees, subsidies, grants, bans/restrictions/permits, tariff- and non-tariff barriers, etc. These will be evaluated by the total amount of allocated budget funds. The following types of regulation are to be incorporated in the model in the future:

- tax regulation (tax burden reduction, special tax treatment);
- monetary regulation (concessional lending, greater credit availability);
- foreign exchange regulation (for example, protection of domestic producers in foreign trade);
- regulation of specific product markets, antimonopoly, cost, and customs tariff regulation;
- institutional regulation (introduction and alteration of norms and rules defining interaction between business entities).

The simulation algorithm of the agent-based model (Fig. 2) consists of the following stages:

1) initialisation: creating agents and, if necessary, locating them, assigning parameters from the given database, as well as setting environmental parameters and establishing external factors;

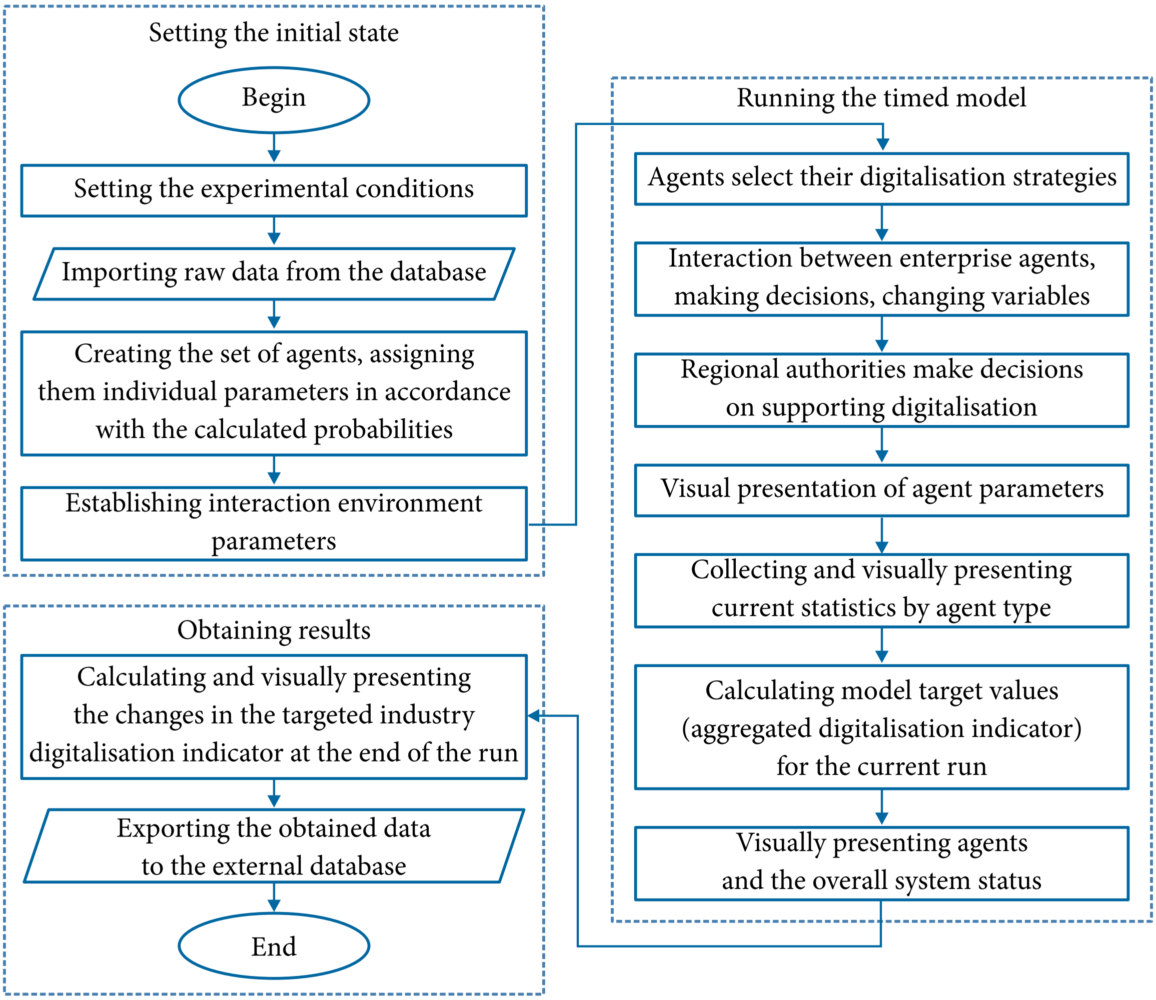


Fig. 2. Agent-based model algorithm
Рис. 2. Алгоритм работы агент-ориентированной модели

2) imitation: running rules of interaction, agents select individual strategies, communicate, share resources, collecting statistical data;

3) obtaining results: downloading statistical data, analysing aggregated indicators, evaluating the system's macro-parameters, processing and visually presenting the data.

Formalisation of the behaviour rules followed by heterogeneous agents is the most challenging and critical part of model development. As the model's architecture is developed, general relations that determine the actions of the agents can be established. At each model run enterprises select their own strategies as a function of their internal state, external environment, actions of regional government and, possibly, actions of other enterprise agents. In addition, the choice of a digitalisation strategy depends on personal qualities of the company managers. The decision to adopt a digitalisation strategy can be expressed by a Boolean function:

$$Ds_i = f(DigLev, V_i), \quad (1)$$

where $Ds_i$ is a Boolean variable that denotes whether or not an enterprise agent $i$ decided to digitalize; $DigLev$ is the overall level of industry digitalisation in the region; $V_i$ is the probability of adopting the digitalisation strategy by the enterprise $i$ management which is established on the basis of the survey conducted among industrial enterprises, taking into account their sectoral and technological profiles.

The very decision to launch the programme depends on the chosen strategy and the current financial capabilities of a particular enterprise, external factors, and the amount of support from the regional government:

$$D_i = f(Ds_i, I_i, O, G_i), \quad (2)$$

where $D_i$ is a Boolean variable that denotes whether or not an enterprise agent $i$ decided to digitalize; $I_i$ is the aggregate of the current financial state of an enterprise $i$; $O$ is the aggregate of the state of the current environment where an enterprise operates; $G_i$ is the assistance from the regional government estimated based on the total amount of support and its allocation in accordance with the criteria set by the authorities.

In case of a positive decision, an enterprise agent initiates the process of digitalisation, bears additional costs, and creates additional demand for the technical means and services including telecommunication services provided by regional agents. After a certain number of model runs, the agent passes into the transformed state, and as a result its technological and financial characteristics change.

The agent providing IT responds to the higher demand from the industry and improves its financial performance which becomes even stronger as the agent accumulates placed orders for digitalisation.

Taking the overall state of the industry into consideration, the regional government agent makes a decision on supporting digitalisation based on the aggregates of industry performance and its own financial capabilities. The amount of support will also depend on the industry digitalisation strategy adopted by the regional authorities:

$$RgSupp = f(DigLev, RgS), \quad (3)$$

where $RgSupp$ is the amount of support allocated by the regional government for the industry digitalisation; $RgS$ is the strategy adopted by the government regarding the industry digitalisation in the region.

External environment will be characterised by the common macroeconomic and social indicators changing in accordance with the simulation conditions. Individual and integral indicators of digitalisation will be computed. The obtained data will be included in the model, and used in the follow-up calculations in each run.

At this stage, this is a general framework to formalising interactions within the model that will be specified during its implementation in the AnyLogic environment. Further development of the model will involve calculation of parameters for the above functions and programming the agents. Calibration and verification of the agent-based model is complicated by the implicit and indirect nature of relationship between local properties of individual agents and those of the modelled system as a whole. The model will be calibrated against the available historical data on the digital development of the industry in Sverdlovsk oblast

Scenarios of strengthening government support for the digital development of the industry, improving general economic conditions, emerging digital technologies, and a deepening economic crisis will be considered as possible options to be tested with the verified model.

## Conclusion

The author investigated modern approaches to agent-based modelling of the socioeconomic processes. The paper analysed the evolution of these approaches, showed the variety of applied methods, and summarised the areas of their application. Based on the literature review, the advantages of the agent-based approach in studying socioeconomic systems were identified, namely its ability to model complex systems by simulating simple behaviours of interacting agents in a given environment. As a result, the chosen approach was proved to be applicable for modelling digital transformation processes in the industrial complex of the region. At the same time, transformation of the industrial complex is the final process divided into stages, and will make the production and business processes in the region's industry rely on the new digital base.

As a result of efforts to determine acceptable model architecture and find a suitable software environment for its implementation, the author identified a set of indicators to monitor the processes of industry digitalisation and its individual stages. The selected indicators together with the results of expert evaluation of the region's industry and assessment of the certain largest enterprises' performance should make up the information base for the model.

The article specified requirements for the model to be developed, proposed classes of agents, described the interaction environment, and summarised its ambient factors. The agents' characteristics feature their key parameters, strategies, and possible states. Allowances are made for incorporating the geographical and sectoral profile, patterns of competitive strategies and business models, as well as particular resource capabilities of certain large enterprises into simulation. The established external environment parameters are limited to those important for the studied process, i.e. full availability of technologies, personnel, production capacities, high-potential external and internal markets, etc. The model algorithm consists of three parts: setting the initial state; determining the specific number of model runs corresponding to the time horizon of the calculations; making final calculations, obtaining results, and visual presentation of the simulation outcomes. The author proposed one of the possible methods to formalise behaviour rules of heterogeneous agents and general relations that predetermine agents' actions. The obtained functions will be specified based on the results of processing the collected statistics from the information basis of the model.

The proposed architecture will make it possible to implement the model in the AnyLogic environment and create the basis for its further development to simulate transformation processes in the industrial complex of a region. Verification of the agent-based model will allow to identify interactions between agents unaccounted for at this stage, adjust their features, and quantify them. At the same time, the expected results will make it possible to create a flexible and adaptable methodological basis to manage the process of the region's industry digitalisation.

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# Архитектура агент-ориентированной модели цифровой трансформации промышленного комплекса региона

***Аннотация.*** Изучение трансформации промышленного комплекса и рынков промышленной продукции ввиду своей сложности предполагает использование инструментов, способных адекватно моделировать сложные системы взаимосвязей. Статья направлена на разработку агент-ориентированной модели цифровой трансформации регионального промышленного комплекса. Методологическую базу исследования составляют положения региональной экономики, теории игр и контрактов, сетевой подход, а также концепции новой индустриализации и четвертой промышленной революции. В качестве методического инструментария используется имитационное моделирование, применяемое для изучения индивидуального поведения агентов. В результате исследования методологически обоснована целесообразность моделирования сложных процессов промышленного развития с помощью имитации поведения взаимодействующих агентов. Структурными элементами предложенной модели являются среда взаимодействия, четыре класса агентов с отдельными параметрами, стратегиями и алгоритмами поведения, комплекс внешних стимулирующих факторов и совокупность индикаторов поэтапной цифровой трансформации промышленного комплекса. Алгоритм разработки модели включает три части: установку начального состояния; определение заданного количества рабочих циклов модели, соответствующего временному горизонту расчетов;

выполнение итоговых расчетов и визуализацию результатов. Предложен вариант формализации алгоритмов действий разнородных агентов, включающий выбор стратегии цифровизации и принятие оперативного решения. Результаты исследования могут послужить методической основой для практической реализации имитационной модели в специальной компьютерной среде и создания на ее основе системы управления процессом цифровизации промышленности региона.

***Ключевые слова:*** агент-ориентированное моделирование; промышленная политика; цифровизация; трансформация промышленности.

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