**Economics of knowledge-intensive and high-tech enterprises and industries.
Management in organizational systems**

**Экономика наукоемких и высокотехнологичных предприятий и производств.
Управление в организационных системах**

UDC 330.342.24
https://doi.org/10.32362/2500-316X-2025-13-4-123-134
EDN XXKOTU

RESEARCH ARTICLE

Industrial revolutions: From Industry 3.0 to Industry 5.0 in the context of the Russian economy

Natalia N. Karpukhina @,
Evgeny S. Mityakov,
Aleksey Yu. Pronin

MIREA – Russian Technological University, Moscow, 119454 Russia
@ Corresponding author, e-mail: karpukhina@mirea.ru

• **Submitted:** 31.07.2024 • **Revised:** 27.01.2025 • **Accepted:** 24.04.2025

Abstract
Objectives. The study set out to substantiate the principles of Industry 5.0 as a necessary development for the classical model of economic growth proposed by Solow. An adapted and expanded Solow model is presented that takes into account technological progress, as well as social and environmental aspects, which influence long-term development and economic growth in the context of the Russian economy.
Methods. The main results of the work are obtained through a comparative analysis of the distinctive features of Industry 3.0, Industry 4.0, and Industry 5.0 in the context of an extended Solow model and an expert survey to assess the factors influencing economic growth.
Results. In order to substantiate the necessity of transition to more promising models of production and development, the main distinguishing features of Industry 3.0, Industry 4.0, and Industry 5.0, are shown to be determined by unique orientations, technologies, objectives, approaches to working with data, and types of interfaces. The Russian economy is shown to be insufficiently prepared for the challenges of Industry 5.0. The principles of Industry 5.0 apply to such factors of the Solow economic growth model as labor, capital, and technological progress, as well as human capital, natural resources, and the current technological level. A survey of experts was conducted to assess the contribution of factors to production processes. The extended Solow model is a convenient tool for developing specific economic policy strategies based on the analysis of the interrelated factors.
Conclusions. The transition to Industry 4.0 technologies and subsequent planning for the implementation of Industry 5.0 technologies are necessary steps prior to the creation of an innovative and competitive economy. The conducted expert survey exemplified the different contributions of various factors to Industry 5.0 production processes, including a decrease in the role of capital and labor, along with a concomitant increase in the importance of human capital, technological development, and natural resources. This transition is evidenced by the presented numerical values for the Solow model coefficients for Industry 3.0, Industry 4.0, and Industry 5.0. Such Industry 5.0 priorities not only do not contradict economic growth, but can be expected to enhance it in the long term.

Keywords: Industry 3.0, Industry 4.0, Industry 5.0, technologies, comparative analysis, Solow model, human capital, digitalization, innovative economy

For citation: Karpukhina N.N., Mityakov E.S., Pronin A.Yu. Industrial revolutions: From Industry 3.0 to Industry 5.0 in the context of the Russian economy. *Russian Technological Journal.* 2025;13(4):123–134. https://doi.org/10.32362/2500-316X-2025-13-4-123-134, https://www.elibrary.ru/XXKOTU

Financial disclosure: The authors have no financial or proprietary interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Промышленные революции: от Индустрии 3.0 к Индустрии 5.0 в контексте российской экономики

Н.Н. Карпухина @, Е.С. Митяков, А.Ю. Пронин

МИРЭА – Российский технологический университет, Москва, 119454 Россия
@ Автор для переписки, e-mail: karpukhina@mirea.ru

• **Поступила:** 31.07.2024 • **Доработана:** 27.01.2025 • **Принята к опубликованию:** 24.04.2025

Резюме

Цели. Цель статьи – доказать, что принципы Индустрии 5.0 являются необходимым развитием для классической модели экономического роста, предложенной Солоу. В статье модель Солоу адаптирована и расширена новыми факторами, которые учитывают технологический прогресс, социальные и экологические аспекты и в контексте российской экономики оказывают влияние на долгосрочное развитие и экономический рост.

Методы. Основные результаты работы получены с помощью сравнительного анализа отличительных особенностей Индустрии 3.0, Индустрии 4.0 и Индустрии 5.0, расширенной модели Солоу и экспертного опроса для оценки факторов, влияющих на экономический рост.

Результаты. Для обоснования необходимости перехода к более перспективным моделям производства и развития выделены основные отличительные особенности Индустрии 3.0, Индустрии 4.0 и Индустрии 5.0, определяемые уникальной ориентацией, технологиями, целями, подходами к работе с данными и типами интерфейсов. Установлено, что российская экономика пока недостаточно готова к вызовам Индустрии 5.0. Доказано, что принципы Индустрии 5.0 расширяют такие факторы модели экономического роста Солоу, как труд, капитал и технологический прогресс, добавляя человеческий капитал, природные ресурсы и уровень технологий. Для оценки вклада факторов в производственные процессы проведен опрос экспертов. Расширенная модель Солоу является инструментом для разработки конкретных стратегий в области экономической политики на основе анализа взаимосвязанных факторов.

Выводы. Переход к технологиям Индустрии 4.0 и последующее планирование внедрения технологий Индустрии 5.0 являются необходимыми шагами для создания инновационной и конкурентоспособной экономики. Проведенный опрос экспертов доказал разный вклад факторов в производственные процессы: уменьшение роли капитала и труда, рост значимости человеческого капитала, технологического развития и природных ресурсов в Индустрии 5.0. Такие приоритеты Индустрии 5.0 не только не противоречат экономическому росту, но и могут его усилить в долгосрочной перспективе.

Ключевые слова: Индустрия 3.0, Индустрия 4.0, Индустрия 5.0, технологии, сравнительный анализ, модель Солоу, человеческий капитал, цифровизация, инновационная экономика

Для цитирования: Карпухина Н.Н., Митяков Е.С., Пронин А.Ю. Промышленные революции: от Индустрии 3.0 к Индустрии 5.0 в контексте российской экономики. *Russian Technological Journal*. 2025;13(4):123–134. https://doi.org/10.32362/2500-316X-2025-13-4-123-134, https://www.elibrary.ru/XXKOTU

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Contemporary Russia has two distinctly pronounced trends of the economic development that make it unique. The formation of a "knowledge economy" in the first decade of the 21st century was focused on the latest knowledge, innovations, and the development of an information society. The process of universal digitalization that actively unfolded since 2010 has led to the development of digital innovation and increased digital competition [1].

Digitalization in Russia differs significantly by sector. According to the Ministry of Digital Development, by the beginning of 2024, more than 90% of government services were provided electronically via the Gosuslugi services portal.[1] The Russian financial sector has always been a leader in the implementation of digital technologies,[2] while retail companies are also constantly increasing their budget for informatization by implementing integrated solutions.[3] However, the level of digitalization used in industrial enterprises is characterized by the chaotic use of individual digital solutions. According to a study by the Russian consulting company SBS Consulting, the level of digital maturity of large and medium-sized manufacturing companies in Russia is only 26.6%.[4]

The digital transformation of industry involves the use of digital solutions to improve the production efficiency and then apply these solutions to the activities of the enterprise as a whole to enable prompt responses to emerging problems [2]. For this reason, many Russian industrial enterprises remain critically dependent on the implementation of Industry 4.0 technologies. This dependence is exacerbated by labor force shortages and the need to increase labor productivity.[4]

The chaotic implementation of technological solutions in industrial enterprises inherent in Industry 3.0 approaches has revealed a number of key problems in the context of the Industry 4.0, including human factors and emerging environmental hazards. Issues related to mismatches between different aspects of the economy include inefficient production and consumption patterns, significant social differentiation, social instability, etc. [3].

The current emphasis of global economic development and scientific research is changing from the robotization and automation inherent in Industry 4.0 to the development of sociocentric and environmentally sustainable technologies. Here the focus is placed on human–machine interactive systems in which humans act as creative participants in collaboration with robots. Traditional enterprises are giving way to the digital ecosystem, which opens new opportunities for the economy, but also brings risks of digital monopolization in virtual sectors [4]. Given these changes, the need for transition to the Industry 5.0 paradigm becomes obvious.

As a new industrial model, Industry 5.0 naturally emerges from the expansion of Industry 4.0. Industry 5.0 heralds a multiple increase in production efficiency and flexibility through automation, process optimization, and improved cooperation between humans and the technosphere. In response to the threat of job losses resulting from the introduction of Industry 4.0 technologies, Industry 5.0 opens up new opportunities for the creation of specialized jobs related to the management and maintenance of new technologies.

The feasibility of transition from Industry 3.0 to Industries 4.0 and 5.0 is especially relevant for the Russian economy, where technologies become a critical factor of competitiveness and are increasingly necessary to ensure the country's technological sovereignty. Industry 5.0 represents a qualitatively new stage in the development of production processes, characterized by an emphasis on a human-centered approach and the concept of sustainable development. The introduction of innovative technologies in this paradigm significantly increases production efficiency, which becomes especially important in the context of

---

[1] Digitalization in Russia: New Development Vectors in 2024. https://www.sostav.ru/blogs/277074/50927 (in Russ.). Accessed November 10, 2024.

[2] Digitalization of the financial sector 2024. https://generation-startup.ru/calendar/82432/ (in Russ.). Accessed November 10, 2024.

[3] Three IT trends in eCommerce in 2024. https://www.retail.ru/rbc/pressreleases/tri-trenda-it-v-ecommerce-v-2024-godu/ (in Russ.). Accessed November 10, 2024.

[4] Analysis of the digitalization level of Russian manufacturing enterprises. https://www.tadviser.ru (in Russ.). Accessed November 10, 2024.

demographic changes, shrinking labor resources and the need to improve the living standards of the population. Adaptation of the Russian economy to these challenges requires a comprehensive analysis and development of system solutions, which emphasizes the relevance of this study.

LITERATURE REVIEW

Currently, there is a significant increase in the number of scientific publications devoted to various aspects of the Industry 5.0 [5]. Many contemporary works focus on global problems of sustainable development, health care, education, industry, and technology development. Studies reflect different views on the terminology of the subject area, as well as questions concerning whether Industry 5.0 is a new paradigm or the next stage of Industry 4.0 development.

Nahavandi describes Industry 5.0 in terms of a vision of the future of humanity. According to this perspective, production within Industry 5.0 combines the advantages of advanced technologies with creativity and human problem-solving skills, which are aimed at making production processes more efficient and flexible, as well as reducing the risk of accidents and injuries [6]. The author argues that the fifth industrial revolution will occur when smart devices are fully integrated with the human mind and the physical world. Such cooperation will ensure high efficiency, production flexibility, and waste minimization.

In [7], it is argued that Industry 5.0 is aimed at enhancing the experience of end-users through the application of various available tools, including artificial intelligence and robotics. The article [8] outlines a design approach in which human operators and intelligent machines form collaborative teams.

In [9], Industry 5.0 is presented as a paradigm aimed at overcoming global social problems resulting from previous industrial revolutions. According to the authors, this paradigm is based on the idea of human-centered intellectual environment and its interaction with robotic systems.

In [10], Industry 5.0 is understood as a renewed human-centered industrial archetype that transforms the processes of industrial production. Examples of technologies that contribute to this transformation include artificial intelligence (AI), blockchain, and the Internet of Things.

In [11] an overview of the benefits of human interaction with the technological environment in industrial automation is presented. The authors consider Industry 5.0 as an evolution of Industry 4.0, in which creative humans collaborate with intelligent systems to improve the efficiency, speed, and scalability of manufacturing systems. Industry 5.0 is also seen in [12] as an extension of Industry 4.0 with a greater emphasis on human-centered interaction with computers.

The article [13] focuses on education to develop the necessary skills and competencies that enable employees to adapt to Industry 5.0 and changes in the university landscape.

A number of authors study common aspects of Industry 5.0 and Industry 4.0 in parallel. For example, article [14] describes the technological elements common to Industry 4.0 and 5.0.

Problems arising in connection with Industry 5.0 are also considered by Russian researchers. Thus, review studies are presented in the articles [15] and [16]. The authors of the article [17] argue that Industry 5.0 involves an integration of virtual and real worlds. The authors of the article [18] point out the advantages of the Industry 5.0 technologies for oil and gas companies.

The article [19] considers the problem of diagnostics of meso-economic systems in the process of evolution to the Industry 5.0. The authors put forward and substantiate the hypothesis about the existence of basic factors affecting the development of the economic system in the conditions of this transition, and propose a classification of methods for the study of such systems.

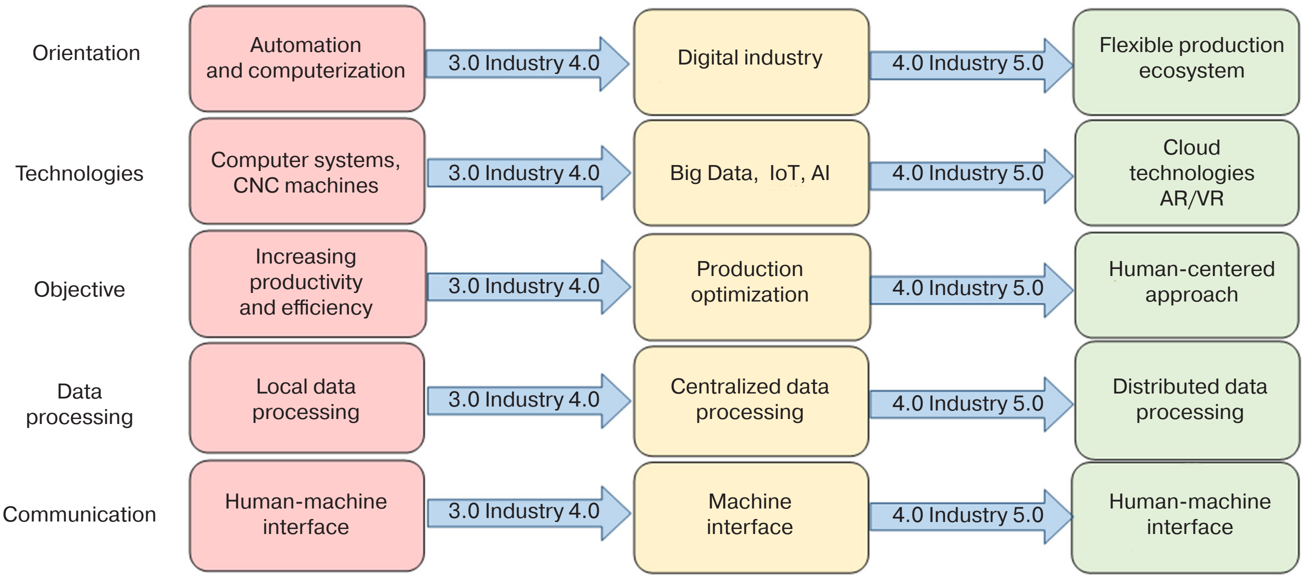
In general, the analysis of scientific literature has shown that the readiness of the Russian economy to respond to the challenges of the Industry 5.0 is insufficiently studied. In conclusion, it should be noted that Industry 5.0 is a relatively new concept. Thus, despite the noticeable increase in the number of works in this area, the formation of strategies for transition to Industry 5.0 technologies is still fragmentary. Examples are presented in the national programs of some countries (here we can highlight the EU program "Industry 5.0", "Made in China – 2025", and the Japanese "Society 5.0") [20].

RESULTS

Analysis of the publications allowed us to identify the main distinguishing features of the Industry 3.0, Industry 4.0, and Industry 5.0 (figure), which are defined by their unique orientation, technologies, objectives, data approaches and types of interfaces.

From the figure it can be seen that each successive industrial revolution represents a significant step in the development of technologies and production methods aimed at increasing efficiency, flexibility, and eliminating human error factors in production processes. In Industry 5.0, the interface between humans and the technological environment has been significantly improved to include advanced technologies such as virtual and augmented reality.

A number of academic economists characterize Industry 5.0 as a "revolution of human participation," where industrial growth is organically combined with the



Sources: developed by the authors on the basis of [21, 22]

Figure. Key differentiating features of Industry 3.0, Industry 4.0, and Industry 5.0. CNC—Computer Numerical Control; IoT—Internet of Things; AI—Artificial Intelligence

solution of socioeconomic issues through the synergy of cyber and physical spaces [23]. One of the advantages of such synergy is the integration of intelligent systems with current work processes, resulting in an increase in operational efficiency in general.

The evolution presented in the figure is relevant in the context of the Russian economy. At present, Russia is actively seeking to accelerate the introduction of digital technologies. Thus, in 2017 the Ministry of Industry and Trade of the Russian Federation initiated the national program "4.0 RU"[5] aimed at digital transformation of all stages of the production process in accordance with the concept of Industry 4.0. However, with the launch of the national project "Digital Economy"[6] in 2018, the focus shifted towards the introduction of so-called "end-to-end technologies" aimed primarily at improving the social sphere, including identification systems and digital services for the population. This shift in priorities has led to a slowdown in digitalization processes in the industrial sector, as well as the lack of integrated digital infrastructure at the enterprise level, which makes it difficult to implement a unified digital environment within the national economy.

Regulatory documents testifying to the ongoing digitalization of government structures and the social sphere include the national program "Digital Economy" and the nine federal projects it encompasses, of which "Digital Technologies" and the national project "Data Economy"[7] currently under development are examples. However, the fully-fledged digital transformation of Russian industry requires the restoration of priorities in the field of digitalization of production processes and the development of specialized program documents aimed at supporting enterprises in the real sector of the economy.

In addition, these program documents do not sufficiently take into account the human factor, which plays a central role in Industry 5.0. The accessibility and inclusiveness of new digital solutions for all segments of society should also be taken into account to avoid deepening the digital divide. It becomes increasingly clear that the data economy is not just about simply using new digital technologies in the economy, society and everyday life, but also includes the creation of a country's own scientific, educational, technological, industrial, socioeconomic and cultural base to ensure its technological sovereignty through import substitution and integration into global value chains.

The transition to Industry 5.0 in Russia is accompanied not only by prospects, but also by various challenges. Since the introduction of innovative technologies requires highly qualified specialists, one of the key challenges involves the need to train and retrain labor resources. In particular, the following

[5] https://niieap.com/2017/07/24/minpromtorg-rossii-i-ryad-vysokotehnologichnyh-kompanij-predstavili-tsifrovoj-proekt-v-sfere-aviastroeniya-industriya-4-0/ (in Russ.). Accessed November 10, 2024.

[6] http://government.ru/info/35568/ (in Russ.). Accessed November 10, 2024.

[7] https://национальныепроекты.рф/new-projects/ekonomika-dannykh/ (in Russ.). Accessed November 10, 2024.

challenges can be noted: exponential growth of data volume, increased vulnerability to cyberattacks, job cuts in enterprises, lack of consideration of ethical issues of artificial intelligence. At the same time, Industry 5.0 envisions increased efficiency of production processes through automation and improved interaction between the technological environment and humans. Thus Industry 5.0 opens new perspectives for the creation of jobs related to the maintenance of new technologies.

While the transition to Industry 4.0 and 5.0 does not imply an automatic and immediate transition for all enterprises of the national economy, the introduction of new technologies and management methods at some enterprises may serve as a catalyst for others, creating a snowball effect according to which the number of enterprises involved increases over time. Awareness of the trends and challenges of Industries 4.0 and 5.0 is necessary for Russian enterprises to maximize their resources and capabilities and successfully complete the transition to Industry 4.0.

Despite the significant potential advantages conferred by the transition to Industry 5.0, this process in the Russian economy faces a number of serious barriers. Key among these are insufficient readiness of technological infrastructure and limited investment in research and innovation activities. The introduction of advanced technologies is hindered by the current level of equipment of enterprises, which does not yet meet the requirements of Industry 5.0. Limited investment in research and development also significantly hinders innovative development [24]. The elimination of these barriers requires a comprehensive approach and state support.

Taking into account that Industry 5.0 "represents the next stage of industrial development" [21], when approaches "to business management emphasizing the human factor"[8] are radically changing [21], it is important to be guided by the following principles of Industry 5.0 [4, 21, 22] in order to successfully overcome the listed challenges and barriers:

1. *The principle of human-centeredness* implies production processes that are based on human needs.
2. *The principle of digitalization* requires the full use of advanced digital technologies in the production of goods and the provision of services.
3. *The principle of integration* implies not only the introduction of technologies to automate production, but also the formation of proper conditions for effective interaction between humans and the technological environment, utilizing the best qualities of both parties.
4. *The principle of synergy* implies the use of modern technologies (cloud technologies, artificial intelligence, etc.) to automate production processes while retaining a significant human role in management.
5. *The principle of optimization* implies the search for models of economic activity that minimize the use of resources to achieve maximum efficiency in the interaction between humans and the technological environment.
6. *The principle of virtualization* implies the creation and implementation of digital twins of physical objects and production and management processes to augment analytics and artificial intelligence applications.
7. *The principle of platformization* implies connection to a single information space of various users for interaction, systems and equipment along the entire chain of the production life cycle.
8. *The principle of personalization* implies the creation of systems that will enable mass production of personalized products and services using digital technologies.
9. *The principle of ecosystemness* implies bringing together elements disparate in time, space, and types of industries to create technology and business collaborations.
10. *The principle of environmental friendliness* implies implementation of energy-efficient technologies in order to reduce the negative impact on the environment.

We may note that each industrial revolution forms its own unique principles. For example, at the stage of Industry 3.0 development, the main focus was on automation and the introduction of electronics, which reduced the relevance of human-technology integration that nevertheless became a key principle for Industry 5.0. At the stage of Industry 4.0 development, where digitalization and the spread of the Internet of Things dominate, principles such as environmental friendliness and human interaction with the technological environment also play a secondary role. At the stage of Industry 5.0 development, the focus shifts to the integration of digital technologies and the human factor, which requires the creation of comprehensive program documents, including by the government and the state, which are aimed at stimulating business and industry to implement new digital technologies. Special attention should be paid not only to large state corporations, but also to private small and medium-sized industrial enterprises.

Incorporating the principle of human-centeredness into production processes provides opportunities to increase productivity and create more sustainable business models. This involves not only modernizing

[8] Industry 5.0: The Human-Centered Future of Business and New Growth Strategies. https://pakhotin.org/technologies/industry-5/ (in Russ.). Accessed November 10, 2024.

technologies, but also adapting them to the real needs of society. In Russia, human-centeredness can be a key factor in the successful implementation of new technological solutions due to increased employee satisfaction, which encourages them to learn and develop, resulting in improved customer experience.

MATHEMATICAL MODEL OF THE PRODUCTION FUNCTION

Comparisons between different industrial revolutions can be made using economic growth models. For example, using the Solow model, it is possible to trace what significant changes in production processes each subsequent industrial revolution brings, as well as to conduct studies of growth processes under conditions of continuous technological development. In this case, the so-called production function is analyzed, which defines the relationship between the volume of production Y, the number of workers L, the amount of capital K and technological progress A:

$$Y = AK^{\alpha}L^{1-\alpha}. \quad (1)$$

In formula (1), the value of the parameter α, which falls within the range from 0 to 1, determines how much of the production is provided by capital.

Typically, the three main factors of production, comprising labor, capital, and technological progress, do not provide a complete picture of the production process. In such cases, extended models are used, or additional variables are added for deeper analysis. For example, the extended Solow model [25] can be formalized as follows:

$$Y = AK^{\alpha}L^{\beta}H^{\gamma}N^{\delta}R^{\varepsilon}. \quad (2)$$

In the extended model, in contrast to the original one, new factors are introduced: human capital H, natural resources N and the current level of technology R. The model parameters (α, β, γ, δ, and ε) determine the impact of these factors on the production process (elasticity of output with respect to each production factor). The sum of the values of these parameters should be equal to 1 to ensure the completeness of accounting for all factors. For example, α shows by how many percent output Y will change if the capital K changes by 1 percent provided that the other factors remain unchanged.

For each industrial revolution, the coefficients of the model should take different values. Let us consider considerations on the values of the parameters of the extended Solow model in the context of Industries 3.0, 4.0, and 5.0.

Industry 3.0. Capital K plays a key role in Industry 3.0 as physical inputs (machinery, equipment) remain the basis of production. Labor L also remains important in Industry 3.0, but arguably has less influence compared to machinery and equipment. Human capital, education, and skills H are less important as compared to physical resources and technology. The influence of natural resources N depends largely on the specifics of the industry, but is still significant, especially in the production of raw materials. The level of technology development R is quite important, but not as important as in Industries 4.0 and 5.0.

Industry 4.0. Capital K remains important; however, the main vector of development is focused on innovative technologies and digitalization of production. With automation and the use of robotics, the human factor L is less significant compared to Industry 3.0, and training and skills H become more important as highly skilled professionals are required to work with new technologies. Considering sustainability and eco-efficiency, the impact on natural resources N may be less, while the impact of R technologies, especially digital technologies, may be significant for production.

Industry 5.0. Capital K in the form of intellectual and digital capital becomes the main factor of production. Human resource L is still important, but more attention can be paid to creativity, innovation, and interdisciplinary cooperation. In Industry 5.0, education, creativity, and flexible skills H are key factors. Sustainability priorities and environmental awareness determine the importance of minimizing the use of natural resources N. The influence of advanced R technologies such as artificial intelligence or nanotechnology becomes a major determinant.

The setting of coefficients α, β, γ, δ, ε for each Industry X.0 iteration depends on the specific conditions and objectives of a certain industrial sector. In order to numerically determine the values of the coefficients of model (2), an expert survey was conducted. To ensure the representativeness and reliability of the study, 110 experts were recruited representing various sectors of the economy, including higher educational institutions (RTU MIREA and R.E. Alekseev Nizhny Novgorod State Technical University), academic research centers, industry, and business (Nizhny Novgorod Regional Branch of the All-Russian Public Organization “Free Economic Society of Russia”), which is generally sufficient for such studies [26]. This approach made it possible to cover a wide range of opinions and ensure the diversity of views on the importance of various factors of production. The experts were asked to assess the contribution of five major factors to the total output for three industrial revolutions. In doing so, each expert had to allocate the factors such that their sum for each industrial revolution equaled 1. The data obtained from the survey were averaged to obtain the total coefficients (Table).

Table. Distribution of coefficients of the extended Solow model

Industry	α	β	γ	δ	ε	Explanation
3.0	0.32	0.18	0.16	0.1	0.24	Capital has the largest impact on output, indicating that Industry 3.0 is capital intensive. The contribution of labor is significant, but less than that of capital. Human capital, important, but inferior to capital and labor. The contribution of natural resources is small. The high contribution of the level of technology development emphasizes the importance of technological progress
4.0	0.26	0.16	0.19	0.09	0.3	Capital contribution is high, but less than in Industry 3.0. The contribution of labor is reduced compared to Industry 3.0. Human capital contributes more than in Industry 3.0. The contribution of natural resources remains the same as in Industry 3.0. The highest contribution among all factors is given to the level of technology development, indicating a high dependence on technological innovation
5.0	0.21	0.11	0.24	0.14	0.3	Lowest contribution of capital and labor among all industries. Highest contribution of human capital, emphasizes the importance of knowledge and skills. Higher contribution of natural resources compared to other industries. Contribution of technology remains high

According to the presented comparative analysis of the contribution of each factor to production in the context of Industries 3.0, 4.0, and 5.0, we can state that the relative contribution of capital is decreasing. The role of labor is also decreasing, generally indicating less dependence on the quantity of labor. On the contrary, the contribution of human capital increases, emphasizing its extreme importance. The role of the factor related to natural resources remains relatively stable, with a slight increase in Industry 5.0, while the importance of technological development remains consistently high, indicating the importance of innovation for economic growth.

Thus, each industrial revolution has its own peculiarities and differences regarding the contribution of each factor, which should be taken into account when designing economic policies and investment strategies. Although from a theoretical point of view the distribution of the coefficients α, β, γ, δ, ε seems reasonable, in order to fully confirm the fairness and adequacy of the model in practical application, it is necessary to carry out its empirical verification.

CONCLUSIONS

The present study discusses conceptual differences between Industries 3.0, 4.0, and 5.0, including unique orientation, technologies, and goals, as well as approaches to data handling and communication. Special attention is paid to the justification of the need for accelerated implementation of Industry 5.0 technologies in Russia. It is noted that the Russian economy is insufficiently prepared for the challenges of Industry 5.0. The main obstacles are the lack of a clear government strategy for digital transformation of industry, the low level of digitalization of most industrial enterprises, limited funding and support for small and medium-sized industrial companies in the implementation of advanced technologies, and a lack of qualified personnel. However, the introduction of Industry 4.0 technologies and planned transition to Industry 5.0 technologies are seen as necessary steps for the formation of an innovative and competitive economy.

The following conclusions can be drawn on the basis of the conducted research: although the transition to Industry 5.0 technologies in the Russian economy is at an embryonic stage, the need to accelerate this process is obvious. Recommendations for accelerating the transition include: the development of a clear strategy for the implementation of Industry 5.0 principles at the level of the national economy, strengthening of state support for small and medium-sized industrial enterprises, and the creation of specialized educational programs to train personnel to work with new technologies.

The Solow model can serve as a basis for the development of economic strategies aimed at accelerating the implementation of the principles and technologies of Industry 5.0. The Solow model can be used to analyze the impact of technological change on long-term economic growth, taking into account the importance of investment in research and development, as well as the impact of human capital and technological progress on the growth of gross domestic product. However, these conclusions are based on theoretical assumptions and expert assessments, which require further empirical confirmation. To fully justify the proposed strategic steps, it is necessary to conduct additional research and test the model on practical data. Here the importance of financial capital and investments in critical infrastructure and human capital development should be emphasized, due to the significant costs and comprehensive analysis required to support the transition to new technologies.

ACKNOWLEDGMENTS

The study was supported by the Russian Science Foundation grant (project No. 23-78-10009).

Authors' contributions

N.N. Karpukhina—the idea of the study, literature analysis, writing and editing the text of the article.

E.S. Mityakov—the idea of the study, literature analysis, substantiation of the mathematical model, interpretation and generalization of the research results, writing and editing the text of the article.

A.Yu. Pronin—the idea of the study, writing the text of the article.

REFERENCES

1. Sitnikova S.E. Digital form of commercialization of innovations in universities and ways to improve its efficiency: international experience and prospects for Russia. *Innovatsionnoe razvitie ekonomiki = Innovative Development of Economy.* 2020;6(60):61–70 (in Russ.).
2. Starozhuk I.N., Komissarov V.D. Digital twin as a mechanism for transition from Industry 4.0 to Industry 5.0. In: *Digital Transformation of Economic Systems: Problems and Prospects: Proceedings of the 6th All-Russian Scientific and Practical Conference with Foreign Participation.* St. Petersburg: POLITEKh-PRESS; 2022. P. 151–154 (in Russ.).
3. Ageev A.I. Managing the digital future. *Mir novoi ekonomiki = The World of New Economy*. 2018;12(3):6–23 (in Russ.). https://doi.org/10.26794/2220-6469-2018-12-3-6-23
4. Rozanova N.M. Industry 5.0: a golden age or a leap into the dark? *Vestnik Instituta ekonomiki Rossiiskoi akademii nauk = Bulletin of the Institute of Economics of the Russian Academy of Sciences.* 2023;6:61–77 (in Russ.).
5. Barata J., Kayser I. Industry 5.0 – Past, Present, and Near Future. *Procedia Comput. Sci*. 2023;219(1):778–788. https://doi.org/10.1016/j.procs.2023.01.351
6. Nahavandi S. Industry 5.0 – A Human-Centric Solution. *Sustainability*. 2019;11(16):4371. https://doi.org/10.3390/su11164371
7. Orea-Giner A., Fuentes-Moraleda L., Villacé-Molinero T., et al. Does the Implementation of Robots in Hotels Influence the Overall TripAdvisor Rating? A Text Mining Analysis from the Industry 5.0 Approach. *Tour. Manag*. 2022;93(2):104586. https://doi.org/10.1016/j.tourman.2022.104586
8. Kaasinen E., Anttila A.H., Heikkilä P., et al. Smooth and Resilient Human–Machine Teamwork as an Industry 5.0 Design Challenge. *Sustainability*. 2022;14(5):2773. https://doi.org/10.3390/su14052773
9. Coronado E., Kiyokawa T., Ricardez G.A.G., et al. Evaluating quality in human-robot interaction: A systematic search and classification of performance and human-centered factors, measures and metrics towards an industry 5.0. *J. Manufactur. Syst*. 2022;63:392–410. https://doi.org/10.1016/j.jmsy.2022.04.007
10. Carayannis E.G., Christodoulou K., Christodoulou P., et al. Known Unknowns in an Era of Technological and Viral Disruptions – Implications for Theory, Policy, and Practice. *J. Knowl. Econ.* 2022;13(1):587–610. https://doi.org/10.1007/s13132-020-00719-0
11. Fatima Z., Tanveer M.H., Waseemullah, et al. Production Plant and Warehouse Automation with IoT and Industry 5.0. *Appl. Sci.* 2022;12(4):2053. https://doi.org/10.3390/app12042053
12. Paul G., Abele N.D., Kluth K. A Review and Qualitative Meta-Analysis of Digital Human Modeling and Cyber-Physical-Systems in Ergonomics 4.0. *IISE Trans. Occup. Ergon. Hum. Factors.* 2021;9(3–4):111–123. https://doi.org/10.1080/24725838.2021.1966130
13. Broo D.G., Kaynak O., Sait S.M. Rethinking engineering education at the age of industry 5.0. *J. Industr. Inform. Integrat*. 2021;25(8):100311. https://doi.org/10.1016/j.jii.2021.100311
14. Alvarez-Aros E.L., Bernal-Torres C.A. Technological competitiveness and emerging technologies in industry 4.0 and industry 5.0. *Anais da Academia Brasileira de Ciências*. 2021;93(1). https://doi.org/10.1590/0001-3765202120191290
15. Gasanov E.A. New form of human-machine connection in the Industry 5.0 production model. *Ekonomika i upravlenie innovatsiyami = Economy and Innovation Management*. 2022;3(22):39–49 (in Russ.). https://doi.org/10.26730/2587-5574-2022-3-39-49
16. Trofimova N.N. Industry 5.0 as a new direction of industrial development. *Ekonomika i Upravlenie: Problemy, Resheniya*. 2023;5(133):24–28 (in Russ.). https://doi.org/10.36871/ek.up.p.r.2023.01.05.003
17. Evgenev G.B. Industry 5.0 as an integration of the Internet of Knowledge and the Internet of Things. *Ontologiya proektirovaniya = Ontology of Designing.* 2019;9(1–31):7–23 (in Russ.).
18. Azieva R.Kh., Taimaskhanov H.E. Modernization of the oil and gas industry in the style of Industry 5.0. *Finansovyi biznes*. 2021;2(212):82–86 (in Russ.).

19. Galimulina F.F., Shinkevich M.V. Diagnostics of mesoeconomic systems in Russia under condition of transition to Industry 5.0. *Ekonomicheskie i sotsial'no-gumanitarnye issledovaniya = Economic and Social Research*. 2023;4(40):23–32 (in Russ.).
20. Tingting Hu. Review of national strategies for transition to Industry 5.0. *Ekonomika i upravlenie innovatsiyami = Economics and Innovation Management.* 2022;3(22):28–38 (in Russ.). https://dx.doi.org/10.26730/2587-5574-2022-3-28-38
21. Makovetskii S.A. Continued evolution: comparison of Industry 4.0 and Industry 5.0 in the context of modern requirements. In: *Business. Education. Economy: Proceedings of the International Scientific and Practical conference*. Minsk; 2023. P. 81–85 (in Russ.).
22. Pronin A.Yu. Tendencies in digital transformation of high-tech enterprises in the transition from Industry 4.0 to Industry 5.0. *Cifra. Ekonomika = Cifra. Economy*. 2024;3(6) (in Russ.). https://doi.org/10.60797/ECNMS.2024.6.1
23. Cherepanov N.V. Principles and approaches of using Industry 5.0 at the enterprise. *Innovatsii i investitsii = Innovation & Investment*. 2019;9:144–147 (in Russ.).
24. Lapaev D.N., Mityakova O.I., Murashova N.A., Mityakov E.S. *Organizatsiya NIOKR* (*Organization R&D*). N. Novgorod: Nizhny Novgorod State Technical University; 2017. 100 p. (in Russ.).
25. Kanametova D.A. Analysis of Models of Dynamic Economic Systems. *Izvestiya Kabardino-Balkarskogo nauchnogo tsentra RAN = News of the Kabardino-Balkarian Scientific Center of the Russian Academy of Sciences.* 2023;4(114):88–97 (in Russ.). https://doi.org/10.35330/1991-6639-2023-4-114-88-97
26. Memon M., Ting H., Hwa C., Ramayah T., Chuah F., Cham T.H. Sample Size for Survey Research: Review and Recommendations. *Journal of Applied Structural Equation Modeling* (*JASEM*). 2020;4(2):i-xx. http://doi.org/10.47263/JASEM.4(2)01

СПИСОК ЛИТЕРАТУРЫ

1. Ситникова С.Е. Цифровая форма коммерциализации инноваций в вузах и пути повышения ее эффективности: международный опыт и перспективы для России. *Инновационное развитие экономики*. 2020;6(60):61–70.
2. Старожук И.Н., Комиссаров В.Д. Цифровой двойник как механизм перехода от Индустрии 4.0 к Индустрии 5.0. В сб.: *Цифровая трансформация экономических систем: проблемы и перспективы* (*ЭКОПРОМ-2022*): *Сборник трудов VI Всероссийской научно-практической конференции с зарубежным участием*. СПб.: ПОЛИТЕХ-ПРЕСС; 2022. С. 151–154.
3. Агеев А.И. Управление цифровым будущим. *Мир новой экономики*. 2018;12(3):6–23. https://doi.org/10.26794/2220-6469-2018-12-3-6-23
4. Розанова Н.М. Индустрия 5.0: золотой век или прыжок в темноту? *Вестник Института экономики Российской академии наук.* 2023;6:61–77.
5. Barata J., Kayser I. Industry 5.0 – Past, Present, and Near Future. *Procedia Comput. Sci*. 2023;219(1):778–788. https://doi.org/10.1016/j.procs.2023.01.351
6. Nahavandi S. Industry 5.0 – A Human-Centric Solution. *Sustainability*. 2019;11(16):4371. https://doi.org/10.3390/su11164371
7. Orea-Giner A., Fuentes-Moraleda L., Villacé-Molinero T., et al. Does the Implementation of Robots in Hotels Influence the Overall TripAdvisor Rating? A Text Mining Analysis from the Industry 5.0 Approach. *Tour. Manag*. 2022;93(2):104586. https://doi.org/10.1016/j.tourman.2022.104586
8. Kaasinen E., Anttila A.H., Heikkilä P., et al. Smooth and Resilient Human–Machine Teamwork as an Industry 5.0 Design Challenge. *Sustainability*. 2022;14(5):2773. https://doi.org/10.3390/su14052773
9. Coronado E., Kiyokawa T., Ricardez G.A.G., et al. Evaluating quality in human-robot interaction: A systematic search and classification of performance and human-centered factors, measures and metrics towards an industry 5.0. *J. Manufactur. Syst*. 2022;63:392–410. https://doi.org/10.1016/j.jmsy.2022.04.007
10. Carayannis E.G., Christodoulou K., Christodoulou P., et al. Known Unknowns in an Era of Technological and Viral Disruptions – Implications for Theory, Policy, and Practice. *J. Knowl. Econ.* 2022;13(1):587–610. https://doi.org/10.1007/s13132-020-00719-0
11. Fatima Z., Tanveer M.H., Waseemullah, et al. Production Plant and Warehouse Automation with IoT and Industry 5.0. *Appl. Sci.* 2022;12(4):2053. https://doi.org/10.3390/app12042053
12. Paul G., Abele N.D., Kluth K. A Review and Qualitative Meta-Analysis of Digital Human Modeling and Cyber-Physical-Systems in Ergonomics 4.0. *IISE Trans. Occup. Ergon. Hum. Factors.* 2021;9(3–4):111–123. https://doi.org/10.1080/24725838.2021.1966130
13. Broo D.G., Kaynak O., Sait S.M. Rethinking engineering education at the age of industry 5.0. *J. Industr. Inform. Integrat*. 2021;25(8):100311. https://doi.org/10.1016/j.jii.2021.100311
14. Alvarez-Aros E.L., Bernal-Torres C.A. Technological competitiveness and emerging technologies in industry 4.0 and industry 5.0. *Anais da Academia Brasileira de Ciências*. 2021;93(1). https://doi.org/10.1590/0001-3765202120191290
15. Гасанов Э.А. Новая форма соединения человека и машины в модели производства Индустрии 5.0. *Экономика и управление инновациями*. 2022;3(22):39–49. https://doi.org/10.26730/2587-5574-2022-3-39-49
16. Трофимова Н.Н. Индустрия 5.0 как новое направление промышленного развития. *Экономика и управление: проблемы, решения*. 2023;5(133):24–28. https://doi.org/10.36871/ek.up.p.r.2023.01.05.003

17. Евгенев Г.Б. Индустрия 5.0 как интеграция интернета знаний и интернета вещей. *Онтология проектирования*. 2019;9(1–31):7–23.
18. Азиева Р.Х., Таймасханов Х.Э. Модернизация нефтегазовой отрасли в стиле Индустрии 5.0. *Финансовый бизнес*. 2021;2(212):82–86.
19. Галимулина Ф.Ф., Шинкевич М.В. Диагностика мезоэкономических систем в России в условиях перехода к Индустрии 5.0. *Экономические и социально-гуманитарные исследования*. 2023;4(40):23–32.
20. Тинтин Ху. Обзор национальных стратегий перехода к Индустрии 5.0. *Экономика и управление инновациями*. 2022;3(22):28–38. https://doi.org/10.26730/2587-5574-2022-3-28-38
21. Маковецкий С.А. Продолжение эволюции: сравнение Индустрии 4.0 и Индустрии 5.0 в контексте современных требований. В сб.: *Бизнес. Образование. Экономика: Материалы Международной научно-практической конференции*. Минск; 2023. С. 81–85.
22. Пронин А.Ю. Тенденции цифровой трансформации высокотехнологичных предприятий в условиях перехода от Индустрии 4.0 к Индустрии 5.0. *Cifra. Экономика*. 2024;3(6). https://doi.org/10.60797/ECNMS.2024.6.1
23. Черепанов Н.В. Принципы и подходы применения Индустрии 5.0 на предприятии. *Инновации и инвестиции*. 2019;9:144–147.
24. Лапаев Д.Н., Митякова О.И., Мурашова Н.А., Митяков Е.С. *Организация НИОКР*. Н. Новгород: Нижегородский государственный технический университет им. Р.Е. Алексеева; 2017. 100 с.
25. Канаметова Д.А. Анализ моделей динамических экономических систем. *Известия Кабардино-Балкарского научного центра РАН*. 2023;4(114):88–97. https://doi.org/10.35330/1991-6639-2023-4-114-88-97
26. Memon M., Ting H., Hwa C., Ramayah T., Chuah F., Cham T.H. Sample Size for Survey Research: Review and Recommendations. *Journal of Applied Structural Equation Modeling* (*JASEM*). 2020;4(2):i-xx. http://doi.org/10.47263/JASEM.4(2)01

About the Authors

Natalia N. Karpukhina, Dr. Sci. (Econ.), Associate Professor, Head of the Department of Innovation Management, Institute of Management Technologies, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: karpukhina@mirea.ru. Scopus Author ID 57190409353, RSCI SPIN-code 7442-9985, https://orcid.org/0000-0003-3378-5230

Evgeny S. Mityakov, Dr. Sci. (Econ.), Professor, Head of the Department of Subject-Oriented Information Systems, Institute for Cybersecurity and Digital Technologies, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: mityakov@mirea.ru. Scopus Author ID 55960540500, RSCI SPIN-code 5691-8947, https://orcid.org/0000-0001-6579-0988

Aleksey Yu. Pronin, Cand. Sci. (Eng.), Associate Professor, Department of Innovation Management, Institute of Management Technologies, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: pronin@mirea.ru. Scopus Author ID 57190872536, RSCI SPIN-code 6833-7914, https://orcid.org/0000-0001-8947-3047

Об авторах

Карпухина Наталия Николаевна, д.э.н., доцент, заведующий кафедрой управления инновациями, Институт технологий управления, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: karpukhina@mirea.ru. Scopus Author ID 57190409353, SPIN-код РИНЦ 7442-9985, https://orcid.org/0000-0003-3378-5230

Митяков Евгений Сергеевич, д.э.н., профессор, заведующий кафедрой КБ-9 «Предметно-ориентированные информационные системы», Институт кибербезопасности и цифровых технологий, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: mityakov@mirea.ru. Scopus Author ID 55960540500, SPIN-код РИНЦ 5691-8947, https://orcid.org/0000-0001-6579-0988

Пронин Алексей Юрьевич, к.т.н., доцент, кафедра управления инновациями, Институт технологий управления, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: pronin@mirea.ru. Scopus Author ID 57190872536, SPIN-код РИНЦ 6833-7914, https://orcid.org/0000-0001-8947-3047

Translated from Russian into English by Lyudmila O. Bychkova
Edited for English language and spelling by Thomas A. Beavitt