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Digital twins and digital technologies: specific features and prospects in the coal industry

S.M. Nikitenko[1], **E.V. Goosen**[1], **A.A. Rozhkov**[2], **M.K. Korolev**[1]
[1] *Federal Research Center for Coal and Coal Chemistry, Siberian Branch of the Russian Academy of Sciences, Kemerovo, Russian Federation*
[2] *Russian Energy Agency, Ministry of Energy of the Russian Federation, Moscow, Russian Federation*
✉ *nsm.nis@mail.ru*

Abstract
Across all sectors of the Russian economy, the adoption of digital technologies (DT) is accelerating, with high-tech industries leading the way. The coal industry, like other extractive sectors, has been slower to embrace these solutions, yet digitalization is advancing both at the industry level and within individual companies. One of the most dynamic areas of DT development is the adoption of digital twins (DTw), which form a core element of integrated digital management systems—acting as an integrator for cross-cutting technologies and sub-technologies. This article examines current approaches to studying and implementing digital twins in the coal sector. The objective is to highlight the specific features of digitalization processes, identify barriers, and outline promising directions for the adoption of DTw in the coal industry. To this end, the article systematizes conceptual and applied approaches to DTw, proposes an original framework for defining, structuring, and classifying digital twins based on maturity levels, and identifies both general and industry-specific trends in the development of DT and DTw. The analysis demonstrates that digital twins are a critical tool for managing value chains, and their effectiveness depends on the maturity of production and digital technologies and on the degree of their interoperability. The study compares and evaluates international and domestic experiences of DT and DTw adoption in mining and coal companies, as well as national-level models. It identifies barriers to adoption in the coal sector and offers recommendations for overcoming them. The research applies systems and comparative analysis, bibliographic review, generalization, and expert surveys. Data sources included media reports, websites of leading coal and mining companies, expert assessments, digital project case studies, consulting reports, and primary and secondary expert surveys. The findings show that digital transformation in the coal industry, including the adoption of DTw, lags behind other sectors. This gap is driven by both general and sector-specific factors: high costs and limited resources, scale effects, the absence of a clear development model and digitalization strategy, low levels of automation in production and management, insufficient digital infrastructure, and an acute shortage of personnel with digital competencies, particularly among executives.

Keywords
coal industry, digitalization, digital twins, typology of digital twins, analysis, experts, implementation, value chains, national models, infrastructure, management

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ЦИФРОВЫЕ ТЕХНОЛОГИИ И ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ

Научная статья

Цифровые двойники и цифровые технологии: особенности и перспективы в угольной отрасли

С.М. Никитенко[1], **Е.В. Гоосен**[1], **А.А.Рожков**[2], **М.К. Королев**[1]
[1] *Федеральный исследовательский центр угля и углехимии СО РАН, г. Кемерово, Российская Федерация*
[2] *Российское энергетическое агентство, Минэнерго России, г. Москва, Российская Федерация*
✉ *nsm.nis@mail.ru*

Аннотация
В настоящее время широко развернулось внедрение цифровых технологий (ЦТ) во всех отраслях российской экономики. Наиболее активно в эти процессы вовлечены высокотехнологичные отрасли. Угольная отрасль, как и остальные добывающие отрасли, отстает во внедрении цифровых технологий. Тем не менее эти процессы идут как на уровне всей отрасли, так и на уровне отдельных компаний. Одним из наиболее популярных направлений развития ЦТ является внедрение цифровых двойников, которые являются частью единой цифровой системы управления компанией – технологией-интегратором всех сквозных ЦТ и субтехнологий. Статья посвящена анализу современных подходов к изучению и практике внедрения цифровых двойников в угольной отрасли. Цель статьи – показать особенности процессов цифровизации, выявить барьеры и перспективные направления внедрения цифровых двойников (ЦД) в угольной отрасли. Для реализации этой цели в статье систематизированы концептуальные и прикладные подходы к изучению ЦД, предложен авторский подход к определению, структуре и типологии ЦД на основе выделения этапов их зрелости. Выявлены общие и отраслевые закономерности развития ЦТ и ЦД. Доказано, что ЦД – это важнейший инструмент управления цепочками создания стоимости (ЦСС), который зависит от степени зрелости производственных и цифровых технологий, а также степени их интероперабельности. Проведены сравнение и оценка опыта внедрения ЦТ и ЦД в зарубежных и отечественных горнодобывающих и угольных компаниях и в страновые модели. Выявлены барьеры внедрения ЦТ и ЦД в угольной отрасли, предложены рекомендации по их устранению. При подготовке статьи использованы следующие научные методы: системный и сравнительный анализ, библиографическое исследование, обобщение, социологический опрос экспертов. Источниками данных послужили материалы СМИ и сайтов ведущих зарубежных и отечественных угольных и горнодобывающих компаний, экспертные оценки, кейс-стади цифровых проектов, аналитические отчеты консалтинговых компаний, материалы первичного и вторичного экспертных опросов. Проведенный анализ показал, что процессы цифровой трансформации и внедрения ЦД в угольной отрасли отстают от других отраслей. Причиной тому являются барьеры как общие для всех отраслей, так и специфичные для угольной отрасли: высокая цена цифровых технологий и нехватка ресурсов, значительный эффект масштаба; отсутствие четко выстроенной модели развития угольной отрасли и стратегии ее цифровизации; низкий уровень автоматизации производства и управления, недостаточность цифровой инфраструктуры; острая нехватка кадров и цифровых компетенций у руководителей компаний.

Ключевые слова
угольная отрасль, цифровизация, цифровые двойники, типология цифровых двойников, анализ, эксперты, внедрение, цепочки создания стоимости, страновые модели, инфраструктура, управление

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Introduction

The implementation of digital technologies (DT) is now rapidly expanding across all sectors of the Russian economy, with the most active engagement observed in high-tech industries. The coal industry, similar to other extractive sectors, lags behind in adopting digital solutions. Nevertheless, digitalization is progressing both at the industry-wide level and within individual companies.

One of the most prominent directions of DT development is the implementation of digital twins (DTw), which serve as an integral component of a unified digital enterprise management system – a technology that integrates all cross-cutting digital solutions and sub-technologies.

Recent advances in artificial intelligence (AI) have accelerated the adoption of digital twins (DTw) in extractive industries, including the coal sector.

DTw now make it possible to automate all key stages of value chains, support the integrated introduction of advanced technologies for deposit exploration, selective coal extraction, beneficiation, and the design of project coal blends, as well as optimize routes for coal transportation and processing.

The purpose of this article is to highlight the specific features of digitalization processes in the coal industry, identify barriers, and outline promising directions for DTw adoption. The objectives are as follows: *1* – To define digital twins and describe their distinctive features and current level of adoption in coal-producing countries; *2* – To identify and characterize the basic national models of coal industry digitalization management, and to determine the role of digital twins within these models; *3* – To identify barriers to the adoption of digital technologies and digital twins in the coal industry and to propose measures for overcoming them.

Data and methods

The study applied systems and comparative analysis, bibliographic review, generalization, and expert surveys.

Data were drawn from online and media sources, websites of leading international and domestic coal and mining companies, expert assessments, case studies of digital projects, consulting reports, and materials from primary and secondary expert surveys.

Research results

Since the early 2000s, the adoption of digital technologies (DT) and digital twins (DTw) has accelerated in the mining and coal industries. The initial introduction of enterprise resource planning (ERP) platforms made it possible to synchronize fragmented production operations, corporate processes, and reporting, significantly improving efficiency. This, in turn, drove major global investments in digital software and infrastructure aimed at developing local digital twins.

The term *digital twin* was first introduced into academic discourse in 2003, but its interpretation remains diverse [1]. Some authors define it narrowly as software that models objects and outcomes [2, 3], while others describe it as a key tool for monitoring and strategic management [4–6]. In international literature, the most widely cited definition presents a DTw as "…an integrated multiphysics, multiscale, probabilistic simulation of a complex product, enabled by a digital thread, that uses the best available physical models, sensor data, and input information to mirror and predict the behavior of its corresponding physical twin across its life cycle" [1]. More recent publications examine the role of DTw in managing companies, regions, and value chains, accounting not only for technological but also for financial, organizational, and other aspects of complex system management [7, 8]. In Russia, research schools focusing on DT [9, 10] and DTw [11, 12] have emerged more recently, including studies on their application in the coal industry [15, 16].

In the authors' view, a digital twin is a comprehensive management tool that creates a realistic virtual model of a physical object, continuously updated in real time.

Leading adopters of DT and DTw include major mining and coal companies in Australia, China, the United States, Canada, and Germany. These companies align DTw with priority digital technologies and apply them not only to individual units, technological stages, and mines, but also as tools for managing the entire value chain. In this article, the value chain refers to the full production sequence in the coal industry, from geological exploration to the sale of processed coal products [17–19]. The primary goals are to identify and maintain optimal operating modes in order to maximize productivity and reliability. This provides a basis for assessing the level of digital transformation and DTw adoption (Table 1).

Analysis of official reports and websites of mining and consulting companies allows for identification of levels of DT and DTw adoption. Level 0 is defined as the stage of standardization and automation of primary and auxiliary operations, marking the onset of basic digital technology adoption. At this level, production processes – including management – are extensively automated, and virtual models of individual products and operations, or quasi-digital twins, are introduced. Level 1 corresponds to the stage of business process optimization and reengineering in line with the requirements of digital technologies. It involves creating local digital twins (LDTw) for the most critical assets and processes, and synchronizing digital models with real business operations. Level 2 reflects the development of integrated digital twins (IDTw), achieved through the convergence of DTw with priority digital technologies. Level 3 represents the formation of a digital twin of the entire value chain (VC), capable of managing all its links and supporting both operational and strategic decision-making.

Alongside these adoption levels, two governance models of DT and DTw implementation in the coal industry have been identified: the corporate model, characteristic of developed economies (BHP, Anglo American, Glencore, and others), and the state-driven model, exemplified by China (China Shenhua Energy Company Limited, China Coal Energy Company Limited, etc.). These models differ in the structure of value chains and the maturity of DT and DTw (Table 2).

Table 1

Features of DT and DTw adoption in major mining and coal companies, 2024

Company	Country of registration / Coal asset location	Autonomous mining equipment and vehicles	Integrated Remote Operations Centers (IROC)	Digital twins at asset, process, and system levels	Artificial Intelligence and Generative AI	Level of digitalization
BHP	UK, Australia / Australia	+	+	+	+	3
China Shenhua Energy	China / China, Australia, Indonesia	+	+	+	+	2–3
China Coal Energy	China / China	+	+	+	+	2–3
Rio Tinto	Australia / no coal assets since 2018	+	+	+	+	2–3
Glencore	UK / Australia, Colombia	+	+	+	–	2–3
Anglo American	UK / Australia	+	–	+	–	2
PT Adaro Energ	Indonesia / Indonesia	+	–	+	–	2
Vale	Brazil / no current coal assets (formerly Mozambique, Australia)	+	–	+	–	2
Yankuang Energy Group	China / China, Australia	+	–	+	–	2
Tata Steel	India / India	–	–	+	–	1
ArcelorMittal	Switzerland / USA, Bosnia and Herzegovina, USA	–	–	+	–	1
Nippon Steel	Japan / indirect coal assets through joint ventures in Australia and the USA	–	–	+	–	1
Teck Resources	Canada / British Columbia	+	–	–	–	1
Peabody Energy	USA / USA, Australia, Venezuela	+	–	–	–	1
Coal India	India / India	–			–	0

Source: Compiled by the authors based on official company reports and websites, and data from McKinsey and GlobalData.

Table 2

Comparison of digitalization and DTw adoption in Australia, China, and Russia

Criterion	Australia	China	Russia
Governance model	Private–corporate	State-driven	None (pilot projects only)
Structure of value chains in the industry	Open, horizontally diversified, global	Closed, vertically integrated, domestic market-oriented	Closed, vertically integrated, export-oriented
Level of adoption	High	Medium	Initial
Core technologies	Autonomous equipment, blockchain	IoT, 5G, AI	Sensors, GIS, ERP systems
Safety	Predictive safety monitoring	Accident prediction models	Local solutions
Efficiency	+5–10%	+15–20%	+2–5%, often negative

Source: Compiled by the authors based on official company reports and websites, and data from McKinsey, Yakov & Partners, and GlobalData.

Another group of countries, including Indonesia, Mongolia, and Russia, is still in the process of shaping their digital transformation models.

In the corporate model, leading companies operate globally and benefit from geographic and functional diversification, which makes their value chains more flexible and resilient. Such groups include enterprises engaged in the mining, transportation, and processing of coal, ferrous and non-ferrous metals, and diamonds. They also encompass service, financial, and research organizations, as well as dedicated digitalization centers.

Case: BHP

BHP is the world's largest diversified mining and metallurgical company, with assets in more than 90 countries. Its sources of competitiveness include high-quality assets, proximity to consumers, transnational scale of operations, production and geographic diversification, and effective corporate governance across the entire value chain.

BHP is a global leader in the adoption of DT and DTw. The company has reached the third level of digitalization, completing the integration of IDTw, AI, and predictive analytics through a unified Integrated Remote Operations Center (IROC). This center functions as a local industrial hub of digital expertise: it monitors and analyzes trends in DT development, establishes standards for the use of DT and DTw, negotiates contracts with partners, and selects and supervises DT projects within both BHP and partner companies.

BHP collaborates with global leaders in DT and mining, including AWS (data analytics, IoT platforms), Siemens, and Schneider Electric (industrial automation). The company also engages in joint projects with Rio Tinto and Vale to standardize digital solutions, while investing in technology start-ups and the creation of innovation centers. In partnership with universities and the national research agency CSIRO, IROC contributes to the development of innovative digital and technological solutions.

Source: Official company website, consulting company data.

The BHP case represents one of the most successful examples of an open, predominantly corporate-driven model of coal industry digitalization. This model is based on close collaboration among leading global companies, supported by national governments, which provide the foundation for technological leadership.

In contrast, state-driven vertically integrated coal companies in China rely on government support and administrative resources to reduce operating costs and accelerate the adoption of DT and DTw, thereby narrowing the gap with global leaders. The case of China Shenhua Energy exemplifies a closed, predominantly state-driven model of coal industry digitalization, aimed at strengthening technological sovereignty and economic security.

Case: China Shenhua Energy

China Shenhua Energy – is the largest coal company in the world. It is part of the state-owned energy holding China Energy Investment Corporation (CEIC). The company's key sources of competitiveness include its scale of operations, low production costs, strict vertical control of the entire value chain (VC) – from exploration to transportation, sales, and processing – state participation, and a focus on a protected domestic market.

A major factor is its status as a "national energy leader," which allows the company to secure government subsidies, preferential loans, reduced tax rates, and guaranteed state contracts for coal and electricity. The government grants China Shenhua Energy priority access to the country's largest coal deposits and provides infrastructure preferences, such as the construction of railway lines and ports at public expense (e.g., Huanghua Port), while restricting foreign companies from entering the Chinese coal market. Through CEIC, China Shenhua Energy actively participates in drafting industry legislation and standards that reflect its interests. In implementing its projects, the company primarily cooperates with national technology firms: Huawei (5G technologies for "smart" mines), Alibaba (cloud-based AI solutions), and XCMG (autonomous mining equipment).

Source: Official company website, consulting company data.

The Russian coal industry and Russian companies lag far behind international leaders in terms of digitalization and DTw adoption[1]. To clarify the situation, the authors conducted a survey in 2024 of ten experts representing the largest coal companies operating in the Kemerovo region. The results largely correspond to those reported by Bratarchuk et al., who carried out a similar survey in 2023 [15] (Table 3).

Experts agreed that Russian coal companies are not yet ready to adopt full-scale digital twins, while digital technologies are being introduced only in selected segments of coal value chains, primarily logistics and safety management (Table 4).

[1] Digitalization of the Russian Mining and Metallurgical Industry in 2024: Long-Term Optimism and Ambitious Goals. Moscow: Yakov & Partners, Tsifra Group; 2024. 20 p.

Table 3

Level of digitalization of Russian coal companies, 2023–2024

Technology	Data from Bratarchuk et al., 2023		Authors' survey data, 2024
	Share of investment in DT, % of total	Average age of deployed systems, years	Share of investment in DT, % of total
APCS	7.2	12.4	8.4
GIS	5.4	8.6	6.2
SCADA	4.0	10.2	5.0
MES	3.2	6.8	3.8
AI	1.2	1.8	1.0
DTw	1.6	2.4	1.2

Source: Compiled by the authors based on Bratarchuk et al. [15], official company reports and websites, and expert survey data.

Table 4

Priority areas of digitalization implemented in Russian coal companies

Company	Priority areas of DT adoption
Russian Coal JSC	Wireless data transmission systems Artificial intelligence technologies Logistics management
East Mining Company LLC	
CC KOLMAR LLC	
Kuzbassrazrezugol Coal Company JSC	
SUEK JSC	Integrated MES-based business process management systems Autonomous robotic technologies Local digital twins
Osinnikovskaya Mine (Raspadskaya Coal Company, EVRAZ coal assets)	
Barzasskoye Tovarishchestvo Open-Pit Mine (Stroyservice JSC)	

Source: Compiled by the authors based on official company reports and websites, and expert survey data.

The adoption of DT and DTw in Russia remains stuck between the first and second levels of digitalization. The DTw currently being introduced are local in scope and, even in large coal companies, fail to deliver the expected results.

Discussion and conclusions

The analysis showed that digital transformation and DTw adoption in the coal industry are lagging behind other sectors. This is due to both cross-industry barriers and challenges specific to coal mining, including:

– high costs of digital technologies and resource shortages, combined with significant scale effects;

– the absence of a coherent development model for the coal industry and a dedicated digitalization strategy;

– limited automation of production and management, combined with inadequate digital infrastructure;

– an acute shortage of personnel and a lack of digital competencies among company executives.

A further obstacle to DT and DTw adoption is the difficulty of assessing the real effects of digital transformation. At present, measurable indicators of objectives, as well as methodologies for evaluating the efficiency and effectiveness of DT implementation, are almost entirely absent. The indicators used for monitoring and ranking are largely oriented toward developed countries and remain unbalanced [20]. As a result, expert judgments and scoring-based evaluations are increasingly applied, but their main drawback is subjectivity. Without the development of national standards and assessment methodologies, these issues cannot be resolved.

In the authors' view, overcoming these barriers requires the development of a coal industry digitalization strategy, defining its key stakeholders, goals, and mechanisms. Under conditions of sanctions and heavy dependence on imported production and digital technologies, this is impossible without active state involvement. Since coal companies in Russia are privately owned, only a mixed model of DT and DTw adoption is feasible. A suitable instrument

for its implementation could be industrial competence centers (ICC) – a mechanism for collaboration between the state, industries, and IT companies launched in 2022. ICCs enable government, private companies, and research and educational organizations to establish standards and priorities for industry digitalization, while co-financing and managing projects. To date, 36 ICCs have been created under the national project Effective and Competitive Economy in all key sectors of the economy on the principles of public–private partnership, but none yet in the coal industry.

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Information about the authors

Sergey M. Nikitenko – Dr. Sci. (Econ.), Associate Professor, Head of the Laboratory of Value Chain Transformation in the Coal Industry, Federal Research Center of Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences, Kemerovo, Russian Federation; ORCID 0000-0001-6684-4159, Scopus ID 56511552300; e-mail nsm.nis@mail.ru

Elena V. Goosen – Cand. Sci. (Econ.), Associate Professor, Leading Researcher of the Laboratory of Value Chain Transformation in the Coal Industry, Federal Research Center of Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences, Kemerovo, Russian Federation; ORCID 0000-0002-1387-4802, Scopus ID 57192160485; e-mail egoosen@yandex.ru

Anatoly A. Rozhkov – Professor, Head of Analytical Research and Short-Term Forecasting Department for Coal Industry Development, Department of Analytics for Coal and Peat Industries, Russian Energy Agency, Ministry of Energy of the Russian Federation, Moscow, Russian Federation; ORCID 0000-0002-4541-0922; e-mail rozhkov@rosenergo.gov.ru

Mikhail K. Korolev – Researcher of the Laboratory of Value Chain Transformation in the Coal Industry, Federal Research Center of Coal and Coal Chemistry, Siberian Branch of the Russian Academy of Sciences, Kemerovo, Russian Federation; ORCID 0000-0001-8102-9830, Scopus ID 57246310900; e-mail m.korolev.gm@gmail.com

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