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Smart Approach of Scientific Knowledge Building to Achieve Sustainable Management in Higher Education System

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Abstract: The modern system of higher education and research is undergoing deep institutional transformations, accompanied by changes in funding mechanisms, increased competition, the growing importance of project forms of scientific activity organization, and more complex requirements for performance. In the conditions of digital transformation and institutional instability, higher education faces the need to form sustainable smart management systems. The modern understanding of smart education goes beyond e-learning and includes the intellectualization of all levels of organization of educational and scientific activities. This requires the creation of new models capable of integrating the behavior of teachers and researchers in the context of digital, project, and institutional logics. Thus, the task of building intelligent models capable of reflecting the complex, multi-layered structure of interactions between researchers, organizations, forms of support, and the system of evaluation of scientific work becomes relevant. This article proposes an agent-based approach to modeling the process of formation of scientific knowledge, considered as a key element of the sustainable development of scientific and educational environment. The model reflects the interaction of agents—researchers with different characteristics: age, qualification level, scientific productivity, affiliation, and trajectory of professional development. The modeling results allow us to draw conclusions about the regularities of the reproduction of scientific potential, the factors of academic environment sustainability, and the effectiveness of institutional support mechanisms. The obtained results have both theoretical and applied significance. The model can be used to forecast the effectiveness of science policy, assess the risks and prospects of scientific teams, and justify incentive systems and the long-term design of the development of scientific organizations. The presented approach allows us to form a comprehensive view of the dynamics of scientific knowledge in the context of sustainable management in higher education.

Keywords: agent-based modeling; sustainable management; scientific knowledge; higher education; grants; government assignment; research teams



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1. Introduction

The modern system of higher education and scientific activity is in a phase of deep transformation due to both internal institutional changes and external socio-economic challenges. The globalization of scientific communication, digitalization of the research environment, increased competition for resources, and growing uncertainty in science policies make it especially important to develop models focused not only on efficiency and effectiveness but also on sustainability as a systemic characteristic of the academic environment [1–5].

Sustainable development in science and higher education includes the ability of the system to maintain and reproduce scientific knowledge, human resources, academic institutions and research communities regardless of short-term fluctuations in the external environment [6–10]. This implies an internal balance between stability and flexibility, between long-term orientation and short-term performance, and between individual strategies and collective forms of work organization.

The complexity of sustainable science management lies in the fact that classical administrative and financial mechanisms are often unable to ensure continuity and stable development. There is a need for an intellectual rethinking of the logic of scientific knowledge formation, taking into account new types of interactions, new models of funding, and new forms of the self-organization of research communities [11].

One of the most significant changes in recent years has been the shift in emphasis from institutional, stable funding to a grant-based project model. In countries with developed scientific systems, this model is often compensated for by strong support from universities, independent foundations, and a stable human resource core. However, in countries with unstable scientific ecosystems, including Russia, the introduction of project mechanisms without a sufficient institutional base leads to increased fragmentation, loss of sustainability, and the destruction of research traditions.

Grant logic, for all its advantages (motivation, competition, and targeted results), in conditions with a lack of institutional support begins to function as a mechanism of short-term mobilization rather than sustainable development. Projects become an end in themselves, and scientific teams disintegrate after funding is completed. This contradicts the very nature of science as a cumulative, long-term process. The result is a systemic risk: the erosion of the foundations of scientific schools, a loss of continuity, and a shortage of young personnel [12–14].

In addition, the individualization of scientific work is increasing, where the researcher has to combine the roles of an author, administrator, manager, teacher, and grant seeker. Such multitasking reduces the depth of research, burns out creative resources, and undermines the sustainability of academic careers.

The current paradigm of scientific evaluation is based mainly on quantitative metrics: number of publications, citation index, amount of funding attracted, and ranking [15]. However, the focus is on short-term performance, while sustainability—the ability of the system relative to self-reproduction, knowledge accumulation, and long-term scientific programs—remains out of the spotlight.

Maintaining sustainability requires not only funding but also specific organizational conditions: stable research teams, mentoring institutions, academic autonomy, and time for the in-depth study of scientific problems. These parameters are poorly taken into account in the current logic of scientific management, which is focused on accountability and “quick” achievements.

This is why there is a need to rethink approaches to the formation and maintenance of scientific knowledge, inextricably linked to the concept of sustainability—both internal and systemic.

Against the background of the described changes, the problem becomes more acute: How can we ensure the sustainable development of the scientific environment in the conditions of institutional instability, fragmentation, and short-term project pressure? How can we build such a model of interaction between researchers, organizations, and funding mechanisms, which would simultaneously ensure efficiency and sustainability?

Despite the diversity of approaches to analyzing science policy, there remains a clear lack of models that can carry out the following:

- Integrate the behavior of individual agents (researchers), their motivations, and resources;
- Take into account the institutional environment (structure of organizations, forms of funding, and performance requirements);
- Model temporary and institutional scientific teams with different degrees of sustainability;
- Analyze the long-term consequences of a given science policy.

Thus, the research objective of this paper is to create an intellectual model that will allow us to study the relationship between individual behavior, institutional structure, and the sustainable formation of scientific knowledge.

Taking into account the stated problems, the main objective of this study is to develop an intellectual approach to the formation of scientific knowledge that is focused on the sustainable development of the scientific environment and the reproduction of human resources in the system of higher education [12,16–18]. The proposed approach is realized in the form of an agent-based model describing the interaction of researchers, scientific teams, and institutions under the conditions of various forms of funding.

In pursuit of this goal, the following research objectives are addressed:

1. To identify the key characteristics of a sustainable scientific environment in the context of modern transformations;
2. To describe the features of the institutional and project financing of scientific activity and their impact on the stability of teams;
3. To formalize the behavior of researchers as agents making decisions under conditions of limited resources and institutional requirements;
4. Develop a model of interaction between individual strategies, the structure of scientific teams, and external incentives;
5. Conduct the simulation modeling of scenarios of scientific environment development under different institutional configurations;
6. Evaluate the model's potential for predicting the performance and sustainability of an academic system.

Hypothesis 1. *The sustainable development of the scientific environment and reproduction of scientific knowledge depend on a balanced combination of two forms of funding—long-term state assignment and short-term grant support. At the same time, the effectiveness of research activity is determined not only by individual productivity but also by the quality of the institutional environment, the structure of scientific teams, and the strategies of time allocation between different types of activity.*

This hypothesis is based on the assumption that a purely grant-based model in the absence of stable institutions leads to staff turnover, reduced sustainability, and the strategic orientation of research. In contrast, the combination of project flexibility and institutional continuity allows the maintenance of the reproduction of scientific knowledge and staff continuum.

The hypothesis is tested by constructing an agent-based model with elements of simulation modeling, in which agents (researchers) act in the context of different forms of teams, types of funding, and science policy conditions. The modeling results allow us to assess the sensitivity of the system to changes in the incentive structure and institutional parameters.

The scientific novelty of this study lies in the formation of an intellectual approach to analyzing the sustainability of the scientific environment on the basis of agent-based modeling, which allows integrating the behavioral level of analysis with institutional and macro-organizational logic. In contrast to traditional quantitative or managerial models, the focus of which is limited to the assessment of performance or resource efficiency, this paper formalizes the dynamics of scientific knowledge as a result of multi-layered interaction between researchers, teams, and the funding system.

In the framework of the developed model, scientific activity is interpreted as a multidimensional process, including not only obtaining scientific and technical results but also teaching, administrative, and self-actualization activities. This allows us to assess the impact of the distribution of time and roles of the researcher on the sustainability of the entire scientific ecosystem. A new element of the model is the mechanism of the dynamic formation of research teams under the conditions of limited time, competition for resources, and institutional requirements for project participants.

In addition, the model takes into account the processes of accumulation and the loss of qualifications that affect the personnel structure and the reproduction of scientific potential. The formalized structure of interactions makes it possible to assess not only the current performance but also the long-term sustainability of teams in terms of their ability to reproduce scientific knowledge and integrate young researchers. Thus, the developed approach allows us to rethink the strategic parameters of science policy in the context of sustainable development.

The methodological basis of the work is the agent-based approach, which allows modeling the behavior of a large number of heterogeneous agents interacting within a limited institutional space. This approach is widely used in economics, sociology, and system dynamics, especially in problems where nonlinear effects, emergent behavior, and the influence of the structure of interactions are important.

This study employs simulation modeling where agents are endowed with a set of strategies, parameters, and behavioral rules. The model takes into account the following:

- The professional life cycle of a researcher (growth and decline of qualifications);
- Career mobility and group formation;
- Time allocation between activities;
- Response of agents to changes in the institutional environment (e.g., new grants or changes in the structure of government assignments);
- The probability of withdrawal from science due to frustration or a lack of resources.

The methods of analysis include computational experiments, scenario analyses, sensitivity to parameters, and the estimation of the collective results of scientific activity on the basis of the derivatives of individual contribution (including the analog of the Shepley vector).

The proposed model is considered not only as a tool for describing the behavior of researchers but also as an element of the system of the sustainable management of science and higher education. Sustainable management in this context is the ability to maintain a dynamic equilibrium between the reproduction of knowledge, personnel, institutions, and funding mechanisms while taking into account long-term goals.

The model allows making decisions aimed not only at the growth of current performance but also at the formation of conditions that ensure sustainability: reducing staff turnover, supporting mentoring, creating effective teams, and distributing roles and resources in accordance with the long-term goals of scientific development.

The presented model is based on the idea of considering scientific knowledge not as a result of a linear process but also as a complex emergent phenomenon arising from interactions between agents in a certain institutional environment. This interaction not

only has cognitive but also social, organizational, and resource components. Thus, the formation of scientific knowledge is not so much a function of a single individual as a result of collective dynamics mediated by forms of funding, structures of scientific teams, career opportunities, and the stability of scientific infrastructure.

The use of an agent-based approach in this context allows us to not only model the behavior of agents depending on their motivations and resources but also trace how changes in the parameters of the external environment affect the stability of the entire system. This is important because science is a system with delayed effects: decisions made today affect the quality of knowledge, personnel, and institutional structure years or even decades later.

Thus, the intellectual approach implemented in this study allows us to broaden the horizon of science policies, shifting the focus from short-term performance to long-term sustainability. This is in line with the logic of sustainable development proclaimed at the global level—in particular, in the framework of the UN Sustainable Development Goals (SDGs), where the role of quality education and science as drivers of transformation is emphasized particularly vividly (Goal 4 and associated goals on innovation and institutional development).

The developed model can be used as an analytical tool in the practice of the strategic management of the scientific sphere, including the following:

- To assess the consequences of changes in the funding structure;
- To analyze the consequences of researchers leaving science;
- To predict the formation or destruction of scientific teams;
- To assess the viability of research areas depending on the personnel and institutional configuration;
- To optimize resource allocation, taking into account not only current productivity but also the potential for sustainable development.

The model acquires special significance in the conditions of the formation of national scientific programs and university strategies aimed at ensuring long-term competitiveness. It can be used both in public authorities and within scientific and educational organizations—as a basis for monitoring and planning the development of human resources, assessing the performance of scientific units, and forming policies to attract and retain young researchers.

In addition, the model can serve as a platform for expanding digital tools to support science policy: intelligent forecasting systems, digital twins of research ecosystems, data-driven decision-making platforms, and scenario analysis.

The modern system of higher education and scientific activity is in a phase of deep transformation due to both internal institutional changes and external socio-economic challenges. There is a need for the intellectual rethinking of the logic of scientific knowledge formation, taking into account new types of interactions, new models of funding, and new forms of the self-organization of research communities.

At the same time, the problem of the reproduction of scientific personnel potential is becoming more and more acute, especially in terms of young scientists. According to the Institute for Statistical Research and Knowledge Economics of the National Research University Higher School of Economics, the share of researchers under the age of 39 in Russia has decreased from 44% to 38% over the last 5 years, despite the launch of programs to stimulate the participation of young people in science. At the same time, there is an aging of the teaching staff: The average age of researchers in universities and academic institutions exceeds 50 years. This trend indicates the structural limitations of the system and the threats to the sustainability of scientific knowledge reproduction in the medium term [19–23].

To substantiate the relevance of the intellectual approach to modeling the sustainability of the scientific environment, we present an extended statistical cross-section reflecting the key structural, demographic, and institutional changes in the Russian scientific sphere for the period 2017–2023 (Table 1). The presented data allow us to not only identify systemic challenges but also empirically support the need to transition to more flexible and adaptive forms of knowledge management.

Table 1. Indicators of sustainability of the research environment in Russia (2017–2023).

Indicators	2017	2023	Change
Number of researchers (full-time equivalent), thousand people	390.5	340.7	−49.8 (−12.8%)
Share of researchers under 39 years of age, %	35.5	44.1	+8.6
Share of researchers 50–59 years old, %	24.0	12.9	−11.1
Average salary of a researcher, thousand RUB/month	60.0	92.0	+32.0 (+53.3%)
Share of R&D expenditures in GDP, %	1.1	1.0	−0.1
Number of publications in international journals (Russian authors)	39,000	45,000	+15.4%
Level of competition for RNF grants (successful applications to submitted applications), %	20%	17%	−3

Source: Open data from Rosstat (2017–2023), HSE analytical reports, and RSF annual statistics; compiled and calculated by the authors.

Thus, the problem of the sustainable development of the scientific environment includes not only institutional and financial aspects but also personnel inertia, the deficit of scientific youth, and the decreasing attractiveness of academic careers. This requires a transition from management decisions focused solely on short-term performance to strategic planning based on intellectual models of sustainability.

2. Literature Review

The modern development of science and the higher education system is accompanied by the introduction of intellectual and digital solutions that contribute to the transformation of educational and scientific environment. In the context of accelerated digitalization, growing volumes of information, increasing competition for resources, and changing models of educational process management, there is a growing need to rethink the principles of the sustainable development of academic ecosystems.

Against this background, studies aimed at modeling sustainable academic systems, taking into account the individual behavior of agents, institutional environments, and resource distributions, acquire special significance. They allow us to not only describe the consequences of current policies but also propose intellectual scenarios for the long-term design of sustainable scientific development.

The current literature on this issue focuses on a number of key areas: digital intelligent environments, project-oriented learning, agent-based models, institutional and resource management, and cognitive and behavioral aspects in science.

Intelligent educational technologies are becoming a critical factor for sustainable development in higher education. Terzieva et al. (2024) [24] propose a conceptual model of an integrated intelligent educational environment (IIEE) that includes sensors, actuators, and adaptive digital components aimed at transforming traditional forms of learning. The authors emphasize the importance of digital skills, cross-curricular literacy, and interaction with digital systems as the foundation for the sustainable scientific and educational potential of future generations.

In turn, Prabhakar Rao and Singh (2020) [25] develop the concept of “disruptive intelligent systems” in engineering education, emphasizing the need for interdisciplinary approaches and project orientation. According to the authors, only through the integration

of digital and cognitive components is it possible to achieve sustainable educational development that provides the training of flexible and adaptive professionals capable of solving the complex problems of the future.

An additional contribution to understanding the sustainability of educational ecosystems is made by Chandra et al. (2024) [26], which considers intelligent resource management in 5G/6G networks in an educational environment. The proposed model, based on edge intelligence and the Social Internet of Educational Things (SIOET) concept, demonstrates the potential to reduce latency and energy consumption while improving the stability of digital infrastructure. The authors emphasize the importance of intelligent systems in shaping a sustainable, adaptive, and reliable educational environment, especially in the context of the digital transformation of universities.

Project-based learning methodology is increasingly considered as a tool to improve the sustainability of educational and research activities. The study by Guraziu et al. (2025) [27] considers project management not only as a managerial paradigm but also as a pedagogical strategy to shape sustainable academic practices. Through project-based courses and interdisciplinary interactions, students acquire research and organizational competencies necessary to integrate into complex academic communities and manage knowledge at different levels. Thus, project-based learning is seen as a way to build intellectual capital and strengthen the internal structures of sustainability in the educational system.

The importance of flexibility and adaptability in AI-based learning models is increasingly recognized, particularly in their ability to accommodate students' individual trajectories [28]. Personalized learning systems promote deeper integration into the educational process, reduce dropout rates, and enhance student engagement—factors that are critical to ensuring the long-term sustainability of educational systems.

In recent years, approaches based on agent-based modeling (ABM) applied to educational and scientific systems have been actively developed. The works of Mammadov et al. (2018) [29] demonstrate the application of expert systems for the evaluation of innovative projects in university technoparks. Such systems allow formalizing the processes of selection of scientific initiatives, increasing the transparency of resource allocation and enhancing the institutional sustainability of scientific development. The author's approach offers intellectual support for management decisions, which allows improving the quality of the scientific environment as a whole.

Agent-based modeling is also increasingly applied to simulate behavior within educational ecosystems [30,31]. In particular, the use of adaptive models supports the development of flexible educational trajectories that are resilient to both external disruptions and internal overload, thereby enhancing system robustness and responsiveness.

However, despite the obvious promise of ABM approaches, most existing models are either limited to describing local behavior or do not include institutional parameters affecting system stability. In this regard, the task of integrating the models of agents' behavior with the parameters of the institutional environment and forms of financing and organizational structures remains relevant.

Recent studies have explored how cognitive attitudes and behavioral patterns influence the sustainability of scientific activity [32,33]. One modeling approach conceptualizes decision-making in scientific environments as an iterative process of hypothesis formulation and testing, akin to entrepreneurial behavior. Findings suggest that applying structured scientific reasoning in resource allocation improves the capacity to discontinue ineffective projects at early stages, thereby enabling the redirection of efforts toward more promising directions [34,35]. This, in turn, enhances both economic efficiency and the long-term sustainability of the research environment by mitigating the persistence of low-impact initiatives.

Finally, the prospects of using artificial intelligence in project management have received serious theoretical and empirical elaboration in a recent study by Craveiro and Domingues (2025) [30]. The authors analyze the impact of various AI technologies on the project management performance domains presented in *PMBOK 7th edition*, including key areas such as stakeholder engagement, planning, uncertainty control, and team performance.

The paper presents the opportunities for using AI tools such as machine learning, neural network models, fuzzy logic, expert systems, and chatbots to improve the efficiency and adaptability of management processes. Special attention is paid to how AI can support decision-making under uncertainty, automate communications with stakeholders, and increase the sustainability of the project environment by optimizing planning, monitoring, and resource allocation. According to the authors, the most promising areas of AI application are planning, outcome measurement, risk management, and teamwork.

The research methodology is also of interest: Along with a systematic literature review, Multivocal Literature Review is used to identify both academic and practice-oriented approaches to the application of AI in project management. As a result, a generalized matrix of correspondence between AI tools and project domains is proposed, reflecting the potential for the sustainable transformation of project activities in education and research [36–41].

This approach can be extrapolated to the behavior of researchers in the academic environment: Making decisions about the choice of topics, entering research teams, and allocating time between different types of activity also require adaptability, rationality, and the ability to self-evaluate. This confirms the importance of including the behavioral dimension in intellectual models of sustainability.

Against the background of the identified trends, it becomes obvious that in order to analyze the sustainability of the research environment, an integrated model combining the behavioral level, institutional context, and digital and intellectual management tools is needed. It is this task that the present study is focused on.

3. Smart Approach Model

The aim of this research is to apply an intellectual approach of scientific knowledge formation to achieve sustainable management in the system of higher education. To achieve this goal, it is necessary to develop an agent-based model that will allow analyzing scenarios of scientific sphere development depending on the nature of tasks and configuration of development drivers such as funding.

The model of the process of formation of scientific knowledge is presented in Figure 1.

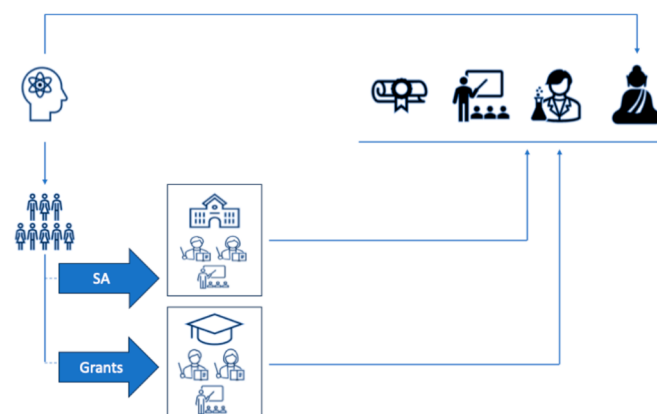


Figure 1. Model of the process of formation of scientific knowledge. Source: Developed by the authors.

This model reflects a researcher who conducts research in a group of scientists within scientific institutes or within groups that are set up to implement grants.

Thus, in order to produce scientific knowledge, a group is needed. As a result, scientific activities can take place within two types of groups: within an institute and within a grant. Together with this, four types of things that can occur within the existence of a scientist are identified:

1. Publications or results of intellectual activity.
2. Teaching.
3. Supervision of graduate students.
4. Self-actualization.

However, self-actualization can be a consequence of the scientist being both in a team and alone. Table 2 describes the essence of the model.

Table 2. Description of the model entity.

No.	Indicators	Type of Entity	Information
1		Agent, researcher	Qualifications, age, number of publications, number of citations, affiliations
2		Organization	Number of employees, region
3		Scientific group	-
4		Scientific and technical result	Publications
5	SA	State assignment	Size of SA of organizations
6	Grants	Grants	RSF terms and conditions, internal competition, etc.

Source: Developed by the authors.

Thus, qualification is a measure of the ability to obtain scientific and technical results of a certain quality. In turn, obtaining scientific and technical results is possible only within scientific collectives (scientific institutes and groups within grants), where the individual is the self-realization of agents. This provision is conceptually related to Table 2, which presents empirical data characterizing the current state of the scientific environment in Russia, including the age structure, workload, and specifics of funding. The dynamics of these parameters allows us to formalize the constraints and conditions in which the agent makes decisions about the distribution of activity between self-development, scientific productivity, and adaptation to the institutional environment.

As a result, the model can be applied in reality only with the help of statistical data on publication activity, data from the reports of academic organizations, and data on the structure of funding (in particular, the share of funding for SA, the share of grant funding, and the type of grant).

Currently, the process of the formation of scientific results in the academic institutions of the Russian Academy of Sciences can be represented as a mastering process carried out by a scientific organization relative to the size of a grant or the SA carried out by a scientific group; this has known co-authorship graphs, which eventually allows researchers to obtain a scientific and technical result (Figure 2).

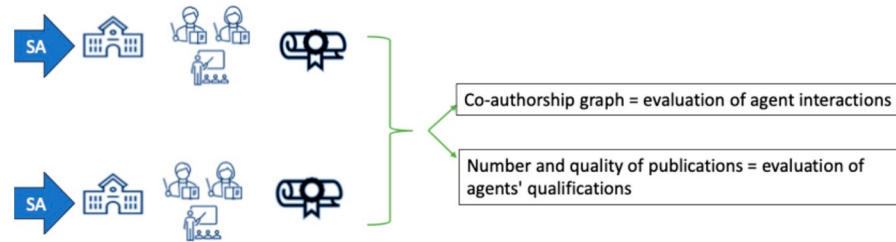


Figure 2. A real-world model of scientific result generation. Source: Compiled by the authors. Source: Developed by the authors.

Thus, as illustrated in Figure 2, the interaction between agents can be based either on the co-authorship of scientific publications or on formal employment relationships within the same research and educational organization.

The following section outlines the key characteristics of the core entities within the model of scientific knowledge production:

The “Researcher” Agent:

- A population of agents classified as “Researchers” $i \in I = \{1, \dots, I\}$.
- Each agent can be engaged in a set of research directions defined by $J = \{1, \dots, J\}$. Within each direction $j \in J$, the agent’s activity is divided into the following:
 - Fundamental research (Res);
 - Applied development (Dev).
- For each direction, the agent allocates effort across the following activities:
 - Skill development (Skill);
 - Production of scientific and technical results (Result);
 - Teaching (Teach);
 - Administrative duties (Adm).

Let $Gr_{i,t} = \{q : i \in S_q, t \in Time(S_q)\}$ denote the set of active collectives (i.e., research teams or research-educational institutions) in which agent i participates at time t .

Agent i allocates their available time to the following activities:

- Working within active collectives $q \in Gr_{i,t}$ across directions $j \in J$, focused on producing research or development results: $z_{i,q,t}^{j,k,Result}$, where $k \in \{Res, Dev\}$;
- Teaching within educational institutions $p \in Org_{i,t}$ across directions $j \in J$: $z_{i,q,t}^{j,k,Teach}$, where $k \in \{Res, Dev\}$;
- Personal skill development across directions $j \in J$: $z_{i,t}^{j,k,Skill}$;
- Administrative work in collectives $q \in Gr_{i,t}$: $z_{i,q,t}^{Adm}$.

The total workload is bounded by the agent’s maximum available time z_i , as described by the following constraint:

$$\sum_{j,k,q \in Gr_{i,t}} z_{i,q,t}^{j,k,Result} + \sum_{j,k,q \in Gr_{i,t}} z_{i,q,t}^{j,k,Teach} + \sum_{j,k} z_{i,t}^{j,k,Skill} + \sum_{j,k,q \in Gr_{i,t}} z_{i,q,t}^{Adm} \leq z_i \quad (1)$$

where z_i denotes the maximum available time resource of agent i .

The following constraints are imposed on the agent’s time allocation. Each agent is characterized by a minimum share $a_i^{Skill} \in [0, 1]$ of their available time, which must be devoted to skill development. This time is distributed across those research domains in which the agent possesses non-zero qualifications. Additionally, for domains in which the agent currently holds an active grant at time t , the time allocated to skill development is multiplied by a factor k_{gr} (a model parameter) compared to domains without active funding.

Administrative work is limited to a predefined share $a_i^{Adm} \in [0, 1]$ of the agent’s total available time. In collectives corresponding to formal academic institutions, a fixed teaching

load is established for academic staff. For those identified as teaching agents, the time spent on teaching activities $z_{i,q,t}^{j,k,Teach}$ is set at a fixed level (defined as a model parameter).

In current practice, teaching activities in research and educational institutions are typically carried out by senior researchers with high academic qualifications and by doctoral students serving as teaching assistants.

Based on the above, each agent i is characterized by engagement in three main types of activity:

1. **Scientific activity** includes the agent's ability to generate scientific and technical results, denoted as $y_{i,t}^{j,k}$, where j represents the field of research and $k \in \{Res, Dev\}$ indicates whether the activity pertains to fundamental research or applied development.
2. The agent's scientific productivity depends on the intensity of self-development and active participation in a strong research collective. Accordingly, the dynamics of scientific performance are modeled as follows:

$$y_{i,t}^{j,k} = (1 - \delta^{j,k})y_{i,t-1}^{j,k} + Y^S \sum_{u \in \mathbb{J}, r \in \{Res, Dev\}} A_{u,r}^{j,k} (z_{i,t}^{u,r,Skill} + Y^{ST} \sum_{q \in Gr_{i,t}} z_{i,q,t}^{u,r,Teach}) + yy(Age_{i,t})(1 + Y^Y \sum_{ii \in Con_{i,t-1}^p} y_{ii,t-1}^{j,k}) \quad (2)$$

where

$\delta^{j,k}$ denotes the rate of qualification depreciation in the corresponding domain;

$A_{u,r}^{j,k}$ denotes the components of the matrix capturing cross-domain knowledge transfer intensities;

$yy(Age_{i,t})$ denotes the age-based adjustment factor for knowledge acquisition from peers in the connection graph, defined as 2 if $Age_{i,t} < 35$ and 1 otherwise;

Y^S , Y^{ST} , and Y^Y denote model parameters.

The probability that an agent exits the scientific system $Exit_{i,t}$ is modeled as a function of both income and age:

$$P_{i,t}^{poor} = P_1^E \mathbb{I}(Inc_{i,t} < Poor_{i,t}), \quad (3)$$

$$P_{i,t}^{age^1} = P_2^E \mathbb{I}(Age^1 \leq Age^2) \quad (4)$$

$$P_{i,t}^{age^2} = P_3^E \mathbb{I}(Age_{i,t} \geq Age^2) \quad (5)$$

$$Exit_{i,t} = P_{i,t}^{poor} + (1 - P_{i,t}^{poor})(P_{i,t}^{age^1} + P_{i,t}^{age^2}) \quad (6)$$

where

$P_1^E, P_2^E, P_3^E, Age^1$, and Age^2 denote calibration parameters;

$Poor_{i,t}$ denotes the poverty threshold for agent i at time t .

3. **Administrative activity** reflects the agent's ability to organize and manage effective research team operations $y_{i,y}^{Adm}$. The administrative activity of an agent depends on the experience of participating and leading teams. Thus, the dynamics of administrative activity will look as follows:

$$y_{i,t}^{Adm} = (1 - \delta^{Adm})y_{i,t-1}^{Adm} + Y_1^A \sum_{q \in LG_{i,t-1}} ResS_{q,t-1} + Y_2^A \sum_{q \in Gr_{i,t-1}} ResS_{q,t-1} \quad (7)$$

where δ^{Adm} denotes the rate of the obsolescence of administrative qualifications; Y_1^A and Y_2^A denote model parameters.

4. **Teaching activities** involve characterizing the agent's ability to impart knowledge and attract the interest of students $y_{i,t}^{Teach}$. Teaching activity is determined by the intensity of knowledge translation and self-development. Thus, the dynamics of teaching activity will look as follows:

$$y_{i,t}^{Teach} = (1 - \delta^{Teach})y_{i,t-1}^{Teach} + Y^T \sum_{u \in \mathbb{J}, r \in \{Res, Dev\}} (Y^{TS} z_{i,t}^{u,r,Skill} + \sum_{q \in Gr_{i,t}} z_{i,q,t}^{u,r,Teach}) \quad (8)$$

where δ^{Teach} denotes the rate of the obsolescence of teaching qualifications;

Y^T and Y^{TS} denote model parameters.

The emergence of new researchers in the model is the result of the teaching activities of existing researchers.

Probability $Enter_{i,q,t}$, which is probability of whether there will be a new researcher as a result of the researcher's teaching i in the organization q , depends on $y_{i,t}^{Teach}$ and $z_{i,q,t}^{j,k,Teach}$, where the set of scientific competencies of the teacher will be relevant to the directions of the group q .

Scientific organization:

- A scientific organization includes rather large research groups.
- The initial distribution of researchers in scientific and educational organizations is set by real data, such as qualification, age, number of publications, and so on.
- The key task of the research and educational organization is to perform the GE.
- Some part of the staff of the scientific-educational organization is engaged in teaching activities, which allows laying a foundation and increasing the scientific interest in research among the student community.
- Work for employees in scientific and educational organization is one of the reasons for the formation of new research groups.

Thus, the scientific and educational organization provides an opportunity for researchers to solve long-term problems and, accordingly, receive a stable income.

A group of researchers:

- A group of researchers is defined as a subset of a set of researchers $S_q \in \mathbb{J}$, $q = 1, 2, \dots$
- The team is formed to carry out some short-term grants and may contain researchers from different organizations. The process of forming a research team begins when the grant in which the research team will participate is identified. The list of new grants appears at the beginning of each period, which initiates the formation of the team. The team to be formed must meet the conditions of the grant: the requirements for the number of participants, their age and the number of results they have obtained so far, and the participants should have sufficient free time and qualifications to obtain the required results. Every researcher i_{st} has a probability $React_{i_{st},t}$. If group formation is started, the researcher selects the largest grant from the ranked list of grants, and the requirements of being the supervisor should be met by the researcher (including having sufficient free time for additional administrative workload). If the researcher satisfies the conditions imposed in the grant on the supervisor, the researcher sends out proposals to other researchers with whom he or she is linked with in the column (see Figure 2). The successful implementation of a grant requires assembling a team that is capable of achieving the required level of scientific and technical results. That is, one that meets

$$\sum_{i \in S_q, (j,k) \in Dir(S_q)} y_{i,t}^{j,k} z_{i,q,t}^{j,k,Report} \geq \frac{ResS_{q,t}}{y_{Lead(S_q),t}^{Adm} z_{Lead(S_q),t}^{Adm}}$$

If a group that satisfies the conditions of the grant has been formed, then, within it, the funding of scientific activities of all participants is determined in proportion to their contribution to the overall result (similarly to the Shepley vector), plus some unconditional levels. After the model year, there may be changes in the structure of the groups. If the grant expires, the group ceases to exist.

Thus, if the scientific and technical result of team S_q is defined by the ratio $Res_{S_q,t} = R y_{Lead(S_q),t}^{Adm} * z_{Lead(S_q),t}^{Adm} \times \left(\sum_{i \in S_q, (u,r) \in Dir(S_q)} y_{i,t}^{u,r,Report} \right)$, then the agent's performance i will depend on the intensity of their work in each of the collectives (organizations and groups).

$$Res_{i,t}^{j,k} = \sum_{q \in Gr_{i,t}} A_{i,t,S_q}^{j,k} Res_{S_q,t}^{j,k}$$

$$A_{i,t,S_q}^{j,k} = \frac{y_{i,t}^{j,k} z_{i,t}^{j,k,Report}}{\sum_{ii \in S_q} y_{ii,t}^{j,k} z_{ii,t}^{j,k,Report}}$$

Grant Objective:

Every grant that appears in the system G_f , $f = 1, 2, \dots$ is characterized by a set of attributes (similarly to the requirements of real RSF grants, etc.):

- Duration of the grant;
- Funding—the amount of disbursements at each point in time;
- Allowable number of participants;
- Requirements for the leader (age and performance);
- Requirements for participants (age and performance);
- Set of relevant research areas;
- Share of young researchers;
- Requirements to the results of the grant.

Thus, the developed agent-based model of the scientific environment allows us to formalize the key elements affecting the sustainability of scientific knowledge and the productivity of research teams. Its architecture takes into account institutional and behavioral parameters, including types of funding, the age and qualification characteristics of agents, modes of workload distribution, the structure of research teams, and the dynamics of inter-agent interactions.

Special attention is paid to modeling factors such as administrative pressure, intrinsic motivation, resource constraints, and the effect of scientific capital accumulation. This ensures the possibility of calibrating the model on the basis of real statistical data and conducting scenario analyses. Thus, the proposed model serves as a tool for the quantitative assessment of the sustainability of the scientific environment, as well as a platform for forecasting the consequences of institutional reforms.

4. Results

The simulation results presented in this section are derived from a multi-agent model that operationalizes the key constructs of academic development—such as faculty advancement, research productivity, and institutional cooperation—in a formal mathematical structure. These constructs, which are typically described qualitatively, are translated into measurable agent attributes and behaviors, enabling scenario-based analysis.

The model is built upon a discrete-time, agent-based framework with bounded rationality and adaptive decision-making. Each agent maximizes a utility function (see Equation (9)) that integrates individual scientific output, the strength of cooperative ties, accumulated seniority, and workloads. Scientific productivity itself is a nonlinear function (Equation (2)) subject to qualification dynamics, time allocation, and cooperation intensity. Cooperation is modeled through a dynamic graph structure (Equation (11)), where the link's strength evolves with shared project experience.

This abstract structure allows the model to represent emergent phenomena such as team stability, researcher burnout, and knowledge reproduction while maintaining agent-level granularity. Although the current version focuses on endogenous system dynamics—funding structures, institutional forms, and agent interactions—the model is

designed to accommodate external variables such as demographic shifts, macroeconomic constraints, or regional disparities in future iterations. These factors are discussed in the Discussion Section as part of future development directions.

By grounding conceptual constructs in formal observables and computational mechanisms, the model serves as both a theoretical and practical tool for assessing the sustainability of scientific systems under different policy regimes. The results that follow illustrate how different funding configurations affect researcher motivation, team formation, scientific output, and systemic resilience.

Within the framework of this study, an agent-based model was implemented to reflect the behavior of researchers under the conditions of changing institutional environment and different funding regimes. The model includes the parameters of individual productivity, scientific career trajectories, team stability, types of scientific activity, and the impact of grant pressure.

To verify and validate the model, scenario-based computational experiments were conducted to analyze the stability of the system under different configurations of science policies.

Four scenarios were developed and tested to assess the sustainability of the scientific environment under different institutional configurations. Each of them reflects one of the characteristic modes of functioning of the scientific system and models the consequences of the dominance of certain factors on the behavior of agents, team dynamics, knowledge reproduction, and performance levels.

The scenarios were built based on an analysis of empirical data reflecting current trends in Russian and international practice, such as increasing dependence on grant funding, decreasing staff stability, increasing project pressure, and growing administrative burden. Within the modeling framework, each agent is given unique parameters, including qualifications, motivation, age, propensity to cooperate, and access to various forms of support. Institutional conditions are modeled separately: the availability of government support, the possibility of forming stable teams, the structure of grant programs, and the level of accountability.

Scenario A: (Baseline) Balanced Financing

This scenario assumes a harmonious balance between institutional stability and project competition. Agents are motivated both by their own scientific results and by their integration into the cooperative environment. Their motivation function takes into account not only their current productivity but also the depth of inclusion in collective forms of work, their age, and the balance of time between the main types of activity. Productivity here is subject to a saturated logistic function reflecting the effect of diminishing returns, and cooperation is subject to a graph evolution model with fading interaction. Collectives persist at average motivation above a given threshold, making them sustainable in the long run.

Thus, the individual utility function of agent i will have the following form:

$$U_i(t) = a_i(t) * \tanh\left(\frac{P_i(t)}{P_0}\right) + \beta_i * \frac{S_i(t)}{1 + e^{-\lambda_i D_i(t)}} - \gamma_i * \left(\frac{L_i^{teach}(t) + L_i^{admin}(t)}{T_i(t)}\right) \quad (9)$$

where $a_i(t)$ denotes the agent's sensitivity to scientific productivity (adaptive parameter);

$P_i(t)$ denotes scientific productivity (publications, applications, and citations);

P_0 denotes the normalizing parameter (the level of productivity at which motivation is saturated);

$S_i(t)$ denotes the strength of cooperative ties (the total weight of an agent's ties in the cooperation graph);

$D_i(t)$ denotes the agent's seniority (number of years in science);
 L_i^{teach} and L_i^{admin} denotes teaching and administrative workloads;
 $T_i(t)$ denotes the total working hours per year (e.g., 1600 h);
 λ_i denotes the agent's trainability (the higher this value, the greater the benefit of mentoring).

Thus, the stability condition will look as follows:

$$\bar{U}_{C_k}(t) = \frac{1}{|C_k|} \sum_{i \in C_k} U_i(t) \geq U^* \quad (10)$$

At $U^* = 0.6$, the collective is maintained. If the average motivation in a collective is ≥ 0.6 , it is considered viable and continues to function.

In turn, the evolution of cooperation looks like this:

$$\frac{dw_{ij}}{dt} = \eta * \left(\frac{P_i(t)P_j(t)}{1 + \|P_i(t) - P_j(t)\|} - \lambda * w_{ij}(t) \right) \quad (11)$$

where $w_{ij}(t)$ denotes the weight of cooperation between agents i and j ;

η denotes the coefficient of cooperation growth;

λ denotes the attenuation coefficient in the absence of new projects.

Figure 3 shows the dynamics of agents' average utility under balanced financing conditions. The graph demonstrates the relative stability of agents' motivation under the condition of balanced pressure from the project and institutional logics. Fluctuations reflect adaptation to external conditions and local changes within collectives.

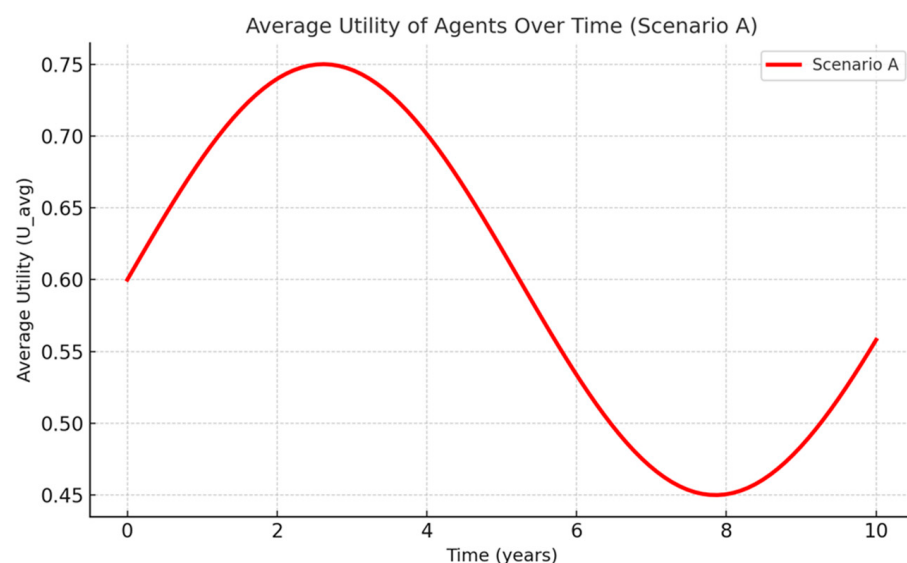


Figure 3. Average utility of agents over time (Scenario A). Source: Developed by the authors.

Figure 4 illustrates the evolution of the strength of ties in research teams. The sustainable development of cooperative relations is observed under the conditions of moderate competition and institutional support, which ensures the formation of stable teams and the accumulation of collective scientific capital.

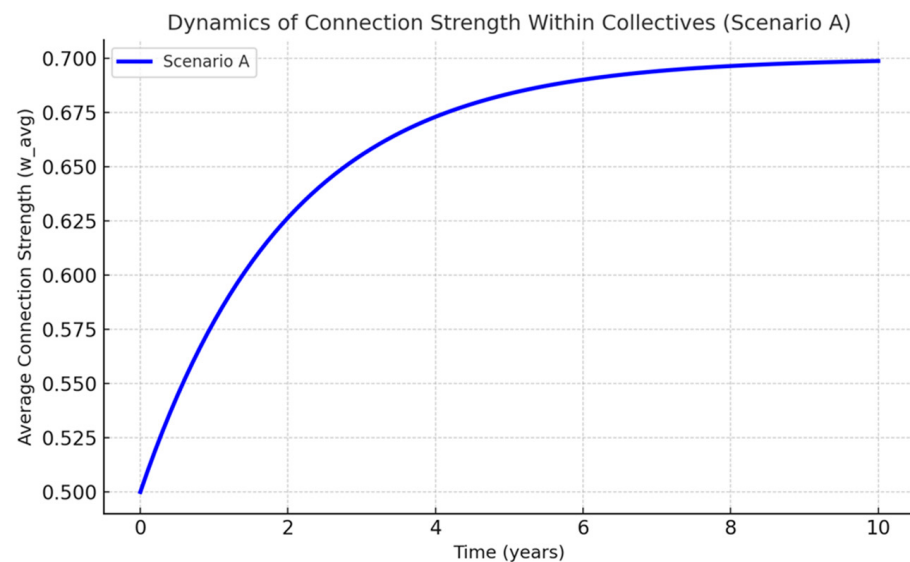


Figure 4. Dynamics of team bonding strength (Scenario A). Source: Developed by the authors.

Figure 5 compares the scientific productivity of agents with high and low degrees of cooperation. Obviously, the presence of dense cooperative ties contributes to higher and more stable performance, while agents with limited interaction demonstrate lower productivity and greater sensitivity to external conditions.

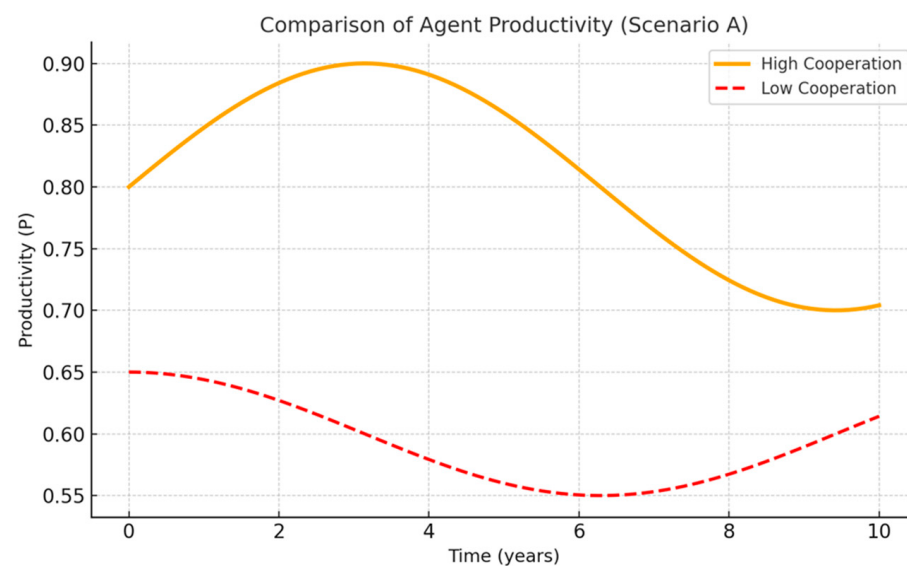


Figure 5. Comparison of agent productivity (Scenario A). Source: Developed by the authors.

Figure 6 is a heat map showing the dependence of agent utility on the level of workload and motivation. As can be seen from the visualization, even with high motivation, a sharp increase in administrative or pedagogical workload leads to a significant decrease in overall efficiency. This confirms the need for a balanced allocation of time and tasks.

Scenario A demonstrates that a balanced combination of institutional and grant funding (50/50) creates the best conditions for the sustainable functioning of the research environment. Agents in this configuration demonstrate stable motivation, high levels of cooperation, and an optimal balance between individual productivity and collective performance.

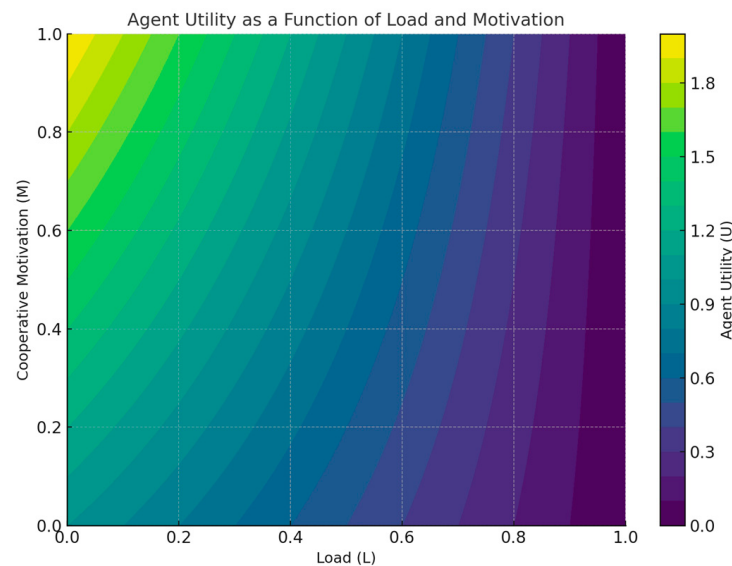


Figure 6. Utility dependence on load and cooperative motivation (Scenario A). Source: Developed by the authors.

The mathematical model shows that the utility function in such conditions depends not only on short-term indicators (publications and grants) but also on the underlying characteristics—seniority, cooperative ties, workloads, and mentoring. This minimizes the risk of burnout and turnover and provides conditions for the translation of scientific capital and continuity.

The visualized data confirm the following theoretical assumptions:

- Agents' motivation is maintained at a sustainable level.
- The strength of scientific ties increases over time.
- The productivity of agents with high cooperation is significantly higher than that of isolated participants.
- Even with a high level of intrinsic motivation, administrative burden significantly reduces performance.

Thus, the scenario of balanced funding is the most favorable in terms of maintaining the sustainability of research teams, the development of scientific knowledge, and the reduction in institutional risks. This scenario can be considered as a reference configuration for the development of a science policy oriented towards sustainable development.

Scenario B (grant dominance) models a situation in which the bulk of funding (up to 80%) comes through grant competitions (Figure 7). This reflects the logic of increased external competition, high accountability, short-term horizontal design, and the withdrawal of basic support.

The figure presents the dynamics of two key indicators—average agent utility (U_{avg}) and interpersonal trust levels—under Scenario B, which reflects a highly competitive and grant-dominated funding environment. While utility exhibits oscillatory behavior and gradual declines due to uncertainty and resource competition, trust levels demonstrate lower initial stability and attenuation over time. The dual-axis plot captures the trade-off between short-term performance peaks and long-term institutional fragility, highlighting the systemic risks associated with excessive reliance on short-term project-based incentives.

Under such conditions, agents are forced to regularly participate in competitions, reallocate resources, frequently change teams, and focus on publication performance. At the same time, the institutional burden increases significantly, the predictability of career trajectory decreases, and there is a risk of a loss of motivation among some researchers.

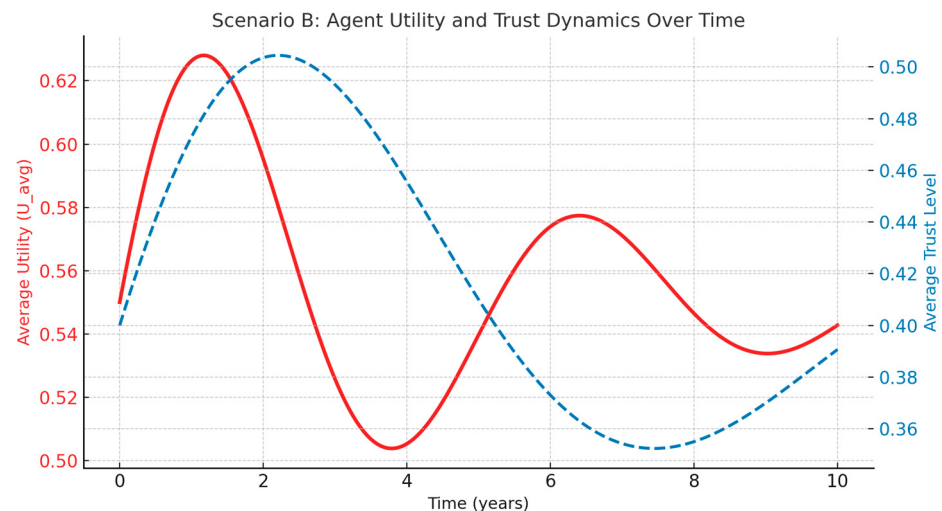


Figure 7. Temporal dynamics of agent utility and interpersonal trust in a grant-dominated academic environment (Scenario B). Source: Developed by the authors.

Scenario C (institutional dominance) represents a situation in which up to 80% of resources come from direct state assignment and institutional support. This may include support for university laboratories, stable funding for research areas, and long-term development programs (Figure 8).

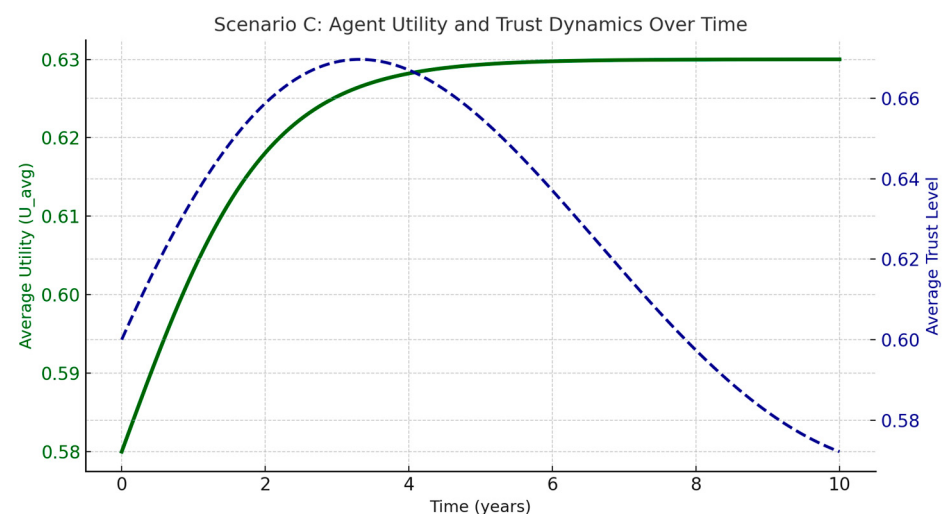


Figure 8. Long-term stability of utility and trust in institutionally anchored academic systems (Scenario C). Source: Developed by the authors.

The figure illustrates the evolution of agent utility and trust under Scenario C, reflecting a stable, institutionally supported research environment. The utility increases gradually and asymptotically, driven by low volatility and collective continuity. Trust among agents remains high due to stable cooperation and shared institutional norms, supporting the long-term sustainability of academic teams.

Under these conditions, teams are able to function sustainably, engage in basic research, and form schools and mentoring relationships. However, this approach may reduce the flexibility and dynamism of the system, slow down changes in topics and methods, and reduce internal competition. The model takes into account the possibility that agents' innovation activities may decrease in the absence of external pressure.

Scenario D (enhanced fragmentation) represents an extreme variant of destabilization: high level of competition for limited resources, shortened funding horizons (less than

1 year), and dominance of reporting and administrative logic. Teams are formed and dissolved quickly, agents demonstrate behavioral instability, and the number of unsuccessful applications leads to increased demotivation and burnout (Figure 9).

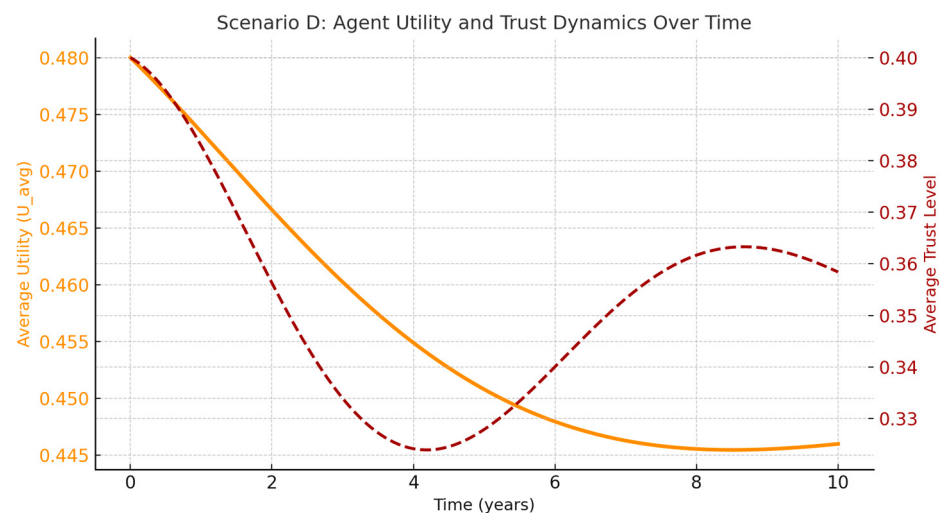


Figure 9. Utility decline and trust erosion in fragmented research environments (Scenario D). Source: Developed by the authors.

This figure shows the deteriorating patterns of agent utility and trust under Scenario D, characterized by institutional fragmentation, short-termism, and weakened collective engagement. Both indicators exhibit declining trends, indicating the systemic erosion of cooperation, reduced motivation, and the collapse of long-term knowledge production networks.

This scenario is constructed by analyzing data relative to the short grant system, KPI pressures, and institutional turnovers. In it, the key characteristics of the system are fragmentation, the predominance of individual strategies, a decreasing density of cooperation, and increasing costs of adaptation.

Each of the scenarios is simulated for a conditional 10-year period (10 model years), during which key indicators are observed: the average life expectancy of teams, the share of agents who left the scientific sphere, average productivity, the density of cooperative ties, and adaptation to changes in the external environment. The model also captures the number of grant exit cycles, the volume of failures, the proportion of agents in a state of overload, the burnout rate, and the distribution of time between activity types.

The modeling incorporates evolutionary logic—that is, the trajectories of agents and teams depend not only on initial parameters but also on accumulated interactions, project experience, level of support, and the availability of mentors. Thus, the scenarios allow us to not only identify average characteristics but also analyze behavioral heterogeneity: who survives in extreme regimes, what types of agents are prone to self-organization, how stable coalitions are formed, and under what conditions they collapse.

This approach allows us to present the scientific environment as a dynamic system in which structural parameters (share of funding, type of assignments, and duration of contracts) determine not only individual behavior but also overall sustainability, the accumulation of intellectual capital, and the reproducibility of knowledge. Scenarios are used not as predictions but as a tool to analyze the sensitivity of the system relative to management decisions and to changes in policy parameters.

Thus, the described scenarios are not only models of alternative realities but also a platform for testing hypotheses, assessing the long-term consequences of institutional reforms, and developing science-based recommendations to improve the sustainability of the scientific environment.

5. Discussion

The development of intelligent models of scientific environment sustainability requires the formalization of complex and multifaceted processes occurring in the system of science and higher education. Despite the high level of detail and the presence of empirical foundations, the proposed agent-based model has a number of significant limitations that need to be recognized and critically understood. These limitations affect both the theoretical and methodological aspects of the modeling and the empirical framework used to parameterize the model.

First, the model relies on the premise of the relative rationality of agents who make decisions based on optimizing their own utility under conditions of limited resources and institutional requirements. However, in real scientific practice, the behavior of researchers often deviates from rationality: It may be emotionally colored and subject to the effects of group pressure, social affiliation, or externally set expectations. Elements such as intuition, personal involvement in the topic, team relations, or reputational risks are not formalized directly but play a key role in decision-making.

Second, the model does not differentiate agents by disciplinary fields. Meanwhile, the features of publication activity, grant strategies, career trajectories, and scientific productivity differ significantly from one branch of knowledge to another. For example, the interval between results is much higher in the humanities than in the technical sciences; medical science requires constant access to laboratory infrastructure; basic physics is highly dependent on collaborative forms of research and long-term design [42,43]. A universal model may not accurately capture the specifics of these differences.

Third, the model does not take into account the regional factor. Under the conditions of the territorial asymmetry of the Russian scientific infrastructure, differences in institutional maturity, the level of available funding, staffing and digital transformation, the behavior of agents, and the stability of teams may radically differ between regions. The application of uniform parameters across the entire system levels out the specificity of territorial clusters and reduces the accuracy of diagnostics for regional science.

The fourth significant limitation is the aggregation of institutional conditions. The model uses generalized variables such as “institutional stability”, “administrative burden”, or “teaching activity” but does not take into account their specific implementation in different types of organizations: federal universities, academic institutions, regional HEIs, private research institutes, etc. At the same time, differences in the regulatory framework, KPI system, performance evaluation procedures, and access to infrastructure directly affect the behavior of agents.

The fifth limitation concerns the modeling of scientific cooperation. Despite the fact that the model implements a graph structure of interactions, it does not yet take into account such characteristics as the degree of trust, the history of previous interactions, the agent’s authority in the community, and interdisciplinary differences in the logic of cooperation. In addition, horizontal institutional ties, including academic mobility, network communities, and participation in international consortia, are not modeled. These aspects are important for assessing the sustainability of the research environment and the potential for self-reproduction.

The sixth limitation is the insufficient integration of stochastic mechanisms into agents’ behavioral models. In the current version, an agent chooses a development trajectory based on a deterministic utility function, which excludes the elements of randomness, external shocks, or sudden events that can affect behavior. In reality, a researcher’s career may be interrupted or change trajectory due to unforeseen circumstances: the departure of a key mentor, the closure of a laboratory, or a change in ministry policy. Integrating stochastic elements will make the model more resilient to uncertainty.

The seventh limitation is the weak accounting of the agent's career life cycle. Although the model realizes the structure of activity by age and professional categories, there are no transitions between statuses: from graduate student to young scientist, from senior researcher to laboratory manager, etc. These transitions are accompanied by changes in motivation, activity patterns, access to resources, and influence on the cooperative network. Their formalization will make it possible to model the mechanism of reproduction of scientific elite and personnel sustainability.

The eighth limitation is related to insufficient attention to institutional policy at the level of organizations and the state. The model considers the environment as a fixed set of parameters, while, in reality, there are institutional reforms, changes in the forms of funding, the introduction of new KPIs, and the creation or liquidation of scientific units. The introduction of an adaptive level of management into the model will make it possible to take into account the response of the system to control actions and build feedback between policies and the behavior of agents.

Finally, it should be noted that the empirical base is limited. Although the model includes statistical data, they are presented at the aggregate level and do not always allow calibrating the individual parameters of agents. A necessary direction of the model's development is the collection and analysis of micro-level data: researcher questionnaires, career trajectories, metrics of academic networks, digital footprints, and internal reports of organizations. This will not only improve calibration accuracy but also introduce elements of machine learning to tune the model in real time.

At the same time, we would like to emphasize that the model has already been applied in a pilot setting to simulate institutional dynamics in two large Russian universities with contrasting organizational structures. One institution is characterized by centralized planning and a high share of state-assigned funding, while the other follows a project-based research model with a strong dependence on external grants. Using available administrative data—including the distribution of researchers by age and qualification, team structures, grant participation rates, and publication records—we configured two separate simulations to reflect their internal conditions.

The model successfully reproduced key differences in research team stability, generational replacement, and responsiveness to funding mechanisms. For example, in the grant-dominated institution, the simulations demonstrated increased researcher turnover, reduced average team lifespan, and lower cooperation density, consistent with observed trends in staff reports and internal assessments. In the state-funded institution, the model predicted the greater persistence of scientific groups and more stable qualification trajectories. These results suggest that the model is not only theoretically sound but also empirically viable for comparative institutional analysis.

Based on this experience, we believe that the model can be extended to simulate multiple concrete cases—including universities, departments, or national research systems—provided that hard data are available. A future research priority is the formal integration of micro-level indicators from institutional databases (e.g., personnel files, funding histories, publication systems) to enhance the model's calibration and enable comparative science policy evaluation grounded in real-world dynamics.

Future research should aim to address these limitations in a step-by-step manner. In particular, the promising directions are as follows:

- Extension of the model by introducing the behavioral and social heterogeneity of agents;
- Realization of stochastic components in motivational functions and cooperation mechanisms;
- Integration of regional and interdisciplinary contexts into the parameterization of the environment;

- Taking into account career dynamics and institutional transitions within scientific organizations;
- Connecting modules of international cooperation and academic mobility;
- Creation of an adaptive layer for modeling the effects of science policies;
- Broadening the empirical base through the use of micro-level data and digital footprints;
- Introduction of optimization tools for finding sustainable trajectories of science development in different institutional configurations.

Thus, the presented model is only the first step towards the creation of intelligent digital twins of the scientific environment. It sets the basis for further development towards hybrid models combining agent-based, network-based, and predictive approaches, and it can be used as a basis for decision-making within the framework of strategic management in the field of science and education.

6. Conclusions

The agent-based model of scientific knowledge formation proposed in the article demonstrates the potential of intellectual approaches in the development of solutions for sustainable management in the system of higher education. The model reveals internal dependencies between the behavior of researchers, the structure of scientific teams, institutional constraints, and the types of funding.

The modeling allows us to argue that the sustainability of the academic environment can be achieved through a balanced combination of long-term state assignment, which ensures stability and continuity, and flexible grant support, which stimulates short-term scientific activity and competition. This approach not only allows an analysis of the current situation but also the forecasting of the consequences of changes in science policies, including the aspect of personnel reproduction, scientific productivity, and the formation of new research groups.

The notion of sustainability in the proposed model is reflected in the emergence of stable regimes characterized by consistent researcher retention, the long-term viability of scientific teams, and the balanced dynamics of cooperation and output. Such regimes are observed when the academic system maintains its capacity to reproduce knowledge and human capital over time, even under varying institutional conditions.

The developed model can be used as a tool to support decision-making in the field of science policy, as well as a basis for further research aimed at developing systems for forecasting and evaluating the performance of scientific activity.

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