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Agent-based modeling and optimization of the characteristics for research-and-production clusters

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Abstract

This paper presents a developed agent-based simulation model for the development of research-and-production clusters in Russia implemented with the use of high-tech enterprises located in four science cities (Troitsk, Obninsk, Pushchino and Protvino) as the case study. A new approach to modeling and optimization of gross metropolitan product (GMP) is proposed, taking into account the influence of the "gravity effect" on the redistribution of labor resources between developing science cities and appropriate enterprises united in single research and research-and-production clusters An important element of this approach is the formation of various scenarios for the strategic development of the research-and-production clusters being assessed and support for the possibility of choosing the most preferable scenario using an evolutionary optimization algorithm. An enlarged simulation model has been developed and implemented in AnyLogic describing the possible development trajectories of science cities with a corresponding change in the values of the most important characteristics: the number of economically active population, the number of research-and-production enterprises, the volume of products produced in high-tech sectors of the economy, GMP, etc. The designed framework is intended primarily for the management of research-and-production clusters implementing the strategy of innovative development. Such a framework uses methods of system dynamics and agent-based simulation modeling supported in the AnyLogic system, genetic optimization algorithms and GIS mapping for science cities, etc. to implement the required functionality. The approbation of the framework was completed with the use of real data published in the approved strategies of the relevant science cities development. As a result of the numerical experiments carried out, some recommendations were proposed for the development of the research-and-production clusters under study considering their mutual influence and the existing base of resources.

Keywords: research-and-production cluster, high-tech enterprise, science city, production characteristics, simulation modeling for enterprises, gross metropolitan product, agent-based modeling, system dynamics, gravity effect, production function, AnyLogic

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Introduction

Currently, a very pressing problem of increasing the efficiency of the public administration system is the development of research and production clusters using the existing human resource potential, including those formed on the basis of research institutes and research-and-production clusters that have experience in using own developments in the real sector of the economy.

Determining the best development scenarios for high-tech enterprises located in science cities, developing and implementing decision support systems for managing research and production clusters is the most important area of business informatics aimed at increasing the efficiency of managing innovative development processes.

As an example, high-tech enterprises located in science cities united within a single conceptual model of innovative development will be considered. Within such a model, it is possible to obtain a significant synergistic effect, due, firstly, to the possibilities of staff cooperation, as well as the use of a common high-tech resource base (e.g., supercomputers, data centers, industrial systems for 3D printing of integrated circuits, etc.). In particular, high-tech enterprises located in cities such as Troitsk, Obninsk, Pushchino and Protvino near the Moscow agglomeration and being essentially neighboring enterprises can be united into single research-and-production clusters, in particular, for the production of a microelectronic element base, precision instrumentation products, etc. At the same time, it is important to ensure the balanced development of high-tech enterprises in all small cities united in the respective research-and-production clusters in order to avoid a one-way flow of highly qualified staff and ensure the harmonious strategic development of all agent enterprises (research institutes, research-and-production clusters, etc.) as existing ones, and those formed in the corresponding science cities.

Therefore, it is necessary to develop a decision support system (software framework) for managing high-tech enterprises located in science cities and implementing an innovative development strategy. Such a complex uses methods of system dynamics and agent-based simulation modeling supported in the AnyLogic system, genetic optimization algorithms and GIS maps of research-and-production clusters, etc. to implement the required functionality.

The first fundamental work on the study of the dynamics of the development of a city and its enterprises is the book [1], in which Forrester formulated the basic principles for constructing simulation models that describe various scenarios for the evolution of the urban environment, taking into account the complex system of existing feedbacks, lag dependencies and internal urban interactions, etc.

Among the recent works in this area, it is worth highlighting [2—4], in which system dynamics methods are used to study the possibilities of achieving sustainable economic development of large cities. In particular, in [2] four scenarios of possible development for the city of Beijing were modeled using a system-dynamic approach. It is shown that the dynamics of sustainable development of the city are implemented differently during three periods (from the growth of the city's economy at the beginning to its slowdown and subsequent growth).

Among the disadvantages of using system dynamics methods, one should note the difficulties of modeling internal interactions, processes of redistribution of labor resources, difficulties with the analysis of spatial development of the city, etc. To overcome such difficulties, it is advisable to use agent-based simulation modeling methods that allow modeling interactions at the microscopic level, taking into account individual adoption systems decisions of each economic agent [5, 6].

Among the important works in this area, [7—10] should be highlighted. In particular, [7] presents an aggregated agent-based model of migration flows of the European Union countries and describes the influence of the "gravity effect" on the inter-country redistribution of human flows. This effect arises due to factors influencing the migration behavior of people, in particular, when there is a significant difference in the ratio of wages, labor market size and gross domestic product (GDP) per capita between a given country (region) and neighboring countries (regions). For instance, relatively low wages combined with a small number of available jobs tend to lead to an outflow of the population to more favorable regions. The "gravity effect" also influences internal migration between cities, when the population (and corresponding labor resources) moves from the agglomerations that are less developed to economically more developed ones. In [8] an agent-based model of population dynamics of two interacting communities consisting of migrants and natives is presented. In such a model, natives search for high-tech workplaces, and migrants search for low-tech workplaces, which is also relevant for enterprises in science cities that actively attract external labor resources. Agent-based modeling can be combined with other methods, e.g., system dynamics, discrete event modeling, etc. to create digital twins of complex socio-economic systems [9, 10]. The developed simulation models can be aggregated according to objective functions and constraints with evolutionary optimization algorithms, in particular, genetic algorithms [11, 12] to optimize the characteristics of such large-scale systems. Agent-based models of territorial development of regional and urban agglomerations can aim at solving important environmental problems, such as reducing the concentration of harmful emissions in socially significant urban areas (e.g., near kindergartens and schools) through landscaping [13], reducing emissions from industrial enterprises due to their environmental modernization [14], transformation of the urban environment [15]. To model the movement of human flows and labor resources in an urban environment, it is advisable to use the phenomenological approach previously proposed in [16], which allows us to take into account various scenarios of interaction of various agents with each other, simulate the behavior of the crowd, etc. Also noteworthy are the works [17—21] devoted to both methodological issues [17] and specific case studies carried out to study the possibilities of developing urban architecture [19], improving traffic [20] and increasing returns in certain sectors of the urban economy [21].

Thus, the combined use of various simulation modeling methods, heuristic optimization algorithms, etc., in particular, supported in the AnyLogic system, makes it possible to design a decision support system for the sustainable economic development of research-and-production clusters and corresponding science cities.

The purpose of this paper is to develop economic, mathematical and computer tools for studying the dynamics of development of individual research-and-production clusters of the Russian Federation under various scenario conditions within the framework of which the balanced development of all interacting economic agents-enterprises (research institutes, research-and-production clusters, etc.) is ensured.

1. Simulation model for the development of research-and-production clusters

This section presents the developed simulation model for the development of research-and-production clusters with implementation using the example of high-tech enterprises located in the science cities of Troitsk, Obninsk, Pushchino and Protvino. The proposed agent-based model consists of several interconnected levels (*Fig. 1*).

Top level model – the environment in which agent enterprises operate, belonging to different cities, between which flow interaction is realized, in particular, redistribution (internal migration) of the population with a corresponding change in labor resources, which can be involved in the high-tech sector of the economy (in research institutes, SPAs and etc.) in the case of the formation of new jobs (*Fig. 1*). Such flow interaction is carried out due to the influence of the "gravitational" effect [7] caused by differences in the level of wages, the size of the labor market and GDP per capita in the corresponding science cities.

The *Low level model* ensures the implementation of the logic of behavior of agent enterprises, the characteristics of which are described using system dynamics methods (*Fig. 1*). Such internal models are systems of finite-difference equations with their own resource and target characteristics [11, 22]. At the same time, to determine the values of individual parameters, integration with the upper level of the simulation model is required. In particular, the main control parameters of the model, the values of which must be the same for all agents, are set at the environment level. At the same time, individual characteristics calculated at the agent level are used in the top-level model, for example, to calculate the gross metropolitan product (GMP) generated by all enterprises.

For each enterprise agent, three possible states are specified:

- the first state, corresponding to low economic growth rates and not exceeding a given lower threshold value, is highlighted in "red";
- the second state, corresponding to the average economic growth rates, the valuesof which are in the interval between the lower and upper threshold values, is highlighted in "yellow";
- the third state, corresponding to high rates of economic growth, the values of which exceed the upper threshold value, is highlighted as "green".

The economic growth rate of agent enterprises (the dynamics of GMP) is influenced by various factors, among which the most important are investments in fixed capital, the number of jobs created, average monthly wages, etc. The production resources that enterprises already have (fixed assets, staff) are also important: the level of scientific and technological progress (STP), the ability to attract highly qualified staff, etc. Within the framework of the developed model, a centralized allocation of resources (investments, new workplaces, etc.) is proposed with their subsequent distribution among enterprises of each science city, taking into account greater support for problem organizations characterized by low rates of economic growth. This approach is relevant, first of all, for state enterprises, e.g., institutes of the Russian Academy of Sciences, research institutes, as well as commercial organizations with significant government participation.

Thus, the most important task of the system under consideration is to minimize the total number of problem ("red") enterprises with the minimum required investment and operating costs.

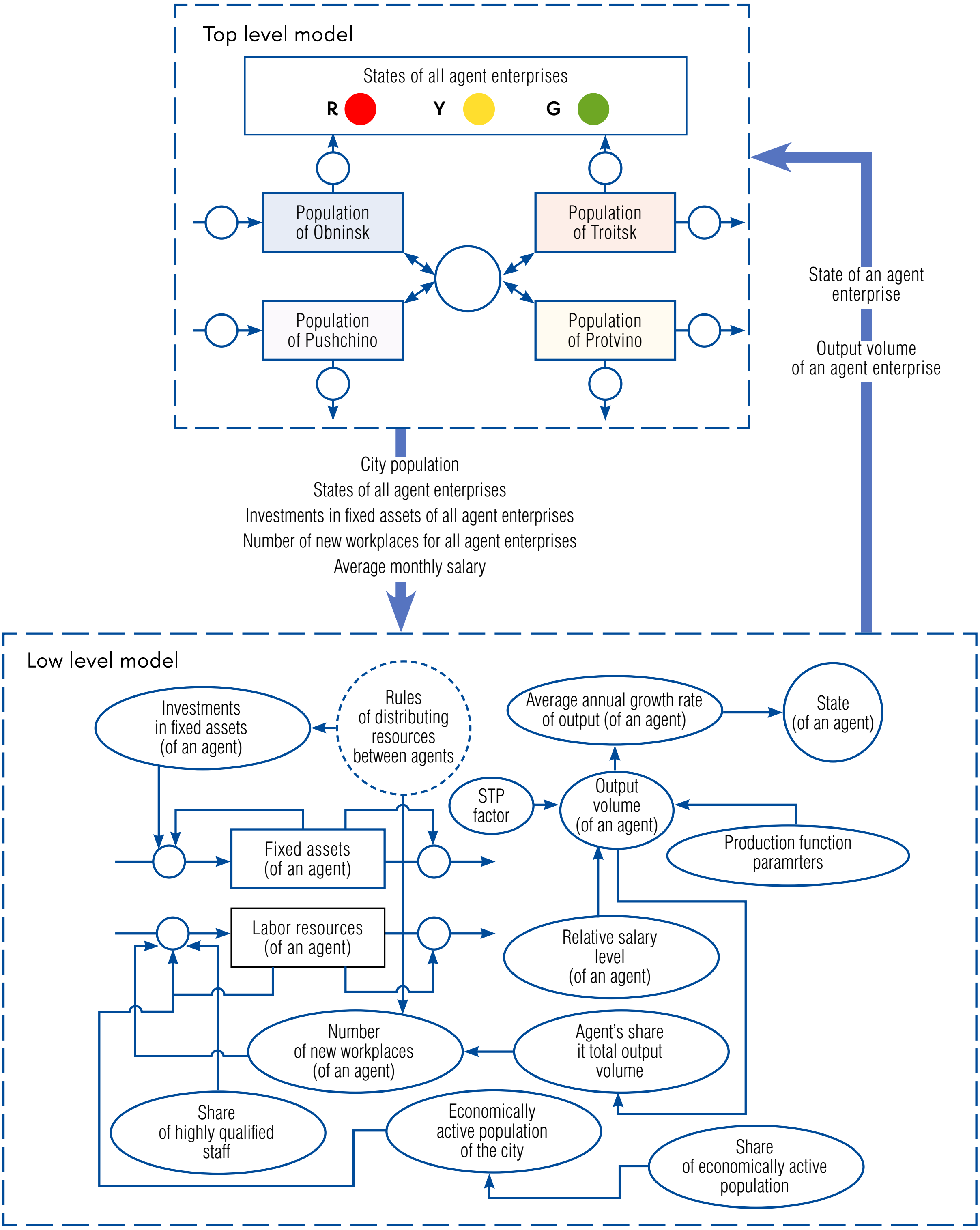

Fig.1. Aggregated architecture of a simulation model of research-and-production clusters.

1.1. Model of labor resource redistribution

The top-level model presented in *Fig. 1* ensures the implementation of the logic of redistribution of population and labor resources, taking into account the influence of the "gravity effect." A similar effect was first described in works [23, 24] devoted to the analysis of human behavior under the influence of social forces. In particular, the decision to migrate to another city is influenced by multiple factors: differences in wages, the size of the labor market, GDP per capita, climatic characteristics, level of social security, etc. To a greater extent, the "gravitational" influence of such differentiation manifests itself at the level of countries that differ significantly in their level and quality of life. However, similar factors promoting migration also apply to cities, including science cities, the features of which allow their residents to move while remaining employed in high-tech sectors of the economy.

Here,

- $T = \{t_1, t_2, ..., t_{|T|}\}$ is the set of moments of the model time (by year), $|T|$ is the strategic planning horizon (10 years);
- $I = \{i_1, i_2, ..., i_{|I|}\}$ is the set of indices of science cities, $|I|$ – total number of science cities;
- $\{v_i, \eta_i\}$, $i \in I$ are the fertility and mortality rates in the i-th science city;
- $\{GMP_i(t_k),\ P_i(t_k)\}$, $i \in I$ are the gross metropolitan product and population of the i-th science city at moment t_k, $(t_k \in T)$;
- $\{W_i(t_k),\ L_i(t_k)\}$, $i \in I$ are the level of wage and amount of labor resources of the i-th science city employed in high-tech sectors of the economy at moment t_k, $(t_k \in T)$;
- $\{\tilde{w}_1,\ \tilde{w}_2,\ \tilde{w}_3\} \in [0,\ 1]$ are the weighting coefficients that determine the level of influence of individual factors on migration flows, where $\tilde{w}_1 + \tilde{w}_2 + \tilde{w}_3 = 1$;
- $\varkappa_i \in [0, 1]$ is the coefficient that determines the level of influence of the "gravity effect" on emigration to the i-th science city.

An emigration rate from the i-th science city $(i \in I)$ to the neighboring ζ-th science city $(\zeta \in I, \zeta \neq i)$ at moment t_k, $(t_k \in T)$ is equal to

$$E_{i\xi}(t_k) = \begin{cases} \varkappa_i \left(\dfrac{1}{g_{i\xi}(t_k)} - 1 \right) P_i(t_{k-1}), \text{ if } g_{i\xi}(t_k) < 1, \\ 0, \text{ if } g_{i\xi}(t_k) \geq 1, \end{cases} \tag{1}$$

where

$$\ln\left(g_{i\xi}(t_k)\right) = \tilde{w}_1 \ln\left(\frac{W_i(t_{k-1})}{W_\xi(t_{k-1})}\right) + \\ + \tilde{w}_2 \ln\left(\frac{L_i(t_{k-1})}{L_\xi(t_{k-1})}\right) + \tilde{w}_3 \ln\left(\frac{\dfrac{GMP_i(t_{k-1})}{P_i(t_{k-1})}}{\dfrac{GMP_\xi(t_{k-1})}{P_\xi(t_{k-1})}}\right). \tag{2}$$

The equations (1)–(2) describe the influence of the "gravity effect" on migration flows. Expression (2) reflects the influence of such key factors as wages $W_i(t_{k-1})$, number of employed labor resources $L_i(t_{k-1})$ and GDP per capita

$$\frac{GMP_i(t_{k-1})}{P_i(t_{k-1})}$$

on the migration behavior of population (i.e., migration rates) in the i-th science city $(i \in I)$. The choice of such factors is determined, first of all, by the observed difference in their values in relation to the science cities under consideration (i.e., Troitsk, Obninsk, etc.). The influence of other potentially important characteristics, e.g., differences in climate, transport accessibility, ecology, etc., is not significant from the geographic proximity and spatial homogeneity of the studied agglomerations. The use of relative and scaled (logarithmized) values of influencing factors allows them to be aggregated using (2) for subsequent calculation of migration rates to neighboring science cities.

From (1)–(2) it follows that if a given science city is less attractive than a neighboring one which has higher wages, more jobs and more GDP per capita, then a positive emigration flow to this science city is provided. The opposite scenario is also possible, when a given science city is more attractive to residents of neighboring cities. In this case, the formation of positive immigration flows will be ensured.

The population of the i-th science city ($i \in I$) considering the emigration to the neighboring ξ-th science cities ($\xi \in I$, $\xi \neq i$), the immigration from the neighboring ξ-ths science cities ($\xi \in I$, $\xi \neq i$), as well as the fertility and mortality at moment t_k, ($t_k \in T$) is equal to

$$P_i(t_k) = P_i(t_{k-1}) - \sum_{\xi=1}^{|I|} E_{i\xi}(t_k) + \sum_{\xi=1}^{|I|} E_{\xi i}(t_k) + \\ + v_i P_i(t_{k-1}) - \eta_i P_i(t_{k-1}). \quad (3)$$

Together with the redistribution of the population between neighboring science cities, the redistribution of highly qualified labor is being implemented accordingly.

The amount of labor resources that can be employed in high-tech enterprises of the i-th science city ($i \in I$) at moment t_k, ($t_k \in T$) is equal to

$$L_i^*(t_k) = \mu_i \omega_i P_i(t_k), \quad (4)$$

where

$\mu_i \in [0, 1]$ is the share of economically active population in the i-th science city ($i \in I$);

$\omega_i \in [0, 1]$ is the share of highly qualified labor resources from the economically active population in the i-th science city ($i \in I$).

1.2. Model of behavior of enterprise agents

The lower-level model presented in *Fig. 1* is used to calculate the dynamics of the average annual growth rate of output of agent enterprises with a corresponding assessment of the states of such agents. The most important characteristic of such enterprises is the production function, which describes the influence of fixed assets, labor resources, the level of scientific and technological development and other factors on the dynamics of output volume. A detailed description of the principles for constructing production functions, including the Cobb-Douglas type used in this work is presented in [25, 26]. There are also examples of constructing multiplicative production functions that take into account the influence of wages on output, as a factor that significantly affects the productivity of labor resources (e.g., [27]). A feature of the production function proposed in this article is that it takes into account the relative (in relation to all neighboring science cities) level of wages. The higher this level, the more qualified labor resources can be employed at enterprises in a given city.

Let be,

- $J_i = \{j_{i1}, j_{i2}, \ldots, j_{i|J_i|}\}$, $i \in I$ is the set of indices of agent enterprises located in the i-th science city, where $|J_i|$ is the total number of enterprises;
- $s_{j_i}(t_k) \in \{1, 2, 3\}$ are the states of the j_i-th agent enterprise of the i-th science city at momen t_k, ($t_k \in T$): $s_{j_i}(t_k) = 1$ is the first state corresponding to low economic growth rates ("red"), $s_{j_i}(t_k) = 2$ is the second state, corresponding to the average rate of economic growth ("yellow"), $s_{j_i}(t_k) = 3$ is the third state, corresponding to high rates of economic growth ("green");
- $\{\tilde{K}_{j_i}(t_k), \tilde{L}_{j_i}(t_k)\}$, $i \in I, j_i \in J_i$ are the fixed assets and labor resources of the j_i-th agent enterprise of the i-th science city at moment t_k, ($t_k \in T$);
- $\{\delta\tilde{K}_{j_i}(t_k), \delta\tilde{L}_{j_i}(t_k)\}$, $i \in I, j_i \in J_i$ are the rate of new fixed assets commissioning and the labor resources inflow of the j_i-th agent enterprise of the i-th science city at moment t_k, ($t_k \in T$);
- $\{Q_i(t_k), Y_i(t_k)\}$, $i \in I$ are investments in fixed assets and the number of new workplaces allocated by the i-th science city at moment t_k, ($t_k \in T$);
- $\{\alpha_{j_i}, \beta_{j_i}\}$ (0, 1), $i \in I$, $j_i \in J_i$ are the coefficients of elasticity of output volume in relation to fixed assets and labor resources of the j_i-th agent enterprise of the i-th science city, where $\alpha_{j_i} + \beta_{j_i} = 1$;
- A_{j_i}, $i \in I, j_i \in J_i$ is the factor (coefficient) reflecting the influence of scientific and technological progress (STP) on the dynamics of output volume;
- $\{\mu, \iota\}$ are the known retirement rates of fixed assets and labor resources, respectively.

Then, the output volume of the j_i-th agent enterprise ($j_i \in J_i$) of the i-th science city ($i \in I$) can be specified with the use of the Cobb-Douglas type production function at momentt_k, ($t_k \in T$):

$$\tilde{V}_{j_i}(t_k) = A_{j_i} S_{j_i} \left(\tilde{K}_{j_i}(t_k)\right)^{\alpha_{j_i}} \left(\tilde{L}_{j_i}(t_k)\right)^{\beta_{j_i}}, \tag{5}$$

where

$$S_{j_i} = \frac{W_i}{\dfrac{1}{|I|}\sum_{i=1}^{|I|} W_i}, \tag{6}$$

$$\tilde{K}_{j_i}(t_k) = \tilde{K}_{j_i}(t_{k-1}) + \delta\tilde{K}_{j_i}(t_k) - \mu\tilde{K}_{j_i}(t_{k-1}), \tag{7}$$

$$\tilde{L}_{j_i}(t_k) = \tilde{L}_{j_i}(t_{k-1}) + \delta\tilde{L}_{j_i}(t_k) - \iota\tilde{L}_{j_i}(t_{k-1}), \tag{8}$$

$$\delta\tilde{K}_{j_i}(t_k) = \begin{cases} Q_i(t_k)\dfrac{\tilde{V}_{j_i}(t_{k-1})}{\sum_{j_i=1}^{|J_i|}\tilde{V}_{j_i}(t_{k-1})}\left(1+\gamma\dfrac{\sum_{j_i=1}^{|J_i|} r_{j_i}(t_{k-1})}{|J_i|}\right), \\ \text{if } s_{j_i}(t_{k-1}) = 1, \\ Q_i(t_k)\dfrac{\tilde{V}_{j_i}(t_{k-1})}{\sum_{j_i=1}^{|J_i|}\tilde{V}_{j_i}(t_{k-1})}\left(1-\gamma\dfrac{\sum_{j_i=1}^{|J_i|} r_{j_i}(t_{k-1})}{|J_i|}\right), \\ \text{if } s_{j_i}(t_{k-1}) = 3, \end{cases} \tag{9}$$

$$\delta\tilde{L}_{j_i}(t_k) = \begin{cases} Y_i(t_k)\dfrac{\tilde{V}_{j_i}(t_{k-1})}{\sum_{j_i=1}^{|J_i|}\tilde{V}_{j_i}(t_{k-1})}\left(1+\gamma\dfrac{\sum_{j_i=1}^{|J_i|} r_{j_i}(t_k)}{|J_i|}\right), \\ \text{if } s_{j_i}(t_{k-1}) = 1, \\ Y_i(t_k)\dfrac{\tilde{V}_{j_i}(t_{k-1})}{\sum_{j_i=1}^{|J_i|}\tilde{V}_{j_i}(t_{k-1})}\left(1-\gamma\dfrac{\sum_{j_i=1}^{|J_i|} r_{j_i}(t_k)}{|J_i|}\right), \\ \text{if } s_{j_i}(t_{k-1}) = 3, \end{cases} \tag{10}$$

$$r_{j_i}(t_k) = \begin{cases} 1, \text{ if } s_{j_i}(t_k) = 1, \\ 0, \text{ if } s_{j_i}(t_k) \neq 1. \end{cases} \tag{11}$$

Figure 2 shows the state-flow chart of the j_i-th agent enterprise ($j_i \in J_i$) of the i-th science city ($i \in I$) implementing the transition rules to new states $s_{j_i}(t_k) \in \{1, 2, 3\}$.

Transitions to new states (indicated by the sign ? in *Fig. 2*) are carried out using the following rule:

$$s_{j_i}(t_k) = \begin{cases} 1, \text{ if } \dfrac{1}{t_k}\sum_{\tilde{t}_k=1}^{t_k}\dfrac{\tilde{V}_{j_i}(\tilde{t}_k)}{\tilde{V}_{j_i}(\tilde{t}_{k-1})} < \varphi_1, \\ 2, \text{ if } \varphi_1 \le \dfrac{1}{t_k}\sum_{\tilde{t}_k=1}^{t_k}\dfrac{\tilde{V}_{j_i}(\tilde{t}_k)}{\tilde{V}_{j_i}(\tilde{t}_{k-1})} < \varphi_2, \\ 3, \text{ if } \dfrac{1}{t_k}\sum_{\tilde{t}_k=1}^{t_k}\dfrac{\tilde{V}_{j_i}(\tilde{t}_k)}{\tilde{V}_{j_i}(\tilde{t}_{k-1})} \ge \varphi_2. \end{cases}$$

Here, $\{\varphi_1, \varphi_2\}$ are the specified threshold values that determine the conditions for compliance of agent enterprises with states of low, medium and high rates of economic growth.

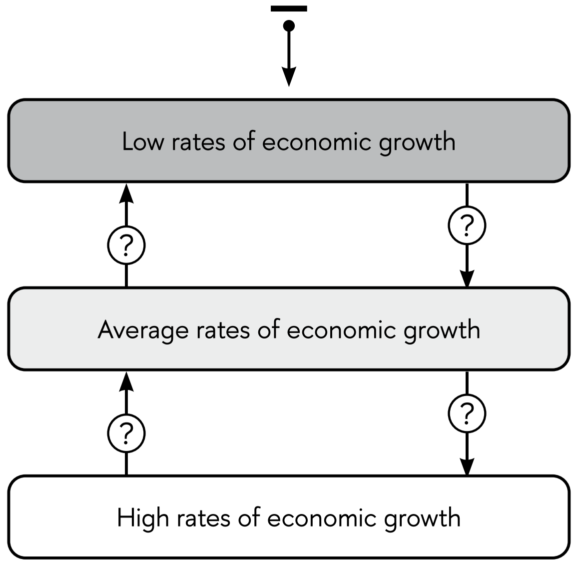

Fig.2. State-flow chart of an agent enterprise.

The proposed model takes into account the influence of the relative wage level (6) on output (5). The use of relations (9)–(11) allows us to provide priority support to agent enterprises that are in the first state of low economic growth rates. Here, $\gamma \in [0, 1]$ is the coefficient determining the overall level of such support. Thus, investments in fixed assets and new jobs allocated for each science city are distributed among "problem" agent enterprises in proportion to their contribution to the total output.

1.3. Optimization problem statement

A system is considered in which it is necessary to ensure the minimization of the total number of enterprises characterized by low rates of economic growth for all selected science cities. For the sustainable development of research-and-production clusters, it is desirable to ensure the transition of the majority of problem enterprises to states of medium and high rates of economic growth and the preservation of such favorable states for the longest possible time interval. However, in the current conditions of a shortage of investment capital, as well as limited opportunities to create new high-tech jobs, it is important to find such states and modes of operation of the system in which minimizing the number of problem organizations is achieved with minimal costs at least by some given point in model time. As a result, a qualitative improvement in the characteristics of the corresponding enterprises will be ensured, practically guaranteeing the preservation of the states they have achieved over a sufficiently long time interval due to the inertia of the values of production factors. In the absence of statistical information about the existing budget and investment restrictions, it is justified to reduce such an optimization problem to a single-criteria one with the following objective functional, estimated at the final moment of model time $t_{|T|}$, $(t_{|T|} \in T)$:

$$N(t_{|T|}) = n_1 \sum_{i=1}^{|I|} \sum_{j_i=1}^{|J_i|} r_{j_i}\left(Q_i(t_k),\, Y_i(t_k),\, W_i(t_k)\right) + \\ + n_2 \sum_{i=1}^{|I|} Q_i(t_k) + n_3 \sum_{i=1}^{|I|} \left(Y_i(t_k) W_i(t_k)\right), \qquad (13)$$

where

$$r_{j_i}\left(Q_i(t_k),\, Y_i(t_k),\, W_i(t_k)\right) = \begin{cases} 1, \text{if } s_{j_i}(t_k) = 1, \\ 0, \text{if } s_{j_i}(t_k) \neq 1. \end{cases} \qquad (14)$$

Here,

- $\{Q_i(t_k),\ Y_i(t_k),\ W_i(t_k)\}$, $i \in I$ are the investments in fixed assets, number of new workplaces and wages in the i-th science city at moment t_k, $(t_k \in T)$ which are control parameters of the model;
- $\{n_1, n_2, n_3\}$ are the normalizing factors that are used to reduce the values of the elements of the objective function values to the uniform scale.

The choice of values of the control parameters of the model is carried out at each moment t_k, $(t_k \in T)$ and leads to changes in the production characteristics of agent enterprises, i.e., fixed assets, labor resources and output volumes in accordance with (5)–(11). As a result, the impact on the average annual rate of economic growth and the state of the corresponding enterprises is ensured, see (12)–(14).

Then the optimization problem can be formulated as follows.

Problem A. *The need to minimize the value of the total number of enterprises characterized by low rates of economic growth at the final moment of the model time* $t_{|T|}$, $(t_{|T|} \in T)$, *as well as the investment and operating costs associated with the implementation of the strategy:*

$$\min_{\{Q_i(t_k),\, Y_i(t_k),\, W_i(t_k)\}_{k=1}^{|T|}} N(t_{|T|}) \qquad (15)$$

s.t.

$$\underline{Q} \leq Q_i(t_k) \leq \bar{Q},\ \underline{Y} \leq Y_i(t_k) \leq \bar{Y},\ \underline{W} \leq W_i(t_k) \leq \bar{W}, \\ i \in I,\ k = 1, 2, \ldots, |T|.$$

Here, $\{\underline{Q}, \underline{Y}, \underline{W}\}$, $\{\bar{Q}, \bar{Y}, \bar{W}\}$ are known lower and upper limits of the simulation model control parameter values.

Problem A can be solved using a genetic optimization algorithm aggregated by objective function with the proposed simulation model. The implementation of such algorithms is based on methods of evolutionary search for the best potential solutions and is described in detail in [12, 28]. To simplify the problem under consideration, the values of control parameters in such a system can be specified for each i-th science city ($i \in I$) as constants at the initial moment of the model time.

2. Software implementation of the model

The software implementation of the developed simulation model (1)–(15) was carried out in the AnyLogic system. A feature of the proposed approach is the use of GIS maps to visualize the states of enterprise agents located in given spatial coordinates, as well as the integration of the model with a previously developed genetic optimization algorithm [28], which, in particular, provides a solution to **Problem A**.

The developed software package provides the ability to navigate through all the science cities being studied, vary the values of the control parameters of the model and visualize the states of agent enterprises on the map.

Figure 3 shows the implementation of the model for the redistribution of population and labor resources between the science cities under consideration (top-level models) in AnyLogic.

As seen from *Fig. 3* the system dynamics methods are used to construct this model (e.g., [11, 22]). The population of Obninsk, Troitsk, Protvino and Pushchino is modeled using four system levels (“reservoirs”) interacting through flows at rates whose values depend on the difference in wage levels, the size of the labor market, etc. Thus, the influence of the “gravity effect” on the rate of internal migration. Fertility and mortality rates with their known values are also taken into account. The reinforcing and balancing feedbacks present in the model are marked with the letters R and B, respectively (*Fig. 3*).

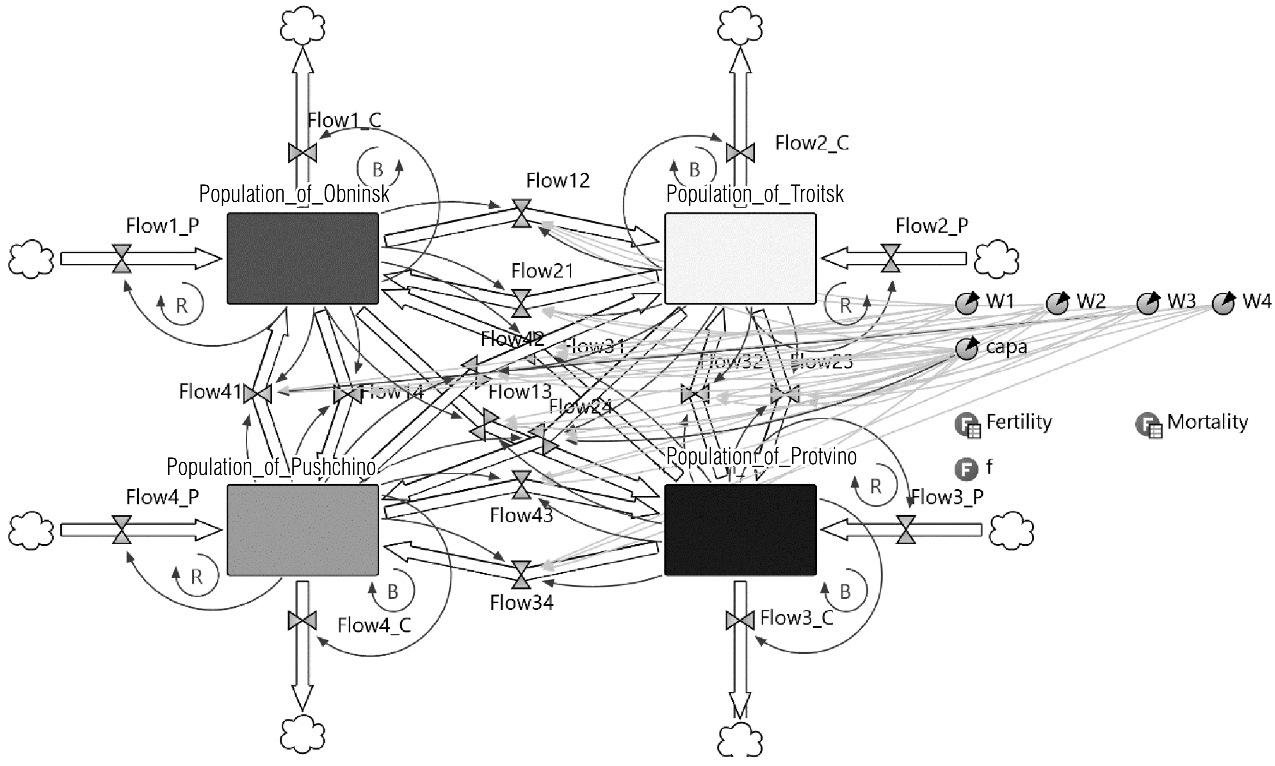

Fig. 3. Model of redistribution of labor resources in AnyLogic.

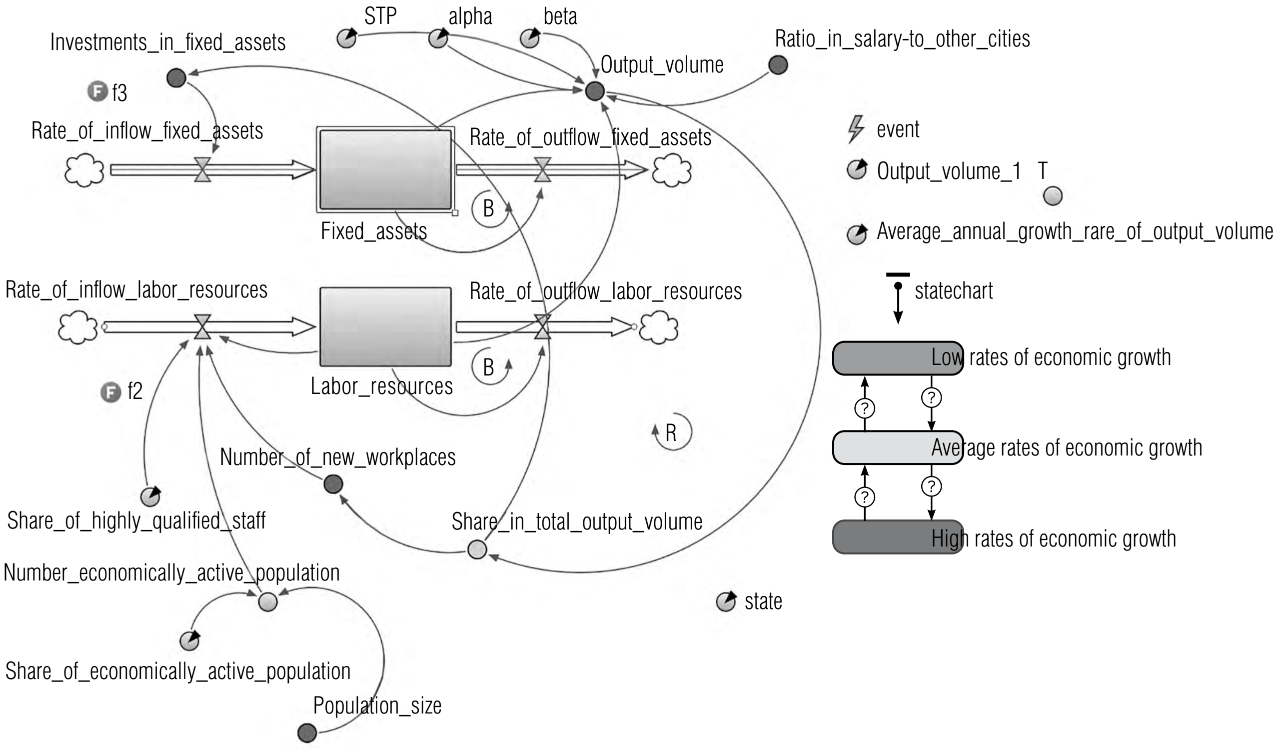

Fig.4. Model of behavior of enterprise agents in AnyLogic.

Figure 4 shows the implementation of the behavior model of enterprise agents (low-level model) in AnyLogic.

Figure 4 shows that to build this model, both the system dynamics and agent-based modeling methods are used (e.g., [5, 6, 13, 14, 16]). In particular, to model possible changes in the states of agents in accordance with the given rules, a state-flow chart is used (that is shown in *Fig. 4*). At the same time, to determine the values of the average annual growth rate of output volume, the value of which is compared with the given threshold values for the implementation of transitions between the states of each agent, the calculation uses the system dynamics model (the left part of *Fig. 4*). The model (5)–(11) uses the function of the Cobb-Douglas type to calculate the output volume, taking into account the values of control parameters. The results of simulation modeling, in particular, the state of each agent enterprise, the output volume, the amount of labor resources, etc. are automatically uploaded to the top-level model and used to simulate the "gravity effect" that determines the process of redistribution of population and labor resources (*Fig. 3*).

3. Results of optimization experiments

To improve the state of the entire ensemble of agent enterprises, in particular, to minimize the number of organizations with low rates of economic growth (less than 2% per year), the optimization experiments were carried out aimed at finding recommended values of control parameters of the model. As initial data, aggregated statistics on science cities were used, that is shared in [29], as well as the strategies for the socio-economic development of science cities published on the websites of city administrations. An example of initial data on agent enterprises for the Obninsk city is presented in *Table 1*.

Figure 5 presents a visualization of the states of agent enterprises obtained as a result of optimizing the values of control parameters of the simulation model ("Scenario based on recommended parameters") in comparison with previously approved investment and staff strategies ("Initial scenario (before optimization)".

The states of agent enterprises presented in *Fig. 5* correspond to a ten-year strategic planning horizon. A scenario for changes in such states based on recommended parameters (*Fig. 5*) was generated using a genetic optimization algorithm, aggregated by target functionality with a developed simulation model implemented in AnyLogic. *Table 2* presents the values of the control parameters of the model that correspond to the scenarios under consideration.

Table 1.

An example of initial dataset for agent enterprises of the Obninsk city (for 2016 year)

No	Company	Longitude	Latitude	Labor resources, people	Investments in fixed assets, thousand rubles	Fixed assets, thousand rubles	Issue volume, thousand rubles
1	JSC "SSC RF-IPPE"	55.089851	36.591257	2612	14782	594124	3199431
2	JSC ONPP "Technology"	55.105885	36.636379	2641	488089	6527163	5856985
3	JSC "SSC RF NIFHI"	55.063435	36.623261	528	103226	1300044	803209
4	MRNC named after A.F. Tsyba – the branch of the FSBI "NMRRC" of the Ministry of Health of the Russian Federation	55.111844	36.617534	1559	136132	2230550	2052357
5	ASP "Typhoon"	55.104454	36.609027	580	1551	80820	293792
6	VNIIRAE	55.106651	36.638687	270	3058	110706	242231
7	Public JST "Instrument Plant "Signal"	55.11013	36.59102	308	48217	996640	1061128
8	LLC "Hemofarm"	55.13496	36.6424	209	169412	2247154	1374894
9	JSC "Progress-ecology"	55.12122	36.58286	236	14758	696989	1709746
10	LLC "Nearmedic Pharma"	55.11442	36.61703	125	2810003	29994145	3506284

Obnsk city	**Initial scenario (before optimization)**	**Scenario based on recommended parameters**
LLC "Hemofarm"	R	Y
JSC "Progress-ecology"	G	G
LLC "Nearmedic Pharma"	R	Y
MRNC named after A.F. Tsyba – the branch of the FSBI "NMRRC"	Y	Y
Public JST "Instrument Plant "Signal"	Y	G
JSC ONPP "Technology"	Y	Y
ASP "Typhoon"	G	G
JSC "SSC RF-IPPE"	G	G
VNIIRAE	G	G
JSC "SSC RF NIFHI"	R	Y

R First stage (low growth rate)

Y Second stage (average growth rate)

G Third stage (high growth rate)

Fig.5. States of agent enterprise before and after optimization.

From *Table 2* it follows that in order to improve the conditions of agent enterprises in the science cities under study, it is necessary to significantly increase investments in fixed assets (mainly in Troitsk, Protvino and Pushchino), as well as to multiply the number of workplaces that should be created. At the same time, it is recommended to increase the level of wages in Obninsk and Pushchino in order to prevent the outflow of staff to neighboring cities (in particular, Troitsk). As a result, a fundamental improvement in the conditions of agent enterprises will be ensured (see *Fig. 5*), most of which will move to the third state of high economic growth rates.

Conclusion

This paper presents a new agent-based simulation model for the development of individual research-and-production clusters in Russia with implementation in the AnyLogic system. The model

Table 2.

Values of model control parameters

Control parameters	Science city	Basic scenario (before optimization)	Scenario based on recommended settings
Investments in fixed assets (million rubles/year)	Obninsk	3320	4341
	Troitsk	453	3108
	Protvino	246	2252
	Pushchino	374	2100
Number of new jobs (units/year)	Obninsk	1000	3020
	Troitsk	500	2550
	Protvino	300	1551
	Pushchino	200	1121
Average monthly salary (rubles/month)	Obninsk	62 000	72 000
	Troitsk	66 000	66 000
	Protvino	60 000	60 000
	Pushchino	45 000	55 000

developed consists of two levels (*Fig. 1*). The top-level model implements the environment in which agent enterprises belonging to various science cities operate, between which flow interaction is realized with a corresponding redistribution of the population and labor resources. The lower-level model provides the implementation of the logic of behavior of enterprise agents, the characteristics of which are described using system dynamics methods. An important optimization problem has been formulated to minimize the total number of enterprises characterized by low rates of economic growth, taking into account investment and operating expenses. The proposed two-level simulation model is implemented in the form of a software package (using the example of research-and-production clusters of Obninsk, Troitsk, Protvino and Pushchino), intended primarily for municipal and regional authorities implementing the strategy of innovative development. The use of such a system made it possible to formulate recommended values of control parameters (such as investments in fixed assets, the number of new jobs, etc.), providing a significant improvement in the conditions of agent enterprises located in the science cities under study over a ten-year strategic planning horizon (*Fig. 5* and *Table 2*). The economic-mathematical and computer toolkit developed is intended primarily for managing research-and-production clusters implementing the strategy of innovative development.

Further research will be aimed at studying the problems associated with overcoming the shortage of highly qualified labor, as well as the creation of detailed agent-based models for the development of research-and-production clusters. ■

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