



DOI: 10.22363/2313-2329-2026-34-2-321-334

EDN: EWIOED

UDC 330.4

Research article / Научная статья

Economic and mathematical framework of a cognitive platform for managing the lifecycle of high-tech products

Alexander A. Chursin *RUDN University, Moscow, Russian Federation*✉ chursin-aa@rudn.ru

Abstract. This study examines in detail the creation of cognitive production ecosystems, where various enterprise elements (equipment, information systems, human resources) interact as a single intelligent organism, as such systems are capable of self-organization, automatic optimization of work processes, and adaptation to changing external conditions. According to the author, the integration of cognitive technologies and artificial intelligence into design, preparation, and production organization processes facilitates the creation of new automated intelligent solutions and changes approaches to managing production structures. The advantage of this study is the development of a unified cognitive management platform, including a system of interconnected equations that describes the digital transformation of an industrial enterprise through the lens of cognitive technologies. Summarizing the formation of three interconnected digital lifecycle management loops for high-tech products, the author presents the architecture of a cognitive digital manufacturing ecosystem that reveals the logic of integrating digital, service, and intelligent components within a single manufacturing ecosystem. The author concludes that the economic and mathematical framework of a cognitive platform for high-tech product lifecycle management enables the integration of digital twins, machine learning methods, neural network analytics, and self-learning planning mechanisms. This, in turn, creates the conditions for the emergence of closed intelligent ecosystems capable of adapting to external changes and redistributing resources in real time.

Keywords: digitalization of production, lifecycle, high-tech products, cognitive production ecosystems, artificial intelligence, digital twin

Acknowledgements. The author wishes to thank his colleagues and the editorial board for their helpful recommendations during the preparation of this publication.

Data Availability Statement. All data obtained during this study are included in this published article (and its supplementary information files).

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Conflicts of interest. The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Article history: received 29 November 2025; revised 27 January 2025; accepted 25 February 2026.

For citation: Chursin, A.A. (2026). Economic and mathematical framework for a cognitive platform of managing the lifecycle of high-tech products. *RUDN Journal of Economics*, 34(2), 321–334. <https://doi.org/10.22363/2313-2329-2026-34-2-321-334> EDN: EWIOED

Экономико-математический аппарат когнитивной платформы управления жизненным циклом высокотехнологичной продукции

А.А. Чурсин 

Российский университет дружбы народов, Москва, Российская Федерация

✉ chursin-aa@rudn.ru

Аннотация. Подробно изучено создание когнитивных производственных экосистем, где различные элементы предприятия (оборудование, информационные системы, человеческие ресурсы) взаимодействуют как единый интеллектуальный организм, так как такие системы способны к самоорганизации, автоматической оптимизации рабочих процессов и адаптации к изменяющимся внешним условиям. По мнению автора, интеграция когнитивных технологий и искусственного интеллекта в процессы проектирования, подготовки и организации производства способствует созданию новых автоматизированных интеллектуальных решений и изменяет подходы к управлению производственными структурами. Достоинством данного исследования является разработка единой когнитивной платформы управления включающую систему взаимосвязанных уравнений, которая описывает цифровую трансформацию промышленного предприятия через призму когнитивных технологий. Автор, обобщая формирование трех взаимосвязанных цифровых контуров управления жизненным циклом высокотехнологичной продукции, представляет архитектуру когнитивной цифровой производственной экосистемы, которая раскрывает логику интеграции цифровых, сервисных и интеллектуальных компонентов в рамках единой производственной экосистемы. В качестве вывода отмечено, что экономико-математический аппарат когнитивной платформы управления жизненным циклом высокотехнологичной продукции дает возможность интеграции цифровых двойников, методов машинного обучения, нейросетевой аналитики и механизмов самообучающегося планирования, а, это, в свою очередь, формирует условия для возникновения замкнутых интеллектуальных экосистем, способных адаптироваться к внешним изменениям и перераспределять ресурсы в режиме реального времени.

Ключевые слова: цифровизация производства, жизненный цикл, высокотехнологичная продукция, когнитивные производственные экосистемы, искусственный интеллект, цифровой двойник

Заявление о доступности данных. Все данные, полученные в ходе этого исследования, включены в опубликованную статью (и дополнительные файлы к ней).

Благодарности. Автор выражает благодарность коллегам и редакции журнала за полезные рекомендации в процессе подготовки публикации.

Заявление о конфликте интересов. Автор заявляет об отсутствии конфликта интересов.

История статьи: поступила в редакцию 29 ноября 2025 г.; доработана после рецензирования 27 января 2026 г., принята к публикации 25 февраля 2026 г.

Для цитирования: Chursin A.A. Economic and mathematical framework for a cognitive platform of managing the lifecycle of high-tech products // Вестник Российского университета дружбы народов. Серия: Экономика. 2026. Т. 34. № 2. С. 321–334. <https://doi.org/10.22363/2313-2329-2026-34-2-321-334> EDN: EWIOED

Introduction

Modern conditions of digitalization of industrial production require fundamentally new approaches to product lifecycle management based on the integration of cognitive technologies and advanced development methods (Susov, Samoldin, 2023). The formation of competitive product solutions in high-tech industries is impossible today without the creation of integrated digital ecosystems that combine all stages — from conceptual design to recycling¹ (Gokhberg, 2021).

The central role in this transformation is played by the integration of cognitive systems to support management decisions, which have the ability to process significant amounts of information about market dynamics, innovation potential, and end-user requests. Such platforms, built on the basis of artificial intelligence and machine learning algorithms, provide the opportunity to:

- 1) predict changes in demand in different market segments;
- 2) optimize product parameters at the digital design stage;
- 3) simulate different production and sales scenarios.

A special role in this process is played by digital twins of a new generation, integrating not only technical but also economic parameters of products (Sosfenov, Shahova, 2023; Grieves, 2014). Such doubles allow for a comprehensive assessment of the minimum effective production volumes, taking into account:

- dynamics of market demand;
- flexibility of production systems;
- the level of product customization;
- the speed of technology commercialization.

The purpose of the study is to identify the features of the creation and functioning of cognitive production ecosystems capable of self — organization, automatic optimization of work processes and adaptation to changing external conditions.

¹ Ministry of Science and Technology of the Russian Federation. (2023). Concept of technological development for the period up to 2030. Moscow: Ministry of Science and Technology of the Russian Federation. (In Russ.).

Materials and methods

The modern digital transformation of industrial enterprises is increasingly shifting towards cognitive technologies that not only automate processes, but also introduce elements of artificial intelligence into the management of production systems. The key trend is the transition from traditional automation to intelligent self-learning systems capable of adapting to changing conditions and predicting the development of technological and market processes (Omelchenko et al., 2019).

An important aspect of digital transformation is the introduction of cognitive interfaces for interaction between humans and production systems. Natural language interfaces, augmented reality and voice control systems simplify staff interaction with complex industrial systems, reducing the likelihood of errors and increasing work efficiency.

Thus, cognitive technologies are becoming the foundation of a new industrial production paradigm, where adaptability, prognostication, and the ability to continuously self-learn are key characteristics. This creates the basis for a fundamentally new level of efficiency, quality and competitiveness of industrial enterprises in the digital economy.

The formation of three interconnected digital control circuits is becoming critically important for industrial enterprises:

1. Cognitive Marketing Contour — a system for monitoring and forecasting the needs of government and commercial customers, including big data analysis and predictive analytics.

2. Technological Contour is a digital design and virtual testing platform that combines methods of parametric modeling and adaptive engineering.

3. Production circuit — intelligent planning and management systems that ensure optimal use of resources.

The introduction of cognitive technologies fundamentally changes approaches to the formation of product lines (Drogovoz et al., 2021). Digital platforms allow for:

- cross-sector technology transfer;
- optimize the degree of unification of components;
- simulate different commercialization scenarios.

Of particular importance is the ability of cognitive systems to analyze the “market readiness” for fundamentally new products, assessing not only current demand, but also the potential ability of consumers to adapt to innovative solutions.

Development prospects are related to the creation of fully autonomous product lifecycle management systems, where cognitive technologies will:

- 1) automatically adjust design parameters based on changes in market conditions;
- 2) optimize production processes in real time;
- 3) predict when new modifications will be launched on the market.

Thus, the integration of cognitive technologies into product lifecycle management processes creates fundamentally new opportunities for industrial enterprises in the digital economy, ensuring not only technological leadership, but also sustainable economic development.

In the context of digital production, sustainability should be considered as the ability of a system to maintain target development parameters under the influence of external and internal disturbing factors, which is achieved through the integration of cognitive technologies into strategic management processes.

A key element of sustainable development is the introduction of intelligent decision support systems that, based on big data analysis, allow:

- 1) predict the lifecycles of product lines;
- 2) optimize break-even points based on the innovation component;
- 3) to model various scenarios of market behavior (Abueva et al., 2025).

Cognitive digital twins, which combine the economic and production parameters of an organization, play a special role in this process. Such twins provide a comprehensive sustainability analysis in three key areas:

Technological sustainability — the ability to maintain product competitiveness through continuous updating.

Financial stability — optimization of break-even points, taking into account R&D costs.

Market stability — adaptation to changes in consumer preferences.

New generation cognitive systems allow rethinking the traditional approach to calculating the break-even point, integrating into the analysis:

1. The cost of creating competitive advantages.
2. The dynamics of commercialization of innovations.
3. The likelihood of technological copying by competitors.
4. The rate of moral aging of technology.

A new model of sustainability analysis, where cognitive algorithms make it possible to predict:

- Growth trajectories for innovation-oriented companies.
- Critical points of transition to new products.
- Optimal timing for launching update processes.

Of particular importance is the ability of cognitive systems to analyze the “resource triangle of sustainability”:

1. Scientific and technical potential — assessment of the adequacy of competencies to create breakthrough solutions.

2. Production capabilities — analysis of the flexibility of technology platforms.

3. Market intelligence — predicting the market’s readiness for innovation.

Development prospects are related to the creation of autonomous sustainability management systems, where cognitive technologies will:

1. Automatically adjust product strategies.
2. Optimize investment flows in R&D.
3. To form predictive models of market behavior.

Thus, the integration of cognitive technologies into the system of ensuring economic sustainability creates fundamentally new opportunities for industrial enterprises in the context of digital transformation, ensuring not only stable development, but also the ability to outpace growth.

However, for the successful realization of these opportunities, it is important to take into account the provision of enterprises with appropriate resources.

Knowledge and competencies are a key resource for creating products with high competitiveness². They are formed both within the company and through the transfer, purchase or use of available resources of the global information space. Thus, the sources of competence formation and development are based on a thorough analysis of market needs and scientific achievements in various fields³.

For the successful integration of science and production, it is necessary to effectively organize the management of strategic resources using an integration and logistics approach that ensures the interaction of various components in a single digital information space. This management is impossible without the formation and development of competencies, information solutions and digital technologies aimed at creating and selling unique products with outstanding consumer properties.

An important point is also the creation of an industry information base of technologies and competencies. Such databases, which are already used in international practice, make it possible to link specific technologies with the competencies necessary for their development and application, which significantly increases the effectiveness of technology transfer and innovation. The adaptation of the knowledge management concept is organically integrated into this system. Competencies, understood as a synergetic system of knowledge, rules and methods, become an integral part of management at all levels: from design to the implementation of high-tech products.

Knowledge in an organization can be classified into three types: data, information, and competencies (Simarova, Alekseevicheva, Zhigin, 2022). Data represents fixed facts and indicators, information is a formalized textual interpretation of this data, and competencies are the synergy of knowledge needed to solve specific tasks. The management structure of these three types of knowledge should ensure continuous access to the necessary information and competencies, which is carried out through multidimensional databases that allow data to be extracted and analyzed in various aspects.

Modern cognitive technologies occupy a key place in the functioning of this system. Thanks to their implementation, it becomes possible to analyze large-scale data arrays, discover previously unnoticed relationships and insights, and automate a significant number of decision-making procedures. The application of machine learning and artificial intelligence methods in practice helps predict changes in consumer demand and improve production chains. Cognitive technologies not only increase the efficiency of knowledge management processes, but also become the basis for generating innovations and allow enterprises to flexibly respond to rapidly changing market circumstances.

² Tulin, A.E., & Chursin, A.A. (2022). *Product competitiveness management: Textbook for master's degree*. Moscow: INFRA-M. (In Russ.). <https://doi.org/10.12737/1081761>

³ Chursin, A.A., & Abueva, M.M.S. (2024). *Innovation Management: A Textbook for Students, Undergraduates, Postgraduates, Faculty and Professionals*. Moscow: INFRA-M. (In Russ.). <https://doi.org/10.12737/1862682> EDN: DDGMIU

Thus, the implementation of lifecycle management of high-tech products in a digital production environment becomes possible through the integration of the latest digital technologies, effective competence management and skillful organization of financial flows. All these elements should work together, forming a single concept that will contribute to the creation of competitive products capable of meeting market needs and adapting to modern challenges.

This provides the conditions for a significant increase in labor efficiency and leads to significant economic and social changes. The Industry 4.0 model provides for a transition to management strategies based on deep integration of robotic systems and artificial intelligence, which is projected to transform organization and management in most high-tech enterprises by 2030^{4, 5} (Shiboldenkov, Vanyashkina, Pakhomova, 2023).

The introduction of innovative solutions in such industries is a key factor in advancing development and increasing competitiveness, contributing to strengthening positions on the international market and forming new market niches (Kashevarova, Ivanov, 2023). To ensure sustainable economic growth, it is necessary to improve production processes, develop integration and cooperation, as well as create scientific and production alliances and professional centers based on digital and cognitive technologies.

In the new conditions, the modernization of organizational structures requires the introduction of software-adaptive management methods that ensure flexibility and readiness for transformation. This approach allows you to quickly adjust the parameters of production activities and constantly monitor the performance of key indicators with a qualitative analysis of the deviations that occur. The organization of a specialized production process management center is becoming an effective tool for adjusting corporate strategies and increasing enterprise efficiency. One of the most important elements is the introduction of adaptive management systems for innovative production.

Effective feedback is a key element of adaptive system stability. The need to make efforts to stabilize the system arises when targets are not met or exceeded. The manager begins to use his entrepreneurial abilities to ensure the balance of the system, which can also lead to a state of insecurity with a lack of information.

Thus, the introduction of an adaptive production management system allows you to quickly respond to changes, speeding up the management decision-making process (Zhou et al., 2022).

In the context of modern challenges and opportunities, it is additionally necessary to integrate cognitive technologies into the management structure of production systems. These technologies, including machine learning and big data analysis, provide new levels of automation and decision support, allowing for

⁴ Ministry of Science and Technology of the Russian Federation. (2023). Concept of technological development for the period up to 2030. Moscow: Ministry of Science and Technology of the Russian Federation. (In Russ.).

⁵ Digital Transformation of Industry: Collection of Materials. (2023). Ekaterinburg: UIETs. (In Russ.).

more efficient processing of information about current processes and predicting results. Cognitive technologies are becoming an important aid in resource management and process optimization at all levels, providing not only support for existing mechanics, but also the development of new strategies based on real data and forecasts.

Thus, the introduction of cognitive technologies becomes a logical step for the further evolution of product lifecycle management and the improvement of corporate digital platforms.

Modern cognitive technologies play an important role in this system. They provide deep analysis and prediction using machine learning and big data processing techniques. These technologies can automate product lifecycle management processes, adapting to changing market requirements and improving management decision-making principles. Such solutions are based on high-quality data and an algorithmic approach, which improves the speed and accuracy of analysis.

The formation of effective mechanisms and methodologies for managing the product lifecycle using cognitive technologies makes it possible to create product lines that take into account demand and competitiveness, as well as increase the investment attractiveness and economic sustainability of companies (Hamdouna, Khmelyarchuk, 2025). This approach ensures the rapid development of high-tech organizations and their competitiveness in the market.

In a rapidly changing global market, it is important to increase the efficiency of product lifecycle management based on a complex economic and mathematical apparatus that integrates artificial intelligence methods with traditional economic modeling approaches. The foundation of such a system is a multi-level architecture of analytical models that provides end-to-end digital support for products from concept to disposal.

The core of the platform consists of hybrid models that combine:

- neural network algorithms for forecasting market demand;
- methods of stochastic optimization of production parameters;
- agent-based competitiveness models;
- cognitive systems for big data analysis (Nikitina, 2023).

A special feature of the mathematical apparatus is its adaptive nature — the coefficients of the models are continuously adjusted based on incoming data from production lines, product sensors and market indicators. Dynamic competitiveness equations take into account both technological parameters of products and macroeconomic factors, including exchange rates, commodity prices and regulatory changes (Chursin, 2017).

The key component of the system is digital twins of a new generation, described by multidimensional matrices of technical and economic indicators. These models allow for a comprehensive “what-if” analysis for various modernization scenarios and market positioning. Economic efficiency is assessed through a system of discounted cash flows complemented by indicators of strategic value and synergetic effect.

The optimization apparatus of the platform implements the principle of adaptive management, where target functions are dynamically recalculated depending on the

phase of the lifecycle and changing market conditions. This ensures a balance between short-term profitability and long-term product competitiveness.

Special attention is paid to innovation risk management models, including:

- probabilistic estimates of technological feasibility;
- analysis of market demand volatility;
- assessment of the rate of moral aging of technologies;
- modeling the behavior of competitors.

The results of the study

A unified cognitive lifecycle management platform
for high-tech products

Modern approaches to product lifecycle management require the creation of an integrated cognitive platform that ensures the integrated interaction of all stages — from design to disposal. Such a platform is being formed as a digital ecosystem (Kashevarova, Shiboldenkov, 2020), combining horizontal integration of lifecycle processes with vertical data coordination — from the level of engineering solutions to strategic economic indicators (Table 1).

Table 1

Product lifecycle stages

Lifecycle stage	Applied cognitive technologies	Economic effect	Key advantages
Design and development	• Digital product doubles • Generative Design (AI) • Predictive performance modeling	Reduction of R&D costs by 25–40% Acceleration of market launch by 30–50%	Minimizing design iterations (Zheng, Kiritsis, 2022) Optimal choice of materials and technologies
Production	• Cognitive quality control systems • Adaptive robotic systems • Self-optimizing production lines	Cost reduction by 15–25% Reduction of marriage by 40–60%	Real-time adaptation to changes Continuous self-learning of systems
Operation and service	• Predictive maintenance • Cognitive diagnostic systems • Adaptive user interfaces	Increased service life by 20–35% Reduced maintenance costs by 30–45%	Service personalization Predicting failures before they occur
Modernization and disposal	• Residual resource analysis systems • Cognitive processing systems • Lifecycle Optimizers	Increase in the residual value by 15–30% Reducing environmental costs by 25–40%	Maximizing value at all stages Environmentally sustainable solutions

Source: compiled by A.A. Chursin.

The fundamental feature of this platform is its adaptive architecture based on the principles of continuous machine learning. The system updates analytical models in real time by processing data from production lines, operational sensors and

market indicators, providing dynamic adjustment of control algorithms in accordance with changing environmental conditions and internal production parameters.

The key functional advantage of the cognitive platform is its ability to predict. Based on multi-agent modeling and neural network analysis, it generates probabilistic scenarios for product development, taking into account technological trends, market dynamics and consumer behavior (Singh, Sharma, 2025). At the same time, stochastic optimization methods make it possible to find effective solutions even in conditions of high uncertainty.

The economic and mathematical basis of the platform includes a set of interrelated models, from discrete event modeling of production processes to neural network demand forecasting algorithms. Special attention is paid to cognitive analytical tools that can identify hidden patterns in large amounts of diverse data.

The implementation of such a platform requires the creation of a single information space that will ensure:

- end-to-end digitalization of all stages of the lifecycle;
- compatibility of heterogeneous systems and data formats;
- secure information exchange between process participants;
- scalability of computing resources.

The architectural implementation of these principles of cognitive product lifecycle management is presented in the following diagram, reflecting the structure of the digital ecosystem within which the cognitive platform unfolds its functional mechanisms (Figure 1).

The scheme is a functional and architectural projection of a cognitive product lifecycle management platform that reveals the logic of integrating digital, service, and intelligent components within a single production ecosystem.

At the process organization level, the diagram illustrates the distributed interaction of project centers, digital platforms, the external information environment, and highly automated production. The integration of blockchain technologies and global data sources ensures transparency and verifiability of operations, while the introduction of AI and adaptive solutions at the production level forms the prerequisites for the transition to autonomous self-optimizing production (Kashevarova, Kulikova, 2024).

The cognitive functionality is central to the system, implemented through digital and service platforms that serve as carriers of machine learning, predictive analytics, and intelligent planning mechanisms. Their synergy makes it possible to ensure consistency of actions between participants in the life cycle (Gutenev, Kulikova, 2024), reduce costs, increase adaptability to external changes and create conditions for sustainable technological development.

The final point of the evolution of this architecture is the formation of autonomous adaptive production as a key element of a cognitive platform capable of redistributing resources, reconfiguring production circuits and launching new product solutions without operator involvement. Thus, the scheme reflects not only the current state of the digital production environment, but also the strategic direction of its transformation towards full intellectual self-sufficiency.

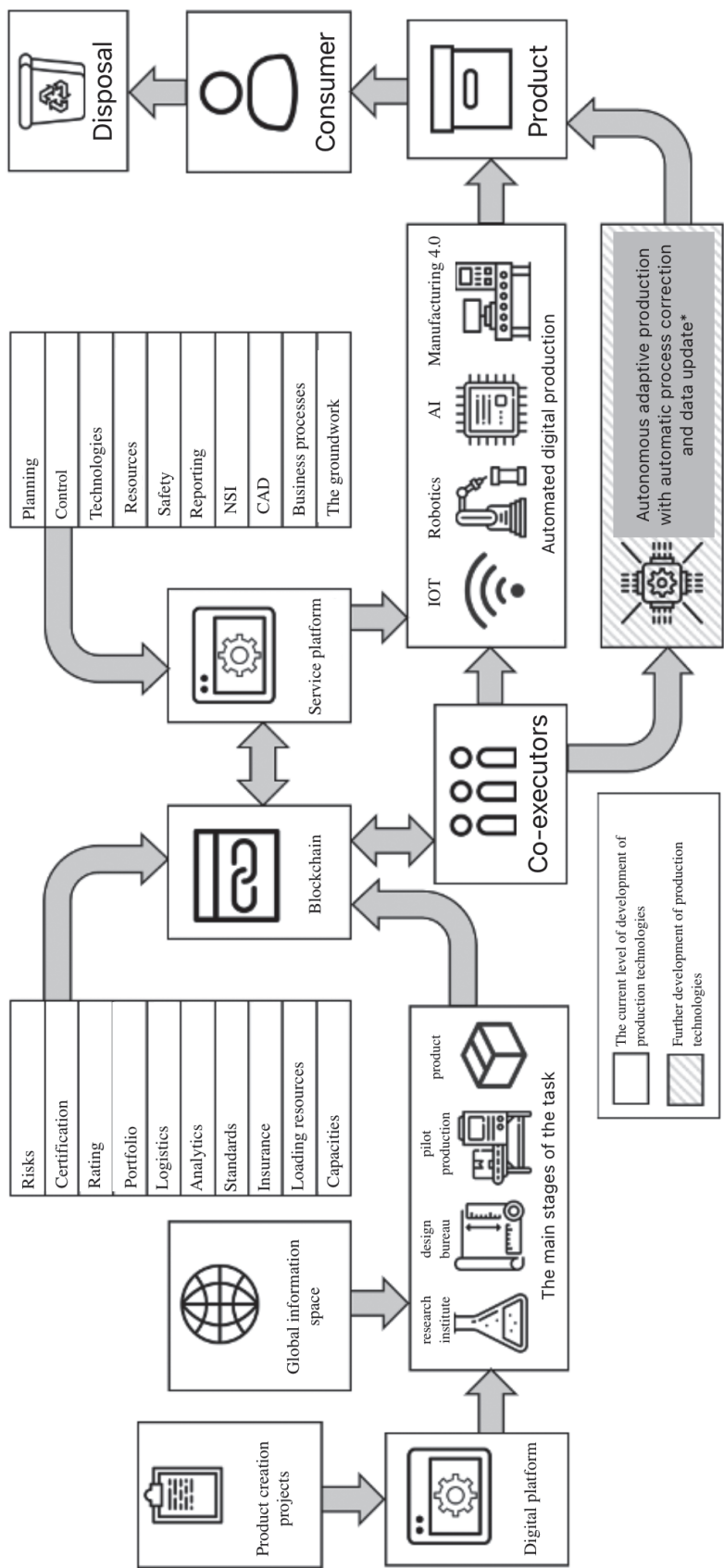
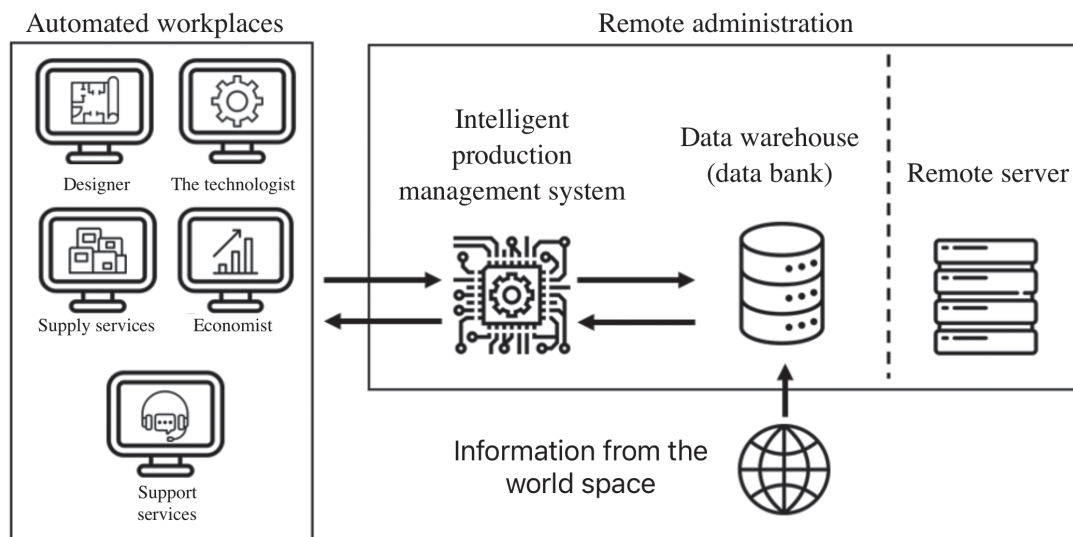


Figure 1. Architecture of the cognitive digital manufacturing ecosystem
Source: compiled by A.A. Chursin.

In addition to the general architecture of the cognitive platform, the model presented above can be supplemented with private implementations at the level of individual production circuits. Within the framework of the overall ecosystem, such circuits provide specific functions, from design and supply to management of production resources.

Figure 2 shows one of these fragments of cognitive architecture, reflecting the work of an intelligent production management system and its interaction with automated workplaces, remote services and global data sources



The number of automated workplaces depends on the volume of design and technological work, the range of products and the volume of its sales and may change under conditions of uncertainty

Figure 2. The local production circuit in the architecture of the cognitive platform

Source: compiled by by A.A. Chursin.

The presented scheme reflects the structure of the local intelligent production circuit, which includes automated workplaces of various categories of specialists and a single intelligent production management system. The latter receives data from both internal storage and the global information space, processes it using analytics and optimization algorithms, and then generates management decisions and recommendations.

This structure provides flexibility in scaling — the number of jobs and the intensity of interactions depend on the product range, capacity utilization, and degree of remote administration. In conditions of uncertainty and high variability of the environment, such architectures make it possible to quickly rebuild processes by integrating new data sources and resources.

The key result of the introduction of a unified cognitive platform is the transformation of the traditional linear approach to product lifecycle management into an intelligent adaptive system capable of continuous self-optimization and forecasting of future conditions of both the product itself and the market environment of its functioning.

Conclusion

The analysis showed that the transition to a cognitive model of product lifecycle management requires a rethink of the architecture of production systems.

Based on the considered theoretical and applied aspects, a functional architectural scheme was proposed that reflects the implementation of a cognitive platform in a digital production environment. The model pays special attention to the logic of evolution — from digital design and distributed interaction between participants in the lifecycle to the formation of autonomous adaptive production, which has the ability to dynamically rebuild production circuits and independently make decisions based on current and forecast data.

The considered approach allows us to form a holistic concept of cognitive management, which ensures not only the optimization of processes, but also their stability, predictability and the ability to scale development. This creates the basis for the formation of a new technological structure in the industry, focused on flexibility, intellectual independence and full digital connectivity of all stages of the product lifecycle. It is worth noting that in the future this opens the way to the creation of production systems capable not only of executing specified algorithms, but also of independently formulating goals, building strategies to achieve them and adapting to new conditions, at a level approaching the cognitive functions of strong artificial intelligence.

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Bio note / Сведения об авторе

Alexander A. Chursin, Doctor of Economics, Professor, Consulting Professor, Department of Applied Economics, Graduate School of Management, RUDN University, 6 Miklukho-Maklaya st., Moscow, 117198, Russian Federation. ORCID: 0000-0003-0697-5207. SPIN-code: 9123-8913. E-mail: chursin-aa@rudn.ru

Чурсин Александр Александрович, доктор экономических наук, профессор, профессор-консультант кафедры прикладной экономики Высшей школы управления, Российский университет дружбы народов, Российская Федерация, 117198, Москва, ул. Миклухо-Маклая, д. 6. ORCID: 0000-0003-0697-5207. SPIN-code: 9123-8913. E-mail: chursin-aa@rudn.ru