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The use of Digital Twins to improve the operational efficiency in the extractive industries

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Abstract

The article examines the impact of Digital Twins on the business processes of mining companies. Mining companies can optimise their operations, from stripping and mining to enrichment and transportation. By modelling different scenarios, identifying bottlenecks and making informed decisions, companies can improve resource efficiency, reduce downtime and increase productivity, making a positive impact on their operational efficiency. Predictive maintenance strategies implemented with the help of Digital Twins help increase efficiency by minimising unexpected equipment failures and maximising uptime.

The main technological effects of the use of Digital Twins in the mining industry, which affect the operational efficiency of the company, are: (1) an increase in the volume of output of commercial products after coal enrichment; (2) an increase in the coefficient of output to the production line of mining equipment.

These effects lead to an improvement in the operating efficiency of the mining company, which increases indicators such as EBITDA and cash balance at the end of the period. This impact on operating efficiency is achieved by increasing the volume of commercial products, improving the efficiency of production processes, and by reducing the fixed and operating costs of the business.

In order to assess the impact of the use of Digital Twin technology on mining companies, a methodology has been developed to assess the impact of the use of Digital Twin technology on mining companies. According to the results of the survey, a number of key production processes have been identified where the introduction of a Digital Twin is expected to have an impact.

As a result of the empirical study, the expected increase in EBITDA from the implementation of the Digital Twin was 28%, the actual increase in EBITDA over the study period was 21%. The expected increase in free cash at the end of the period was + 593 million rubles (+130%), the actual increase in free cash for the period under study was 441 million rubles (+96%).

The introduction of Digital Twins in mining companies has shown great potential for improving operational efficiency and solving complex challenges facing the industry.

Keywords: Digital Twin, digital transformation, business processes, operational efficiency, digital technologies.

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应用数字孪生提高采矿行业企业的运营效率

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简介

文章探讨了数字孪生对采矿企业业务流程的影响。采矿企业可以从开采和采矿开始，一直到选矿和运输，优化其运营流程。通过建模不同场景，识别瓶颈并做出合理决策，企业可以提高资源利用效率，缩短停工时间，提高生产力，从而对其运营效率产生积极影响。通过数字孪生实施的预测性维护策略有助于提高效率，通过最小化设备意外故障和最大化无故障运行时间来实现。

数字孪生在采矿业中对企业运营效率产生影响的关键技术效应包括：在煤炭精矿化后增加产品产量和提高采矿设备生产线性能系数。这些效应导致了采矿企业运营效率的改善，增加了EBITDA和期末现金余额等指标。这种对运营效率的影响是通过增加产品产量和提高生产过程效率以及减少企业固定和运营成本实现的。

作者开发了一种评估数字孪生技术对采矿企业影响的方法。根据调查结果，确定了一系列关键生产流程，并预期了数字孪生技术的实施效果。

根据进行的实证研究，预期的数字孪生技术引入带来的EBITDA增长率为28%，而实际上研究期间的EBITDA增长率为21%。预期期末自由现金余额增长为5.93亿卢布（增长130%），而实际上研究期间的自由现金余额增长为4.41亿卢布（增长96%）。

数字孪生技术在采矿企业的应用展示了提高运营效率和解决行业复杂问题的巨大潜力。

关键词：数字孪生、数字化转型、业务流程、运营效率、数字技术。

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Introduction

Managing a modern mining operation is a complex task that requires the use of a variety of methods and tools to achieve set goals and reduce costs. Modern trends in the development of production imply profound changes in the operating conditions of enterprises, such as the widespread introduction of new technologies and software, increasing costs of labour and material resources, the need for rapid restructuring of production processes to replace the product range, and the constant intensification of competition. These factors require an organisation's business processes to be flexible and able to adapt to changing conditions without compromising productivity.

The concept of digital twins can be useful for a company to solve the problems described above. It is worth noting that digital twins can be used not only to digitise physical objects, but also to perform analysis, planning, forecasting and modelling without the need for physical objects.

The use of digital twin technology can lead to changes in outdated process and organisational designs in the mining industry, which in turn can improve operational efficiency, increase productivity, improve safety, reduce costs and limit negative environmental impacts. In addition, the real-time data and analytics provided by digital twins can improve business decision-making by identifying patterns and trends in operations, making informed decisions and developing more effective strategies.

The findings and recommendations of the study can be applied to various industries and sectors undergoing similar changes as a result of the introduction of innovative digital technologies. As such, this work can contribute to the general field of digital transformation and broaden the understanding of how digital twin technology can be used to assess improvements in operational efficiency and sustainability.

1. Literature review

Digital twin technology is gaining popularity due to its ability to simulate the behaviour and operation of physical assets, processes and systems in a virtual environment. This technology enables companies to analyse and optimise their operations, reduce costs and increase efficiency.

A digital twin is a virtual copy of a physical asset, process or system that is used to simulate its behaviour and operation in a virtual environment. It is a combination of the physical and digital worlds where data from physical assets and processes is collected, analysed and modelled in a digital environment.

The concept of digital twins has been widely discussed and researched in recent years. However, there is no generally accepted definition of a digital twin. Different authors present different definitions of digital twins, but many of them have some drawbacks or limitations.

One of the earliest definitions of digital twins was presented by M. Greaves in his work 'Virtual Reality and the Transformation of Product Development' [Greaves, 2002]. He defined a digital twin as 'a virtual representation of a physical product or process used to understand and predict the performance characteristics of the product or process'. This definition focuses on the use of digital twins for product development and performance prediction. Since then, the concept has evolved and digital twins have become an integral part of Industry 4.0, where data-driven decision-making and optimisation are key success factors.

Another definition of digital twins has been proposed by the National Institute of Standards and Technology (NIST, USA) in its 2018 publication 'Taxonomy and Terminology for Cyber-Physical Systems'. NIST defines a digital twin as 'a virtual representation of a physical system or process that uses data to enable understanding, learning, and reasoning'. This definition emphasises the use of data to enable understanding and reasoning, which is important for many digital twin applications. However, it does not clearly define the purpose of using a digital twin or its relationship to the physical system it represents[1].

In 2018, Gartner introduced a more comprehensive definition of digital twins. According to it, a digital twin is 'a software representation of a physical object or system that simulates its physical properties, behaviour and dynamics in a virtual environment and can be used for analysis, prediction, monitoring and optimisation'[2]. This definition includes several important aspects of digital twins, such as their software representation, simulation of physical properties, and reuse. However, it does not address the use of digital twins for learning or reasoning, which is a key aspect of the NIST definition.

In 2021, the authors of [Tao et al., 2019] presented a more detailed classification of digital twins, identifying five types based on their characteristics and functions: analytical digital twins, cyber-physical digital twins, hybrid digital twins, physics-based digital twins, and data-driven digital twins. This classification provides a deeper understanding of the different types of digital twins and their applications. However, it may be too complex for some users and does not take into account the purpose of digital twins or their relationship to physical systems.

According to the definition given in [Borovkov et al., 2018], a digital twin of an enterprise is a collection of data in various forms of representation (drawings, diagrams, documentation, historical archives, algorithms and

[1] NIST Trustworthy and Responsible AI NIST AI 100-2e2023. https://nvlpubs.nist.gov/nistpubs/ai/NIST.AI.100-2e2023.pdf.

[2] Top 10 Strategic Technology Trends for 2018: Digital Twins. https://www.gartner.com/en/documents/3867164.

software of control systems, complex multidisciplinary mathematical models with a high degree of adequacy to real materials, structures, and physical and mechanical processes) describing the dynamic behaviour of an object and its components over time.

According to M.V. Samosudov, a digital twin of an enterprise is a product of digitalisation (digital copy) of the production processes of an enterprise, which helps to optimise activities and increase their efficiency [Samosudov, 2018].

The concept of a 'digital twin of a company' should be distinguished from the concept of a 'digital twin of a product'.

According to the definition of R.A. Isaev, a digital twin of a product is a system consisting of a digital model of a product and two-way information links with the product (if there is a product) and/or its components [Isaev, 2023, p. 44].

In general, the understanding of the digital twin is rather vague. The study of different opinions and materials made it possible to identify a number of approaches to defining the concept of 'a digital twin' (Table 1).

2. Concept and classification of digital twins

In general, existing definitions of digital twins have some shortcomings or limitations. Some focus on specific aspects of digital twins, such as their use for product development or data analysis, while others may be too complex or vague. A more precise and comprehensive definition of digital twins should include the following elements:

- a digital twin is a software representation of a physical system or process [Karapetyan et al., 2020];
- a digital twin simulates the physical properties, behaviour and dynamics of a physical system or process in a virtual environment [Kritzinger et al., 2018];
- a digital twin is used for analysis, prediction, monitoring, optimisation, learning or reasoning [Merdan et al., 2022];
- a digital twin is closely linked to the physical system or process it represents and can be updated with data from sensors, IoT devices or other sources [Barricelli et al., 2019].

Including these elements provides a more complete understanding of what a digital twin is and how it can be used in different applications. This definition also allows for flexibility in the specific types and functions of digital twins, while emphasising their relationship to physical systems and processes.

The essence of digital twins lies in their ability to replicate the behaviour and operation of physical assets and processes in a digital environment. The essence of digital twins lies in their ability to replicate the behaviour and operation of physical assets and processes in a digital environment. Digital twins use real-time data from sensors, IoT devices and other sources to simulate the behaviour and operation of physical assets and processes in a virtual environment.

There are several ways of classifying digital twins, depending on the criteria used. These are some of the most common:

1) based on the application in which they are used. For example, there are digital twins for manufacturing, healthcare, finance and transportation [Arenkov et al., 2019];

2) by level of detail. Some digital twins provide a high-level overview of the system, while others provide detailed information about individual components and processes [Barricelli et al., 2019];

3) based on the data source they use. Some digital twins use data from sensors and other physical sources, while others use data from computer systems and other digital sources [Bao, 2020];

4) by level of sophistication. Some digital twins are relatively simple, modelling only a few components or processes, while others are very complex, modelling entire systems [Grieves, Vickers, 2017].

Digital twins are also classified according to their level of maturity (Table 2).

Let's take a closer look at each level.

The first level is the pre-digital twin, or the precursor to the digital twin. A highly accurate model created before the digital shadow of a physical object appears. In the scientific literature, it is also referred to as the 'digital twin of the design phase'.

The second stage is a classic digital twin. Appears at the stage when the 'physical object - digital twin' pair has already been formed and the digital twin model is refined based on the digital shadow.

The third level is the adaptive digital twin. The models used in this digital twin level are constantly updated in real time based on data transmitted from the physical site. Such a digital twin is already capable of real-time planning and decision-making during operation or maintenance.

The fourth level is an intelligent digital twin. In addition to the characteristics of a third-level digital twin, the fourth level adds the capability of machine learning, i.e. such a digital twin can recognise objects and patterns found in the information environment. This means that the digital twin already has enough autonomy to analyse data about the performance, health and maintenance of the physical asset in more detail.

Digital twins are therefore a tool that can help businesses improve efficiency, productivity and profitability. By creating virtual models of physical systems, companies can optimise their processes, predict future outcomes and identify areas for improvement. By

Table 1
Scientific approaches to defining a Digital Twin

Approach	Features and sample definitions
General approach	A digital twin is a digital copy of a living or non-living physical entity. By connecting the physical and virtual worlds, data is transferred, allowing the virtual entity to exist simultaneously with the physical entity [Saddik, 2018].
Virtual model	A digital twin is a digital dynamic model in the virtual world that fully corresponds to its physical object in the real world, with the ability to simulate its properties, behaviour, lifecycle and performance [Zhuang et al., 2018]. A digital twin is the modelling of a production system based on simulation rules as part of forecasting and production planning; a digital representation of an active unique product or unique product-service system, including its selected characteristics, properties, conditions and behaviour through models, information as well as data within one or more phases of the life cycle [Stark, Damerau, 2018].
Data exchange tool	The defined approach emphasises the need to exchange information between two spaces through sensors, models and actuators [Negri et al., 2017]. A digital twin is a virtual dynamic representation of a physical system that is connected to it for bi-directional data exchange throughout its life cycle [Trauer et al., 2020].
Cyber-physical system element	A digital twin is an exact virtual copy of a physical system that truly represents all of its functionality, or an element of a cyber-physical system that represents data about the production system for employees [Alam, Saddik, 2017].
Digital technology complex	The digital twin is a set of digital technologies that use approaches from statistical analysis, machine learning, chemistry, physics, control theory, reliability theory, queuing theory, numerical modelling, and optimisation.
Functional approach	A digital twin is a learning system made up of a set of mathematical models of varying complexity, refined on the basis of the results of full-scale experiments, which makes it possible to obtain the first full-scale sample of a product that meets the requirements of the technical specifications and also predicts its behaviour throughout its life cycle. A digital twin involves using the best available physical models, sensors and historical data to accurately reflect the life of its counterpart - a physical object [Glaessgen, Stargel, 2012]. The digital twin is designed to reflect all manufacturing defects and updates, taking into account wear and tear from use, and has intelligent control functions

Source: compiled by the author.

understanding the different types and classifications of digital twins, organisations can choose the approach that best suits their needs and make the most of this powerful technology.

It is worth noting that on 1 January 2022 the world's first national standard in the field of digital twins was introduced in the Russian Federation - GOST R 57700.37-2021 'Computer models and simulation. Digital twins of products. General provisions', which brings certainty to the terminology and specifies the technical requirements for solutions of this class. It directly states: 'A digital twin is a system consisting of a digital model of a product and two-way information links with the product (if there is a product) and/or its components'[3].

Let's summarise and differentiate the definition of the term 'digital twin' in Fig. 1.

Thus, the evolution of the term continues, and the digital twin has not outlived the characteristics of its predecessor. In addition, the definition of a digital twin may change as technologies change.

3. Applications of digital twins

Today, digital twins are increasingly in demand in industry. This trend is being driven primarily by large enterprises in the oil and gas and mining industries, i.e. industries with continuous production. Digital twin technology makes it possible to increase output or reduce wear and energy consumption without having to replace and rebuild expensive industrial equipment - a significant amount of money that covers all the risks and costs of implementing an innovative solution in a matter of months.

There are many examples of digital twins being used in the mining industry at all stages (extraction, transport and processing), helping to reduce the company's capital costs and speed up production. This technology is particularly relevant for mining in hard-to-reach areas.

Digital twins are increasingly being used in the mining industry to optimise mining operations, reduce costs and improve safety. The coal industry is no exception and there are several use cases for digital twins in this sector.

One of the main applications of digital twins in the coal mining industry is equipment monitoring and maintenance. By creating a digital twin of equipment, operators can monitor equipment performance, identify potential problems and schedule maintenance activities. This can minimise downtime, reduce maintenance costs and improve safety. For example, Joy Global (now Komatsu Mining Corp.) has developed a digital twin of its underground longwall system that allows operators to

[3] GOST R 57700.37-2021 Computer modelling and simulation. Digital twins of products. General regulations. https://files.stroyinf.ru/Data/758/75810.pdf?ysclid=lte5z2k0n4828230466.

Table 2
Maturity level classification of Digital Twins

Level	Level of model complexity	Physical object	Receiving data from a physical twin
1. Predigital twin	Virtual model with focus on technology/technical risk mitigation	Does not exist	Cannot apply
2. Digital twin	Virtual model of a physical object	Exists	Technical condition, performance, updating, maintenance
3. Adaptive digital twin	Virtual model of a physical object with an adaptive interface	Exists	Technical condition, performance, updating, maintenance; real-time data update
4. Intelligent digital twin	Virtual model of a physical object with adaptive interface and training	Exists	Technical condition, performance, updating, maintenance; update in batch update mode

Source: compiled by the author.

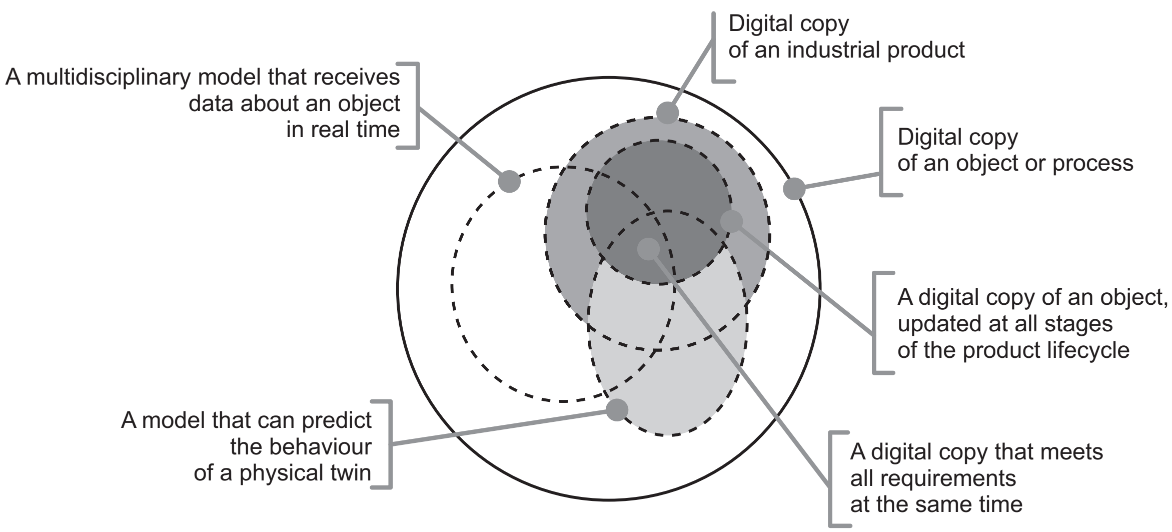
monitor equipment performance in real time and predict maintenance needs[4].

Digital twins can also be used to optimise mine planning and design. By creating a digital twin of a mine site, operators can simulate different scenarios and assess the impact of various factors on mining operations. This helps identify inefficiencies and opportunities for improvement, as well as optimising equipment use and minimising waste. Mining software company Maptek, for example, offers a digital twin solution that allows mines to be planned and designed in 3D[5].

Digital twins can also be used for environmental monitoring in the coal mining industry. By creating a digital twin of a mine site, operators can monitor air and water quality, monitor the environmental impact of mining operations and plan remediation efforts. This helps ensure compliance with environmental regulations and improves the sustainability of the business. Consulting firm GHD, for example, has developed a digital twin of a coal mine in Australia to monitor environmental factors in real time[6].

Digital twins can also be used for safety management in the coal mining industry. By creating a digital twin of

Fig. 1. The limits of the 'Digital Twin' definition



Source: compiled by the author.

[4] Mining technology. Digital transformation Anglo American. 21.11.2019. https://www.mining-technology.com/features/anglo-americans-digital-transformation/.
[5] Id.
[6] https://www.ghd.com/en/expertise/digital/digital-intelligence.

a mine site, operators can model potential safety risks and evaluate the effectiveness of safety protocols. This helps to identify areas for improvement and improve worker safety. For example, engineering and technology company Sandvik has developed a digital twin of an underground mine that allows operators to assess safety risks and plan safety protocols[7].

Digital twins can also be used for training and simulation in the coal mining industry. By creating a digital twin of a mine site, operators can simulate different scenarios and train workers on safety protocols and work procedures. This can improve safety and efficiency, minimise downtime and reduce costs. Mining technology company Immersive Technologies, for example, offers a digital twin solution that enables training and simulation of various mining scenarios[8].

Digital twins offer a range of potential applications in the coal mining industry, including equipment monitoring and maintenance, mine planning and design, environmental monitoring, safety management, and training and simulation. By harnessing these capabilities, coal mining companies can optimise operations, reduce costs, improve safety and achieve sustainability. In recent years, several coal mining companies have introduced digital twins into their operations.

BHP Billiton, one of the world's largest mining companies, has implemented a digital twin at its Olympic Dam mine in South Australia. The digital twin contains real-time data on mine operations, including equipment and processes, and is used to optimise production, reduce downtime and improve safety. The digital twin also allows BHP Billiton to simulate different scenarios and test the impact of changes before implementing them in the real mine. This has led to significant improvements in productivity and safety, as well as reduced costs[9].

Rio Tinto has implemented digital twins at several of its coal mining operations. One example is the Hail Creek mine in Queensland, Australia, where a digital twin was used to improve the efficiency of the mine's concentrator plant. The digital twin has enabled Rio Tinto to optimise plant operations, reduce downtime and improve the quality of the coal produced. The digital twin also allowed Rio Tinto to simulate different scenarios and test the impact of changes before implementing them in the real factory[10].

Peabody Energy, one of the world's largest coal mining companies, has implemented a digital twin of its North Antelope Rochelle mine in Wyoming, USA. The digital twin contains real-time data about a mine's equipment, processes and environment and is used to optimise production, reduce downtime and improve safety. The digital twin also allows Peabody Energy to simulate different scenarios and test the impact of changes before implementing them in the real mine. This innovation has led to significant improvements in productivity and safety, as well as reduced costs[11].

Glencore, a multinational mining company, has implemented digital twins in several of its coal mining operations. One example is the Bulga mine in New South Wales, Australia, where a digital twin has been used to optimise mine production and reduce downtime. The digital twin allowed Glencore to simulate different scenarios and test the impact of changes before implementing them in the real mine, resulting in significant improvements in productivity and safety, as well as cost reductions[12].

Anglo American, a global mining company, has implemented digital twins in several of its mining operations, including coal mines. One example is the Moranbah North mine in Queensland, Australia, where a digital twin was used to optimise the mine's ventilation system. The digital twin allowed *Anglo American* to simulate different scenarios and test the impact of changes before implementing them in a real mine, significantly improving safety and productivity[13].

The above examples illustrate the benefits of implementing digital twins in coal mining operations, which include increased productivity, reduced downtime, improved safety and cost savings. The above examples illustrate the benefits of implementing digital twins in coal mining operations, which include increased productivity, reduced downtime, improved safety and cost savings.

Digital twins are used in various business processes of coal mining companies to improve operational efficiency, reduce costs and improve safety. Some of the key business processes where digital twins are used include:

- geological exploration - digital twins can be used to create virtual models of the geology of the mining area, helping to identify potential mineral deposits and optimise exploration processes;
- design and planning of open pits and mines - digital twins can be used to create virtual models of the mine site to optimise the design and planning of the mine. This includes the design of infrastructure such as roads, power lines and water pipes, as well as the layout of the mine itself;
- optimisation of equipment performance - digital twins can be used to create virtual models of mining equipment, allowing operators to optimise equipment performance and minimise downtime.

[7] Mining technology… https://www.mining-technology.com/features/anglo-americans-digital-transformation/.
[8] Id.
[9] BHP Billiton 2021 Annual Report. https://www.bhp.com/media-and-insightsreports-and-presentations/annual-reports.
[10] Rio Tinto. Innovation in mining. https://www.riotinto.com/invest/capital-programs-and-projects/rio-tinto-innovation-in-mining.
[11] Peabody Energy. Digital twin. https://www.peabodyenergy.com/sustainability/safety/d.
[12] https://www.glencore.com/publications.
[13] Anglo American will expand its use of digital twins to optimise operations. https://www.mining-technology.com/news/anglo-american-digital-twins-optimise-operations/.

For example, digital twins can be used to predict equipment failures before they occur, allowing maintenance to be planned in advance;
- production optimisation - digital twins can be used to create virtual models of the production process, allowing operators to optimise flow and minimise waste. This includes optimising blasting, loading, transport and processing;
- safety - digital twins can be used to create virtual models of a mine site, allowing operators to identify potential safety hazards and take action to mitigate them. For example, digital twins can simulate emergency scenarios, allowing operators to test emergency response plans in a safe and controlled environment.

Optimisation has the greatest impact on the operational efficiency of a coal mine:
- predictive maintenance of specialised equipment;
- transportation of coal and rock mass;
- warehouse management;
- design of the mine site, resulting in a reduction in the stripping ratio;
- coal enrichment.

Digital twins can help coal mining and processing companies to optimise their processes, reduce costs, increase productivity and improve safety. Although the use of digital twins is a complex and time-consuming process, their implementation in manufacturing business processes is preferable and effective because the expected effect of using a digital twin is more predictable.

4. Research methodology

The implementation of a mining company's digital twin is expected to have a number of positive effects that can significantly improve operational efficiency and overall productivity. These expected effects include: an increase in production volumes, an increase in plant productivity and a reduction in the cost of producing marketable products.

To assess the potential impact of digital twins on mining operations, a survey was conducted using a methodology that identified key business processes from an asset management perspective and characteristics of open pit mines.

The study consisted of several stages. The first stage was to select mining operations that were already using digital twins or considering using them in the future.

The following companies were included in the sample: 'Antratsit Invest Proyekt', Siberian Coal Energy Company, 'Vorkutaugol', 'Meltek', 'Amurugol', New Mining Management Company ('Sibuglemet'), 'Beringpromugol' и 'Karakan Invest'. Each of these companies operates an open pit mine, so we can assume that the survey results are comparable.

The next step was to identify key business processes across these assets that management felt should be combined with digital twins. These processes included stripping, drilling and blasting, mining, reserve management, coal preparation and processing, and rock and coal haulage.

The survey also sought to identify specific ways in which digital twins could optimise these business processes. These include: geological exploration, mine design and planning, equipment operation optimisation, production optimisation and industrial safety.

To assess the expected impact of digital twins on mining companies, the survey focused on the existing/expected impact of implementation and the identification of key production processes (Table 3).

Employees of coal mining companies, such as Siberian Coal Energy Company, 'Antratsit Invest Proyekt', 'Meltek', 'Sibuglemet', etc. (Fig. 2).

Each of the respondents holds a management position at the level of Deputy Director General and above:
– has a scientific interest in the field of digital technologies in coal mining;
– has an idea or knows of examples of the use of digital twins in mining companies;
– potentially interested in testing digital twins;
– has a clear understanding of the production processes used by mining companies.

Based on the study of the impact of digital twins on coal mining companies, the following conclusions can be drawn:

1. The main limiting factors, from the point of view of the top management of coal mining companies, are: difficulties in purchasing mining equipment, coal quality, geology and seasonality of production (Fig. 3).

However, difficulties in acquiring mining equipment are a situational problem caused by external macroeconomic and geopolitical factors in 2022-2023. At the same time, the quality of the coal, the geology and the territorial location of production are among the constant factors influencing business activities.

2. Only two of the companies surveyed use digital twins in their sections: 'Invest Proyekt' and Siberian Coal Energy Company. At the same time, the head of Siberian Coal Energy Company commented, 'The digital twin is not being used at all SUEK fields because all the fields are quite old and have infrastructure built under the USSR; many of the company's assets are nearing depletion. Digital twins were only used in areas where there was potential for long-term development and a process of improvement.'

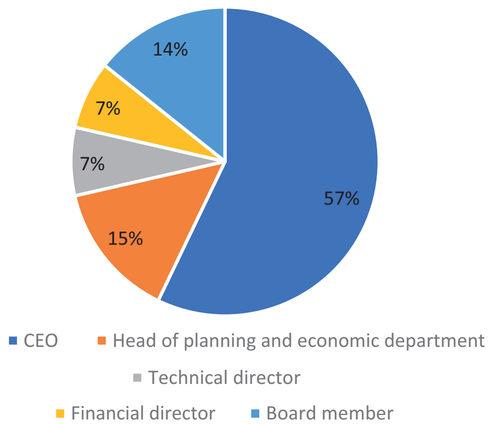
We can therefore conclude that, despite the improvements expected from the introduction of this technology, it is only being used in cases where there is an expectation of a long-term effect from its implementation.

Table 3
The survey form in the mining company

Question	Answer
Full name	
Company name	
Position	CEO
	Financial director
	Head of planning and economic department
	Technical director
	Board member
	Other
Coal production volumes (thousand tons/year)	Up to 1000
	1000–2000
	2000–3500
	3500–6500
	Over 6500
Do you have a processing plant?	Yes/No
What are the main limiting factors to your activities? (You can choose more than one answer)	Geology
	Coal quality
	Geographical location (seasonality)
	Stock depletion
	Difficulties in obtaining the necessary mining equipment
	Sales markets
FCA coal cost (USD/tonne)	
Do you use digital twin technology on your sites?	Yes/No
If not, are you considering/ have you considered such an opportunity for yourself?	Yes/No
Which business processes at your plant have the greatest impact on costs?	Overburden
	Drilling and blasting works
	Mineral extraction tax
	Coal storage, crushing and loading at the open pit Enrichment
	Road maintenance
	Maintenance of separate divisions (warehouses, household infrastructure)
	General production
	Maintenance of railway infrastructure
	Transportation of products to the railway station warehouse
	Coal storage and loading at the railway station
	Wagon supply and cleaning
	International certification (SGS, INCOLAB)
	Management company, property tax
What business process do you think is key to your asset?	Intelligence service
	Development
	Production
	Transportation
	Enrichment
	Warehousing
	Marketing
For which processes do you find it most useful to use digital twins?	Geological exploration
	Design and planning
	Optimisation of equipment operation
	Production optimisation
	Industrial safety
What impact do you expect the implementation to have?	Reducing costs by optimising variable costs
	Increased production volumes due to higher equipment productivity
	Improved industrial safety
	Improving the quality of planning and design
By what percentage do you expect production volumes to increase?	
By what percentage do you expect the cost of commercial products to fall?	
By what percentage do you expect the project's annual EBITDA to grow?	
Comment	

Source: compiled by the author.

Fig. 2. Positions of the employees interviewed



Source: compiled by the author.

This hypothesis is confirmed by the practice of 'Antratsit Invest Proyekt,' LLC. The organisation's chief technologist notes, 'The digital twin has been implemented relatively recently, and the company is actively increasing production volumes and training production staff. Not all processes can be influenced by a digital twin. In the future, however, it will significantly reduce the cost of mined coal, which will be particularly noticeable when production volumes increase to 6.5 million tonnes per year. It was the right decision to start implementing it at the business development stage, as it helps to identify and focus management attention on bottlenecks in ongoing processes, but it will take another two to three years for the technology to reach its full potential.'

We can therefore conclude that it is advisable to introduce a digital twin at the stage of business development, but at the same time this tool needs time to unfold its potential and have a significant impact on the company's business processes.

3. Among companies that do not use digital twin technologies, opinions are divided on the advisability of implementing them.

The management of Amurugol', Karakan Invest and Vorkutaugol' do not believe that the introduction of digital twins in their companies will have a significant effect.

AmurUgol' and KarakanInvest do not consider the possibility of introducing a digital twin due to the fact that lignite is mined and sold on the territory of the Russian Federation, and the open pit mines have good geology, which makes it possible to mine coal with a low stripping ratio, which ensures low costs.

VorkutaUgol' has an open-cast mine that produces less than 400,000 tonnes of coal a year, and the main production takes place in the Komsomolskaya mine, the largest and deepest mine since the times of the USSR. A digital twin is not used there for the same reasons that Siberian Coal Energy Company has not implemented a digital twin at all its sites.

At the same time, New Mining Management Company (Sibuglemet), Meltek and Beringpromugol' are planning to introduce a digital twin of their mines.

New Mining Management Company anticipates the development of the new Mrassky coking coal site and is considering the integration of a digital twin to improve operational efficiency. From a management perspective, there are two key issues that the implementation of a digital twin will help to address:

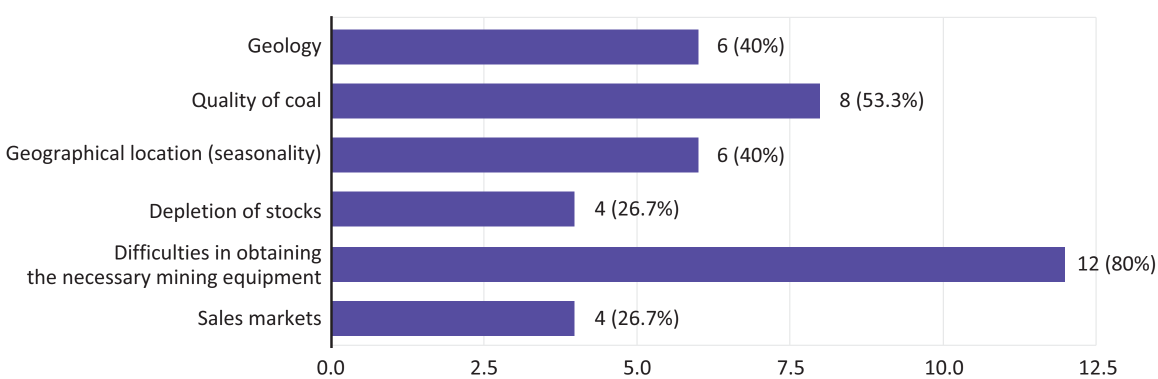
– the new site is combined with the main field, which will be depleted by the end of 2023, increasing the distance for overburden transport and mining;
– the high spontaneous ignition of coal requires better organisation of storage operations.

The introduction of technology in the working areas is impractical due to the depletion of reserves in the main field in 2023 and in the mines in 2025.

Meltek and Beringpromugol are exploring the possibility of introducing a digital twin at operating coal mines.

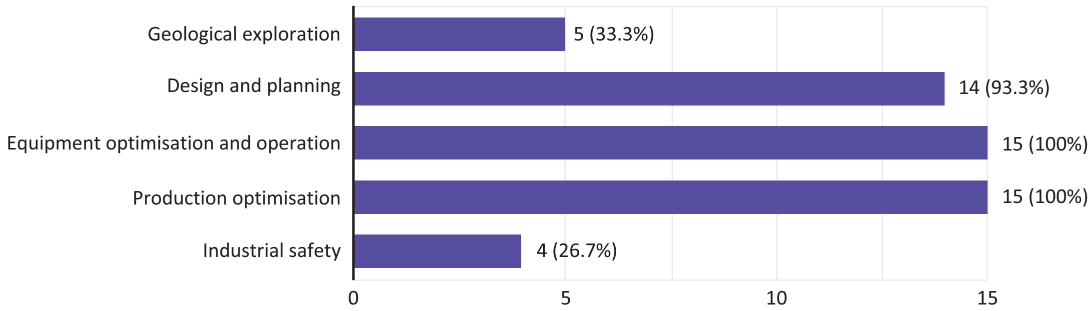
Meltek faces geological constraints that require significant investment to prepare the mine for large-scale production. According to the company's CEO, 'A digital twin could increase the productivity of the rock stripping equipment; currently the stripping ratio is around 12, which is almost the same as the stripping ratio in mining.' Meltek plans to develop its facility to produce 10 million tonnes of coal per year and, like New Mining Management

Fig. 3. Obstacles to the introduction of Digital Twins



Source: compiled by the author.

Fig. 4. Priority areas for the application of Digital Twins



Source: compiled by the author.

Company, sees the digital twin as a tool to help develop its new internal investment project.

Beringpromugol is also an investment project that will reach a production volume of 1.2 million tonnes of coking and thermal coal per year by 2022. By 2030, the plant plans to increase its production volume to 6 million tonnes per year, but it has very different needs, for which it plans to integrate a digital twin. The coal is mined throughout the year, but is sold through a seasonal port that can only handle coal during the summer season. Optimising the road transport logistics of commercial products from the mine to the port will enable increased sales volumes. It will also be necessary to integrate a digital twin into the port to optimise shipments.

As a result, each organisation will have its own unique characteristics when identifying the need to integrate a digital twin, and will expect different benefits from its implementation. At the same time, there is a logic in which management considers the introduction of this technology in promising investment projects with relatively high coal costs to be inappropriate at the moment due to insufficient debugging of key business processes.

4. Key business processes for which the use of digital twins is recommended include optimising equipment operation and optimising production (Fig. 4).

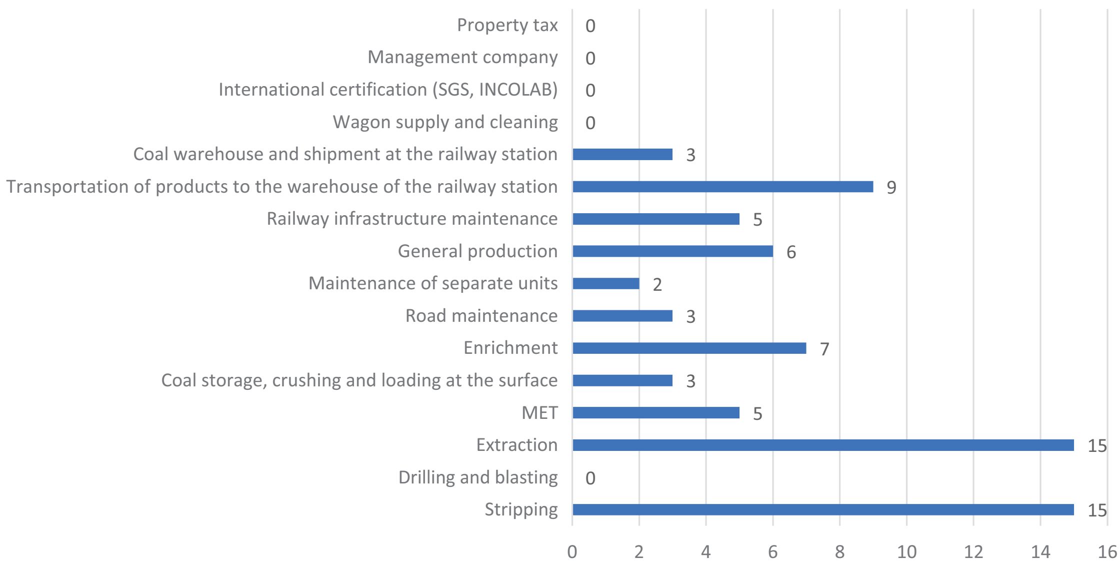
At the same time, respondents expect that the main impact of implementing a digital twin will be to reduce the cost of commercial products by optimising variable costs and increasing production volumes without additional capital investment in specialised equipment, which together will have a positive impact on the operational efficiency of the company.

Mine design and planning is also a promising area for implementing a digital twin, but this process has less impact on the operational efficiency of a mining company.

5. During the survey, coal mine management identified processes such as stripping, mining, beneficiation and transportation of coal and rock as key and having the greatest impact on the operational efficiency of a coal mine (Fig. 5).

The digital twin has the potential to influence and improve the efficiency of these manufacturing processes. As evidence of this hypothesis, we can cite an example provided by the head of Antratsit Invest Proyekt. ‘The

Fig. 5. The most significant business processes for cost formation



Source: compiled by the author.

digital twin has had the greatest impact by optimising the transport of coal from the mine stockyard to the rail stockyard (75km), increasing the number of daily road hauls from four to five through route optimisation and thus increasing the volume of coal shipments. The digital twin has also been integrated into the coal enrichment process, virtually eliminating middle fraction coal.'

6. All of the companies surveyed expect to see a significant improvement in their financial results as a result of introducing a digital twin into their operations. The average expert estimate of annual EBITDA growth was 14%, driven by the full implementation of a digital twin of the business and the debugging of business processes. The range of annual EBITDA growth from the implementation of a digital twin among respondents was 6.5% to 30%, as each expert assessed this effect based on their company's unique external parameters and the degree of streamlined business and production processes at that time.

The operational efficiency effects of using a digital twin can be divided into effects that affect production volumes and effects that reduce fixed costs, depending on the production processes used. The most important and common production processes have been identified as stripping, mining, processing and transportation of overburden and coal. Introducing digital twins into these processes means optimising equipment operation and production.

The main impacts on production processes that affect the operational efficiency of mining companies are therefore: increasing the productivity of mining equipment, increasing the yield of coal after the beneficiation process, and increasing the productivity of equipment used to transport marketable products.

5. Methodology for assessing the impact of a digital twin on the operational efficiency of a mining company

Based on the research conducted, it is possible to make the necessary key assumptions to assess the complex effect of using a digital twin in coal mining companies. The research conducted allows us to make assumptions about the potential impact of a digital twin on a coal mining company and to determine the specific coefficients of the potential impact on the production processes of coal mining companies, which can be used to model the expected impact on operational efficiency.

In order to identify these specific coefficients, it is necessary to resort to the method of weighting expert judgements: the weights are distributed according to the effects expected by the respondents (Table 4). The weights are distributed to take into account the size of the company and the position of the expert to further determine the weighted average of the effect, as the sample of respondents includes both large holdings, such as Siberian Coal Energy Company, and assets operating at a coal mine, such as Antratsit Invest Proyekt, LLC.

Table 4
Weights for the placement of points

Parameter	Points	Parameter	Points
Up to 1000	1	CEO	4
1000–2000	2	Financial director	2
2000–3500	3	Head of planning and economic department	1
3500–6500	4	Technical director	3
Over 6500	5	Board member	4

It is also necessary to take into account the actual results of the Siberian Coal Energy Company, Antratsit Invest Proyekt, Vostokugol' and Mechel-mining, since this information reports on the effects that have already occurred within the first three years of using digital twin technology (Table 5).

Once the points have been allocated, it is necessary to identify the weighted average results that will be applied as an assumption to the company for which the digital twin integration is planned:

$$S = \frac{\sum_m^n (V1n + V2n) \times Qn}{\sum_m^n (V1 + V2)},$$

where $S1$ - is the weighted average expected increase in the coefficient of reaching the productivity line of mining equipment - 8.4%, $S2$ - is the weighted average expected increase in the output of marketable products after enrichment - 5.4%, $S3$ - is the weighted average expected increase in the coefficient of reaching the productivity line of dump trucks carrying out transport of coal from the warehouse at the open pit to the warehouse at the railway station - 5.1%.

Having obtained the specific coefficients S1, S2, S3, which reflect the expected impact of the use of a digital twin on a mining company, it is necessary to carry out a series of steps to assess the impact of the use of a digital twin on operational efficiency.

Step 1. Creation of a financial and economic model of the company

The financial and economic model must include a detailed calculation of the productivity of specialised equipment and the operation of mining complexes. Such a calculation will make it possible to determine possible production volumes according to the productivity of mining complexes and to identify changes in the on-line coefficient due to the integration of a digital twin.

A similar calculation is used to determine the efficiency of transporting commercial products from the open pit warehouse to the rail yard warehouse to determine the productivity of the dump trucks that reach the line.

To analyse the effect of the introduction of a digital twin in the operation of a washing plant, it is sufficient

Table 5
Ranking of the expected effects of Digital Twin usage

Company	Position	Extraction volumes (thousand tonnes/year)	$V1$	$V2$	$Q1$ (%)	$Q2$ (%)	$Q3$ (%)
Antratsit Invest Proyekt	Board member	1000–2000	4	2	10,0	6,0	6,0
Antratsit Invest Proyekt	Financial director	1000–2000	2	2	7,5	4,0	4,0
Antratsit Invest Proyekt	CEO	1000–2000	4	2	15,0	7,2	8,0
Antratsit Invest Proyekt	Head of planning and economic department	1000–2000	1	2	10,0	7,0	6,0
Antratsit Invest Proyekt	Technical director	1000–2000	3	2	8,5	6,0	6,0
Antratsit Invest Proyekt	Board memeber	1000–2000	4	2	10,0	7,5	8,0
Siberian Energy Company	Head of planning and economic department	Over 6500	2	5	10,0	6,5	4,0
Siberian Energy Company	CEO	Over 6500	4	5	8,5	5,5	8,0
Vorkutaugol’	CEO	Up to 400 000	4	1	6,5	2,5	4,0
New Mining Management Company	CEO	Over 6500	4	5	15,0	8,0	3,0
Karakan Invest	CEO	3500–6500	4	4	10,0	4,5	5,0
Meltek	CEO	3500–6500	4	4	12,5	6,5	6,0
Meltek	CEO	3500–6500	4	4	4,5	8,5	4,0
Amurugol’	CEO	2000–3500	4	3	7,5	4,5	3,0
Beringpromugol’	CEO	1000–2000	4	2	8,0	12,0	5,0
Implementation practice							
Siberian Coal Energy Company		Over 6500	8	5	4,5	3,5	6,0
Antratsit Invest Proyekt		1000–2000	8	2	6,0	4,0	4,3
Vostokugol’		Over 6500	8	5	7,5	—	5,4
Mechel-mining		Over 6500	8	5	5,5	6,5	3,2

Note. $V1$ – weight by position / Weight for factual information; $V2$ – weight by production volume; $Q1$ – expected increase in online productivity of mining equipment; $Q2$ – expected increase in marketable product yield after enrichment; $Q3$ – creduce transportation distances.

Source: compiled by the author.

to highlight in a separate line the yield coefficient of the enriched coal sent for resale.

Step 2. Application of the previously calculated coefficients S1, S2 and S3 to the compiled production processes

The outcome of this phase will be to determine the expected impact of the use of a digital twin on production processes, and to further contribute to changes in production and sales volumes.

Step 3. Calculation of total operating expenses incurred during the year

The result of this stage will be an indicator in the form of a changed specific cost of 1 tonne of commercial products, which can be compared with the cost of 1 tonne of commercial products without the use of a digital twin, thus identifying the specific effect of introducing a digital twin per 1 tonne of commercial products.

Step 4. Preparation of P&L and CF to determine changes in annual EBITDA and cash flow of the company at the end of the year

The result of this phase is an assessment of the operational efficiency of the mining company using a digital twin.

Step 5. It is necessary to compare the financial result with the result of the expected effects of introducing a digital twin into the production processes and without it, thus calculating the effect of introducing a digital twin on operational efficiency

The outcome of this phase will be the desired assessment of the impact of using a digital twin on the operational efficiency of a mining company.

This calculation method allows:

1) to recalculate possible production volumes according to the productivity of special equipment;
2) to identify the lack of equipment capacity at the plant, both at the mining stage and at the stage of transporting coal from the coal stockyard at the open pit to the coal stockyard at the railway station;
3) to regulate the coal yield after enrichment.

It is therefore possible to assess the expected impact of the introduction of digital twins in mining companies on business processes related to the production of commercial products (optimisation of equipment operation, optimisation of production) by introducing specific coefficients. These include the weighted average expected increase in the coefficient of reaching the productivity line of mining equipment; the weighted average expected increase in the yield of marketable products after enrichment; the weighted average expected increase in the coefficient of performance of dump trucks transporting coal from the open pit to the stockyard at the railway station.

6. Calculation of the complex effect of the introduction of a digital twin at Anthratsit Invest Proyekt, LLC

In order to verify the relevance of the developed methodology for assessing the impact of the use of digital twin technology on the operational efficiency of mining companies, it is proposed to consider the period from the second quarter of 2022 to the first quarter of 2023 (hereinafter referred to as the study period), since it is during this period that the implementation of the digital twin began to have an impact on the operational efficiency of this coal mining company.

Firstly, it is necessary to calculate the cleared performance of special equipment from the digital twin. It is proposed to use the performance of the first quarter of 2022 as an indicator, as the impact of the introduction of the digital twin will not have been felt during this period.

The productivity of mining complexes as of the first quarter of 2022 is shown in Table 6.

Thus, in 12 months the existing mining complexes can provide a volume of stripping of coal rock - 8,064 thousand m3 and a production volume of 1,613 thousand tonnes of coal, which corresponds to the stripping coefficient for a given volume of rock (the stripping coefficient is 5). It is confirmed by the IMC report and the opinion of McKinsey&Company consultants.

Yield after coal enrichment as of Q1 2022 was 68%. Accordingly, the volume of sales of commercial products for 12 months could not exceed 1097 thousand tonnes of coal.

The existing 38-tonne SHACMAN dump trucks made four trips a day to transport the coal from the open-cast mine stockpile to the stockpile at the railway station, with an annual capacity to transport 1094,000 tonnes of coal for sale.

Based on these inputs, it is possible to make an assessment of the operational efficiency of Antratsit Invest Proyekt, LLC without using a digital twin (Table 7).

Thus, EBITDA for the period under review without digital twin amounted to 1,662,141 thousand rubles. The cash balance at the end of the study period without digital twin amounted to 457,490 thousand roubles.

It is then necessary to apply the previously calculated coefficients S1, S2, S3 to the model (Table 8).

Thus, in 12 months, the existing mining complexes are able to extract 8741 thousand m3 of coal and produce 1740 thousand tonnes of coal, which corresponds to the extraction coefficient for a given volume of rock (the extraction coefficient is 5).

The yield after coal enrichment will be 73.2%, taking into account the expected increase in efficiency due to the introduction of a digital twin; accordingly, the volume of sales of commercial products over a 12-month period could not exceed 1274 thousand tonnes of coal.

The existing 38-tonne SHACMAN dump trucks will make five trips a day to transport coal from the open-cast mine stockpile to the stockpile at the railway station, and taking into account the expected increase in efficiency from the introduction of a digital twin, the annual capacity to transport coal for sale will be 1,368,000 tonnes of coal.

Based on these inputs, it is possible to make an assessment of the operational efficiency of using the Anthratsit Invest Proyekt digital twin (Table 9).

Thus, the expected EBITDA of the study period after the implementation of the digital twin is 2,133,971 thousand roubles. The expected cash balance at the end of the study period with the expected effect of the implementation of the digital twin will be 1,050,854 thousand roubles.

Next, it is necessary to compare the results obtained before and after the implementation of the digital twin (Table 10).

The expected EBITDA increase from the implementation of the Digital Twin was 28%, the actual increase for the period was 21%. The expected increase in free cash flow at the end of the period was RUB 593 mln. (+130%), the actual increase during the period was 441 mln. (+96%).

These differences are due to the time cost of the resulting optimisation of production and business processes when implementing a digital twin of a mining company at an asset (Table 11).

The expected result from the implementation of digital twins differs from the actual result within 3%, which allows us to conclude that the results obtained are reliable. The best way to assess the impact of the use of digital twin technology on the operational efficiency of mining companies is to determine the number of trips made by dump trucks to transport coal.

This method has been adopted and used by Antratsit Invest Proyekt, LLC and Evolution Holding Company. The integration of the digital twin has a positive impact

Table 6
Productivity of potential mining complexes from the first quarter of 2022

Variables	Excavator 7 m³, 90 t power	Excavator 7 m³, 130 t power	Excavator 12 m³, 90 t power	Excavator 12 m³, 130 t power
Bucket volume (m³)	7	7	12	12
Loosening coefficient (units)	1.45	1.45	1.45	1.45
Bucket capacity in rear view (m³)	4.8	4.8	8	8
Excavator cycle time (sec.)	27	27	29	29
Excavator net operating time (hours)	10.5	10.5	10.5	10.5
Regulated downtime within a shift (min.)	90	90	90	90
– shift changes (min.)	30	30	30	30
– lunch (min.)	30	30	30	30
– refuelling and personal needs (min.)	30	30	30	30
Truck loading cycle time (min.)	4.4	5.7	3.1	4.4
– time to set up a dumper for loading (min.)	0.7	0.7	0.7	0.8
– number of buckets to load a dumper (units)	7	10	4	6
– dump truck loading time by pass (min.)	3.2	4.5	1.9	2.9
– dump truck departure time from loading (min.)	0.5	0.5	0.5	0.7
Average manoeuvre time per hour (moving along the face, preparing the site for loading) (min.)	6	6	7	7
Net operating time per hour (min.)	54	54	53	53
Hourly excavator productivity (m³/hour)	447	493	609	626
Excavator shift capacity (m³/shift)	4692	5173	6394	6577
Estimated daily excavator productivity (m³/day.)	9385	10345	12788	13154
Number of days per month	30	30	30	30
– duration of repair (maintenance, repair) (days)	1	1	1	1
– number of working days per month	29	29	29	29
Estimated monthly excavator productivity (thousand m³)	272.2	300.0	370.8	381.5
Output rate (line usage)	0.80	0.80	0.80	0.80
Monthly excavator productivity considering CTG 0.85 (thousand m³)	218	240	297	305
Dumper load capacity (t)	90	130	90	130
Rock density (t/m³)	2.5	2.5	2.5	2.5
Body capacity (m³)	36.0	52.0	36.0	52.0
Time to set up a tipper for loading (sec.)	42.0	42.0	42.0	48.0
Charging time (min.)	3.2	4.0	1.9	2.9
Dump truck departure time after loading (sec)	30.0	30.0	30.0	42.0
Transportation distance (km)	1.5	1.5	1.5	1.5
Average driving speed of the tipper (km/h)	19.5	18.5	18.5	18.5
Time to prepare a dumper for unloading (sec.)	42.0	42.0	42.0	48.0
Dump truck unloading time (sec.)	60.0	60.0	70.0	70.0
Travel time (round trip) (min.)	9.2	9.7	9.7	9.7
Turnaround time per flight (min.)	15.3	17.1	14.7	16.1
Trips per hour (units)	3.9	3.5	4.1	3.7
Productivity (m³/hour)	141.4	182.1	146.6	193.8
Trips per shift (units)	41.0	36.0	42.0	39.0
Dump truck shift capacity (m³/shift)	1476.0	1872.0	1512.0	2028.0
Flights per day (units)	82.0	72.0	84.0	78.0
Estimated daily productivity of the dumper (m³/day)	2952.0	3744.0	3024.0	4056.0
Output rate (line usage)	0.8	0.8	0.8	0.8
Trips per month (units)	1902.0	1670.0	1949.0	1810.0
Monthly productivity of a dumper, taking into account the coefficient for the use of shift time (thousand m³)	68.5	86.9	70.2	94.1
Dump truck requirements for maximum excavator performance (units)	3.2	2.8	4.3	3.3

Source: compiled by the author.

Table 7
Calculation of the financial result of the study period without the use of a Digital Twin in 2023

Stripping ratio	5.0
Volume of overburden (thousand m^3)	8 040
Coal production (thousand tonnes)	1 608
Coal sales (thousand tonnes)	1 093
Average FCA price (USD/t)	59
Share of products sold (%)	68
Dollar exchange rate (RUB/USD)	75
Average calorie content (kcal)	5 440
Coal transported by rail (thousand tonnes)	1 093
Income statement	
Turnover (thousand roubles)	4 875 517
Total - domestic market (thousand roubles)	2 302 188
Total - export (thousand roubles)	2 573 329
Cost of goods sold (thousand roubles)	3 086 793
Gross profit (thousand roubles)	1 788 725
Direct variable costs (thousand roubles)	2 028 326
– Drilling and blasting	257 542
– stripping	793 768
– production	147 581
– enrichment	323 208
– MET	285 841
– coal storage, crushing and loading at the open pit	53 583
– transportation of products to the railway station warehouse	166 803
Indirect variable costs (thousand roubles)	69 485
Costs of organising shipments (thousand roubles)	42 833
– locomotive hire	14 753
– other costs (feeding, cleaning wagons, etc.)	28 080
Expenses for support of shipments (thousand roubles)	26 653
– international certification	26 653
Marginal profit (thousand roubles)	2 777 706
Indirect fixed costs (thousand roubles)	1 536 100
Total production costs (thousand roubles)	1 058 466
– maintenance of railway infrastructure	25 966
– maintenance of roads	155 101
– maintenance of public utilities	168 254
– property tax	88 029
– general production	621 115
Other operating expenses (thousand roubles)	143 605
– storage and transport to the railway station	143 605
Administrative and management expenses (thousand roubles)	334 029
– For reference: depreciation included in cost	420 536
EBITDA (thousand roubles.)	1 662 141
Cash at the beginning of the period (thousand roubles)	316 324
Cash and cash equivalents at the end of the period (thousand roubles)	457 490
Financial activities (thousand rubles)	5 347 321
– Receipt of loan funds CA 0051/21	4 012 228
– Receipt of loan funds CA 0758/21	1 335 093
– Receipt of loan funds from participants	–
Operating activities (thousand roubles)	6 712 427
– Other revenue	–
– Revenue from sales	4 875 517
– Cash received on deposits	405 434
– VAT refund - operating expenses	180 686
– VAT refund - investments	1 228 032
– VAT refund - leasing	22 757
Total revenues (thousand roubles)	12 059 748
Financial activities (thousand roubles)	1 838 637
Interest payments (thousand roubles)	1 278 637
– payment of interest on participants' loans	183 662
Debt payment (thousand roubles)	560 000
Operating activities (thousand roubles)	4 067 582
– Operating expenses (excluding VAT)	3 853 963
– Adjustment for royalties paid in advance	74 844
– VAT - operating expenses	288 463
Investment activity (thousand roubles)	6 012 363
– investment activities	3 871 556
– investment activities of an engineer	1 335 093
– leasing and replenishment of security account	805 714
Total disposal (thousand roubles)	11 918 582

Source: compiled by the author.

on the operational activity of coal mining companies, in particular Anthratsit Invest Proyekt, LLC.

It is possible to identify a number of shortcomings in the proposed methodology for assessing the impact of the use of digital twin technology on the operational efficiency of mining companies: the method does not take into account

1) the period of implementation and increasing the effect of the digital twin;
2) changes in external factors affecting the performance of equipment, such as seasonality.

These shortcomings motivate further research into the impact of digital twins on the operational efficiency of mining companies.

7. Discussion and further research

The methodology developed to assess the impact of using digital twin technology on the operational efficiency of mining companies allows us to evaluate the impact of implementing a digital twin and help management formulate a position on the feasibility of implementation. However, in order to clarify the results obtained, it is necessary to clarify a number of parameters, such as the factors for modifying the external parameters, the characteristics of the mined coal grades during enrichment, the expected effects affecting the reduction of the stripping ratio, etc.

Table 8
Productivity of potential mining complexes

Variables	Excavator 7 m³, 90 t power	Excavator 7 m³, 130 t power	Excavator 12 m³, 90 t power	Excavator 12 m³, 130 t power
Bucket volume (m³)	7	7	12	12
Loosening coefficient	1.45	1.45	1.45	1.45
Bucket capacity in rear sight (m³)	4.8	4.8	8	8
Excavator cycle time (sec)	27	27	29	29
Net excavator working time (hour)	10.5	10.5	10.5	10.5
Regulated downtime per shift (min.)	90	90	90	90
– shift changes (min.)	30	30	30	30
– lunch (min.)	30	30	30	30
– refuelling and personal needs (min.)	30	30	30	30
Truck loading cycle time (min.)	4.4	5.7	3.1	4.4
– Time to set up the dumper for loading (min.)	0.7	0.7	0.7	0.8
– Number of buckets for dumper loading (units)	7	10	4	6
– Dump truck loading time according to the pass (min.)	3.2	4.5	1.9	2.9
– Dump truck departure time from loading (min.)	0.5	0.5	0.5	0.7
Average manoeuvring time per hour (moving along the face, preparing the site for loading) (min.)	6	6	7	7
Net operating time per hour (min.)	54	54	53	53
– hourly excavator productivity (m³/hour)	447	493	609	626
– shift productivity of the excavator (m³/shift)	4692	5173	6394	6577
– estimated daily productivity of the excavator (m³/day)	9385	10345	12788	13154
Number of days per month	30	30	30	30
– Duration of repair (maintenance, repair) (days)	1	1	1	1
– Number of working days per month	29	29	29	29
Estimated monthly excavator productivity (thousand m³)	272.2	300.0	370.8	381.5
Output rate (line usage)	0.88	0.88	0.88	0.88
Monthly excavator productivity considering TRC 0.85 (thousand m³)	241	265	328	337
Dump truck load capacity (t)	90	130	90	130
Rock density (t/m³)	2.5	2.5	2.5	2.5
Body capacity (m³)	36.0	52.0	36.0	52.0
Time to set up a tipper for loading (sec.)	42	42	42	48
Loading time (min.)	3.2	4.5	1.9	2.9
Dump truck departure time after loading (sec.)	30	30	30	42
Transportation distance (km)	1.5	1.5	1.5	1.5
Average speed of the tipper (km/h)	19.5	18.5	18.5	18.5
Time to set up a tipper for unloading (sec.)	42	42	42	48
Dump truck unloading time (sec.)	60	60	70	70
Travel time (round trip) (min.)	9.2	9.7	9.7	9.7
Turnaround time per travel (min.)	15.3	17.1	14.7	16.1
Trips per hour (units)	3.93	3.50	4.07	3.73
Productivity per hour (m³/hour)	141.4	182.1	146.6	193.8
Trips per shift (units)	41	36	42	39
Dump truck shift capacity (m³/shift)	1476.0	1872.0	1512.0	2028.0
Trips per day (units)	82	72	84	78
Estimated daily productivity of the dumper (m³/day)	2952	3744	3024	4056
Output rate (line usage)	0.88	0.88	0.88	0.88
Travels per month (units)	2102	1846	2153	2000
Monthly dumper productivity considering coefficient for the use of shift time (thousand m³/month)	75.7	96.0	77.5	104.0
Dump truck requirements for maximum excavator performance (units)	3.2	2.8	4.3	3.3

Source: compiled by the author.

Table 9
Evaluation of the operational effectiveness of using the Digital Twin 'AnthracitInvestProject' in 2023

Stripping ratio	5
Volume of overburden (thousand m^3)	8 700
Coal production (thousand tonnes)	1 740
Coal sales (thousand tonnes)	1 274
Average FCA price (USD/t)	59
Share of products sold (%)	73
Dollar exchange rate (RUB/USD)	75
Average calorie content (kcal)	5 440
Coal transported by rail (thousand tonnes)	1 274
Profit and loss account (thousands roubles)	
– revenues from sales	5 679 186
– total - domestic market	2 681 675
– total - export	2 997 510
– cost of goods sold	3 399 226
– gross profit	2 279 959
Direct variable costs (thousand roubles)	2 339 691
– Drilling and blasting	305 424
– stripping	925 205
– production	160 121
– enrichment	349 740
– MET	330 174
– coal storage, crushing and loading at the open pit	62 137
– transportation of products to the railway station warehouse	206 889
Indirect variable costs (thousand roubles)	78 507
Costs of organising shipments (thousand roubles)	47 461
– locomotive hire	14 753
– other costs (feeding, cleaning wagons, etc.)	32 708
Expenses for support of shipments (thousand roubles)	31 046
– international certification	31 046
Marginal profit (thousand roubles)	3 260 988
Indirect fixed costs (thousand roubles)	1 538 258
Total production costs (thousand roubles)	1 059 535
– maintenance of railway infrastructure	25 966
– maintenance of roads	156 170
– maintenance of public utilities	168 254
– property tax	88 029
– general production	621 115
Other operating expenses (thousand roubles)	144 694
– storage and transport to the railway station	144 694
Administrative and management expenses (thousand roubles)	334 029
– for reference: depreciation included in cost	411 241
EBITDA (thousand roubles)	2 133 971
Cash at the beginning of the period (thousand roubles)	316 324
Cash and cash equivalents at the end of the period (thousand roubles)	1 050 854
Financial activities (thousand roubles)	5 347 321
– receipt of credit funds CA 0051/21	4 012 228
– receipt of credit funds CA 0758/21	1 335 093
– loans received from participants	–
Operating activities (thousand roubles)	7 524 220
– Other revenue	–
– Revenue from sales	5 679 186
– Cash received on deposits	405 434
– VAT refund - operating expenses	188 810
– VAT refund - investments	1 228 032
– VAT refund - leasing	22 757
Total revenues (thousand roubles)	12 871 541
Financial activities (thousand roubles)	1 838 637
Interest payments (thousand roubles)	1 278 637
– payment of interest on participants' loans	183 662
Debt payment (thousand roubles)	560 000
Operating activities (thousand roubles)	4 286 009
– operating expenses (excluding VAT)	4 059 299
– adjustment for royalties paid in advance	74 844
– VAT - operating expenses	301 555
Investment activity (thousand roubles)	6 012 363
– investment activities	3 871 556
– investment activities – technology	1 335 093
– leasing and replenishment of collateral account	805 714
Total disposal (thousand roubles)	12 137 010

Source: compiled by the author.

Further research into the impact of digital twins on mining operations will contribute to the spread of this technology and the development of the industry. As mining, and coal in particular, is one of the key sectors of the global economy, the spread of digital twin technology can indirectly affect global economic growth.

It is advisable to continue research and refine the resulting methodology to assess the impact of using digital twin technology on the operational efficiency of mining companies. There are several promising areas of research that can be explored to assess the impact of digital twins on mining companies. These include:

1) taking into account not only changes in the productivity of the equipment, but also changes in external parameters affecting its productivity, such as transport distance, weight of rock, etc. As mentioned earlier, in addition to predictive maintenance to reduce downtime, the digital twin can optimise transport routes. Such a study would make it possible to clarify the calculated specific coefficients and increase the accuracy of the assessment of the impact of a digital twin on a coal mining company;

2) expanding the sample of experts from coal mining companies, both Russian and international. Such an approach would provide a more accurate estimate of the expected impact of the digital twin on coal mining companies, and may also identify other business processes that have a significant impact on the operational efficiency of a coal mining company. In particular, the study would make it possible to clarify the calculation method and introduce regional coefficients both within the Russian Federation, depending on the deposit and quality of the coal, and by country;

3) as different seams contain different grades of coal, they have different washability characteristics, such as

Table 10
Comparison of the results obtained for the period from the second quarter of 2022 to the first quarter of 2023

Variable	Without digital twin	Expected outcome of implementing a digital twin	Actual result of implementing a digital twin
Stripping ratio	5	5	5
Volume of overburden (thousand roubles)	8040	8700	8522
Coal extraction (thousand roubles)	1608	1740	1704
Coal sales (thousand roubles)	1093	1274	1227
Average FCA price (thousand roubles)	59	59	59
Yield of sold coal after enrichment (%)	68	73	72
Dollar exchange rate (RUB/USD)	75	75	75
Rail transport of coal (thousand rubles)	1093	1274	1227
Physical indicators at the end of the period			
Performance ratio of mining equipment (%)	0.8	0.884	0.86
Yield of marketable product after enrichment (%)	0.68	0.732	72
Coefficient of performance of the dump trucks transporting the coal from the open-cast mine to the railway station stockyard	0.72	0.774	0.763
Number of SHACMAN travels 38 tonnes per day	4	5	5
Direct variable costs (thousand roubles)			
Drilling and blasting (thousand roubles)	257542	305424	293083
– stripping	793768	925205	894252
– production	147581	160121	154225
– enrichment	323208	349740	342600
– MET	285841	330174	318748
– coal storage, crushing and loading at the open pit	53583	62137	60281
– transportation of products to the railway station warehouse	166803	206889	196420
EBITDA (thousand roubles)	1662141	2133971	2009158
Cash balance at the end of the period (thousand rubles)	457490	1050854	898022
Cost of 1 tonne of commercial products (thousand roubles)	39	37	38

Source: compiled by the author.

Table 11
Deviations in natural indicators (%)

Variables	Expected outcome of implementing a digital twin	Actual result of implementing a digital twin	Deviation from natural indicators
Line-to-line performance ratio of mining equipment	88.4	86.0	–3.0
Percentage of marketable product yield after enrichment	73.2	72.0	–2.0
Coefficient of performance of dump trucks transporting coal from the stockyard at the open-cast mine to the stockyard at the railway station.	77.4	76.3	–1.0
Number of SHACMAN trips 38 tonnes per day	5	5	0

Source: compiled by the author.

ash content and Y-Y. The proposed studies would make it possible to clarify the expected yield coefficient of washed coal, which is used to assess the effectiveness of introducing a digital twin in washing plants;

4) taking into account the influencing factors for better planning of section development and geological exploration. As mentioned earlier, digital twins are used for production planning and exploration, among other things. Thanks to the work of the digital twin, it is possible to optimise the formation of edges and the extraction of coal seams, which will lead to a reduction in the coefficient. This process is not directly related to the operational efficiency of a coal mine, but can have an indirect impact on it by optimising the stripping ratio: the lower the stripping ratio, the more coal can be extracted while maintaining the current productivity of the specialised equipment;

5) considering the impact of improved industrial safety on the plant. Reducing the risk of incidents and coal losses at various stages of the production process can lead to increased productivity. Improving safety also has an indirect impact on operational efficiency, as it reduces the risk of breakdowns, losses and incidents that can cause operational downtime;

6) analysing the implementation of technologies for the release of pollutants such as greenhouse gases, waste disposal, etc. This process has no direct impact on operations, but can reduce the risk of being fined for pollution;

7) training and staff development. Research can be conducted to determine the impact of digital twins on staff training and development. This can be done by analysing the training needs of the workforce and the effectiveness of training programmes. Such a study can take into account the time required to train staff to use the digital twin effectively, and assess productivity improvements;

8) reducing payroll expenses by optimising administrative business processes, which will have a direct impact on operational efficiency.

In addition to these areas of research, focused on the formation of additional specific coefficients and the clarification of those used in the current methodology, it is necessary to pay attention to the developed methodology for assessing the impact of the use of digital twin technology on the operational efficiency of mining companies. This involves modelling the impact of the introduction of digital twins.

Future directions for research into the impact of digital twins on the operational efficiency of mining companies could also focus on stock optimisation. This would make it possible to identify the impact on stock turnover and optimise the fixed costs associated with its maintenance, which could potentially affect the operational efficiency of the business as a whole.

In order to clarify the developed method for assessing the impact of the use of digital twin technology on the operational efficiency of mining companies, it is advisable to consider more detailed natural indicators that take into account the individual real characteristics of the equipment and the conclusions of a technical audit on them.

The methodology developed to assess the impact of using digital twin technology on the operational efficiency of mining companies can be openly applied to other mining companies with similar mining technology, such as those involved in the extraction of gold, manganese, ilmenite, etc.

A promising area of research for this method of assessing the impact of digital twin technology on mining operations is to examine the impact of digital twins on underground mining assets. The digital mine concept is relatively popular among mining companies, but the production processes used in the proposed methodology may not be key to underground mining.

Thus, the proposed method for assessing the impact of using digital twin technology on mining companies has the potential for a wide range of applications and leaves ample room for further research and refinement. Each of the subsequent studies will extend and clarify the proposed approach, but will not affect it conceptually, only complement it.

One of the key directions for further research and refinement of the methodology for assessing the impact of using a digital twin on the operational efficiency of a mining company is to identify indirect factors and risk mitigating factors to complement the developed methodology for assessing the impact of using digital twin technology on the operational efficiency of mining companies.

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