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Digital modelling technologies in the mining industry: Effectiveness and prospects of digitalisation of open-pit mining enterprises

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Abstract. Due to the rapid development of the mining industry and the need to increase its competitiveness, digital modelling technologies for open-pit mining enterprises become a relevant and important direction of research. The aim of this study is to analyse integrated digital models for optimising open-pit mining enterprises, aimed at increasing productivity, ensuring safety, and reducing environmental impact. Among the methods used, it is worth mentioning the analytical method, classification method, functional method, statistical method, synthesis method, and others. During the research, an analysis of integrated digital models for optimising the operation of open-pit mining enterprises was conducted. The implementation of integrated digital models in mining enterprises has led to a significant increase in the level of resource extraction productivity, providing a more efficient organisation of work processes. Improvement in the safety system has also been identified, where these models allowed for timely detection and management of potential risks. In addition, the application of digital modelling technologies has contributed to a significant reduction in negative impact on the natural environment, implementing more environmentally sustainable methods of resource extraction and processing. The integration of digital technologies has allowed optimising work processes, making them more efficient and resilient. The study also emphasises the importance of using digital models in the context of predictive analysis and decision-making. The overall conclusion is that

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digital modelling technologies are a key tool for achieving optimal functioning of modern mining enterprises. A detailed study of modern optimisation methods for mining enterprises will allow optimising work processes, increasing efficiency, and reducing negative environmental impact

Keywords: competitiveness; impact on the environment; work processes; strategy; modelling; digitisation

INTRODUCTION

Studying digital modelling technologies in the mining industry holds significant importance in the modern world. With the rapid growth of the mining sector and the constant pursuit of increased competitiveness, the integration of digital models becomes an integral part of optimising open-pit mining enterprises. The implementation of these technologies leads to a substantial increase in productivity in the mining sector. This is achieved by refining extraction processes and resource management through digital models, which allows for more efficient resource utilisation and cost reduction. Digital modelling technologies help avoid excessive resource use, optimise energy efficiency, and minimise emissions of harmful substances. Examples of technology use include drone utilisation for ore deposit monitoring, risk prediction and process optimisation through artificial intelligence, and virtual reality for personnel training, among others. Thus, integrating digital models into the mining industry serves not only as a means of achieving economic efficiency but also as a key element of sustainable development, contributing to the preservation of natural resources and environmental resilience.

The research issue lies in the fact that mining enterprises face challenges of rapid industry development and the need to enhance competitiveness. The negative impact of mining on the environment and workplace safety instability are pressing issues. The absence of optimal strategies and effective use of digital modelling technologies may limit industry development and lead to adverse environmental consequences. However, exploring this issue can identify ways to optimise work processes, increase efficiency, and reduce environmental impact, critical for the sustainable development of the mining industry.

Findings from research by O. Denysiuk & A. Panasiuk (2023) indicate that implementing digital modelling technologies in the mining industry not only enhances productivity but also enables more effective risk management and ensures workplace safety. However, it's important to note that the research does not address potential challenges and limitations that may arise from implementing digital modelling technologies in the mining industry. The work by O. Medvedeva *et al.* (2023) highlights key aspects of environmental sustainability achievable through using digital models to optimise mining enterprises' impact on the environment. Nevertheless, the study does not focus on the social interaction aspects and the impact of digital technology implementation on miners and local communities.

According to research by M. Adamenko *et al.* (2021), which focuses on developing integrated digital models as a strategic tool for enhancing mining enterprises' competitiveness, it's important to consider adaptation strategies and potential difficulties in implementing integrated digital models in various mining enterprise contexts. Researchers A. Burkovskaya & Yu. Syzonenko (2023) discuss optimising work processes and determining effective methods for implementing digital technologies in mining enterprises. However, their work lacks attention to the significant potential for developing and improving personnel management systems in mining enterprises through digital technologies.

The study of M. Nazarenko (2021) emphasises the importance of considering various methods in developing and implementing digital models for optimising mining processes. However, the research does not explore effective implementation strategies and personnel training regarding digital model use. B.I. Yatsikovsky & G.S. Golybka (2022) raise the critical issue of the interaction of digital technologies with various types of mining resources and their potential synergy to enhance overall productivity and efficiency. However, the study does not consider potential risks and challenges associated with the synergy of digital technologies with older, traditional resource extraction methods.

The aim of the research was to provide specific practical recommendations for implementing digital technologies in mining enterprises in the context of contemporary technological development.

MATERIALS AND METHODS

The analytical method helped in thorough examination of the initial data and identification of key parameters influencing the effectiveness of digitisation in mining enterprises. As a result of this study, optimal strategies for implementing digital technologies were identified, which would contribute to increased productivity and sustainable development of the mining industry. The analytical method proved to be an effective tool for considering complex relationships in the field of digitisation of mining enterprises and developing optimal implementation strategies.

Deep analyses were conducted using the statistical method to assess the effectiveness of implementing digital technologies in mining enterprises. This method allowed for collecting and processing large volumes of data to determine statistically significant trends and dependencies. Research results from the statistical method provided detailed indicators of

digitisation effectiveness, particularly regarding increased productivity, risk reduction, and cost optimisation. This statistical study serves as the basis for a comprehensive assessment of the impact of digital technologies on mining enterprises and facilitates the development of well-founded strategies for further enhancing digital transformation in this sector.

By applying the functional method, key functions and roles of digital technologies in the mining industry were identified. This method enabled a detailed examination of how digital innovations could optimise production processes, improve monitoring systems, and risk management in mining enterprises. Based on the acquired data, strategies for implementing digital technologies were developed, which maximally consider the functional needs of the industry and contribute to achieving optimal results in the context of technological advancements and global challenges in the mining sector. The functional method allowed for systematising and determining the role of digital technologies as an effective tool for achieving strategic goals of mining enterprises.

The deductive method helped in determining the basic principles underlying the effective implementation of digitisation in the mining industry. By studying general digitisation principles and existing theoretical concepts, key aspects influencing the success of this process in the resource extraction industry were identified. The deductive approach established connections between theoretical concepts and specific requirements of digital transformation in mining enterprises. This method served as the foundation for developing implementation strategies oriented towards achieving maximum efficiency and compliance with theoretical principles of digitisation in the context of the mining industry.

Through the synthesis method, diverse components and aspects of digitisation in the mining sector were combined to create a comprehensive and integrated model. This approach allowed for the integration of various technologies, methods, and strategies into a unified system aimed at optimising the functioning of mining enterprises. Synthesis proved to be an effective tool for creating a harmonious and interactive digital environment covering all aspects of production and management. The results of the synthesis method serve as the basis for developing integrated digital models that contribute to increasing productivity, efficiency, and resilience of mining enterprises in the modern digital landscape.

The classification method helped in organising various aspects of digitisation in mining enterprises by identifying key categories and types of technological solutions. By studying different approaches to digital transformation in the mining industry, commonalities, and differences between various strategies were identified. This method facilitated the categorisation of digital initiatives based on their key characteristics and functions. Such an approach contributes to the development of individual strategies for implementing digital technologies for different classes of mining enterprises, ensuring consideration of their specific needs and conditions.

RESULTS

In design institutes, digital systems can be used to address various tasks related to planning and designing open-pit mining operations. These systems feature diverse tools and functions that allow mining engineers to create and analyse complex geological models, assess economic feasibility, and plan work at the extraction site. One of the main advantages of these digital systems is their ability to create and enhance geospatial information support. This support can be used to create detailed maps and plans of mining areas, including horisontal plans that can be automatically generated in interactive mode. In addition to geospatial information, these digital systems can also be used for modelling and designing multi-variant quarry spaces, taking into account a wide range of techno-economic data (Kunytska *et al.*, 2023). Digital modelling technologies in the mining industry play a key role in increasing the efficiency and competitiveness of open-pit mining enterprises. These technologies enable the resolution of complex management, safety, and production efficiency tasks.

Ukraine, rich in natural resources including minerals, has significant potential for the development of the mining industry. Zhytomyr region, located in the northwestern part of Ukraine, is one of the regions where open-pit mining enterprises play an important role in economic development and providing employment opportunities. Zhytomyr region is renowned for its geological diversity and the presence of valuable minerals. Ores containing valuable metals as well as construction materials such as limestone and clay are mined in this region. Geological reserves create favourable conditions for the development of open-pit mining enterprises. Modern technologies are used for the detection, extraction, and processing of minerals in this region (Avramchuk, 2021).

As of the end of 2023, the Golovinske deposit of labradorite in the Chernyahivsky district of Zhytomyr region actively employs advanced technologies at all stages of stone extraction and processing. Its development history spans over a century, starting in 1894 with the industrial development of decorative and facing stone. In the 1980s, the deposit underwent a reassessment of reserves and modernisation to meet new standards and technological developments. Additional licensing areas within the deposit, namely North and South, were allocated in 2018, indicating ongoing development and expansion. Geological exploration technologies are used to accurately determine the reserves of labradorite, while modern drilling machines and specialised equipment ensure efficient extraction of

blocks. Automation systems are used for processing and cutting blocks into facing products, ensuring high quality. The modernisation and expansion encompass the allocation of new licensing areas and the application of digital technologies for monitoring and process management. The Golovinske deposit actively utilises advanced tools and methods to achieve efficiency and high product quality, indicating its confident course towards sustainable development (Golovinske deposit, n.d.).

The Omelyanivske deposit of granite employs advanced technologies for efficient extraction and processing of granite stone. Their technological scheme includes modern drilling machines for precise extraction, specialised equipment for block processing, lifting machines for moving large blocks, and transport for their transportation. The machinery and equipment fleet includes automated cutting and polishing systems, as well as transport vehicles for logistical operations. Qualified permanent and shift personnel effectively utilise machinery and control production. Plans for the future may involve the implementation of even more efficient technologies, such as artificial intelligence (AI) for process optimisation, environmentally friendly technologies to reduce environmental impact, and the expansion of automated systems to increase productivity. Continuous modernisation of machinery and equipment may also be part of the plans to achieve greater competitiveness in the market (Omelyanivske deposit, n.d.).

Implementation of automated systems, remote monitoring, and other digital solutions enhances the efficiency of mining processes and ensures worker safety. Mining activities in the region significantly impact the economy and provide new job opportunities for the local population. Revenues from mineral extraction contribute to infrastructure development and social projects, improving the quality of life for residents of the region. An important aspect of open-pit mining enterprises' activities is their social responsibility. Many companies implement social programs and environmental initiatives aimed at preserving nature and improving living conditions for local residents. Despite all the positive aspects, open-pit mining enterprises also face challenges related to ecology and resource management (Marimuthu *et al.*, 2021). It is important to improve technologies and implement innovations to reduce negative environmental impact.

Building sands, pyrophyllite shales, large reserves of gabbro, granite, labradorite, and marble represent valuable minerals in this region. Deposits of rare earth elements such as vanadium, scandium, hafnium, and thorium are in high demand on the international market. The region has nine major deposits (Fig. 1). The Irshansk titanium ore district exploits titanium oxide, known as ilmenite. Among semi-precious stones, the region extracts beryl, topaz, and quartz (Mineral resources of Zhytomyr region, n.d.).

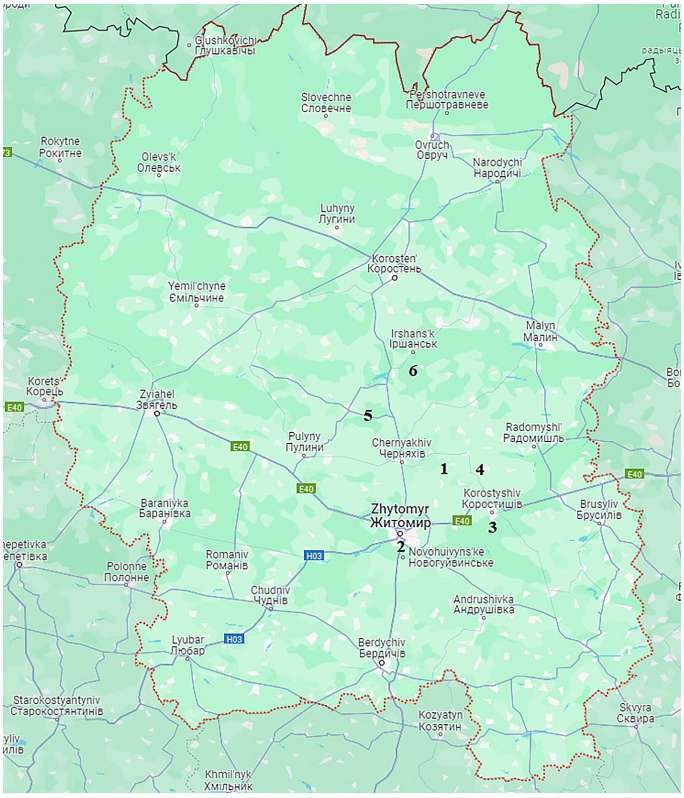

Figure 1. The largest mineral deposits located in the Zhytomyr region
Notes: 1 – Golovinske deposit of labradorite; 2 – Omelyanivske deposit of granite; 3 – Korosten granite deposit; 4 – Korostyshiv granite deposit; 5 – Leznikivske deposit of granite; 6 – Irshansk titanium ore district
Source: compiled by the authors

One of the promising directions in the mining industry is the implementation of autonomous transport vehicles and drilling rigs. Automated systems can accelerate extraction and reduce labour costs, as well as mitigate risks for workers in hazardous conditions. Autonomous transport vehicles, such as drones and unmanned vehicles, can be used for monitoring and surveying the area, identifying extraction sites, and transporting materials. This reduces transportation time and costs while ensuring precision and efficiency in process management. Drilling rigs with automated systems can accurately determine drilling locations, optimise angles and depths of wells, leading to increased productivity and cost reduction.

Monitoring and control systems play a crucial role in ensuring safety and efficiency in the mining industry. The use of modern technologies such as sensors, Internet of Things (IoT) technologies, and remote monitoring systems allows real-time monitoring of equipment parameters and working conditions. IoT systems enable the collection and analysis of data from equipment, facilitating the timely detection of potential issues and avoidance of accidents. Sensors measure various parameters such as temperature, pressure, and humidity, aiding in maintaining optimal conditions for equipment operation. The use of remote monitoring systems allows operators to receive real-time information about the equipment's status and remotely control its operation. This ensures prompt response to any malfunctions or changes in production processes. The implementation of autonomous transport vehicles, automated drilling rigs, and monitoring systems allows for increased efficiency and competitiveness of the extraction process, while simultaneously ensuring optimal working conditions and worker safety.

Digital transformation is a key factor in the modern development of the mining industry, where the use of advanced technologies can improve productivity, safety, and environmental efficiency (Feroz *et al.*, 2021). The process of digital transformation goes through several stages, including automation, digitisation, and the transformation itself (Fig. 2).

Figure 2. Development process of digital transformation of a mining enterprise
Source: compiled by the authors

In the first stage, the mining enterprise implements automation to optimise specific processes and tasks. This may involve the use of automated production systems, automated drilling rigs, intelligent transport vehicles, and monitoring systems. As a result of automation, the enterprise achieves increased efficiency, reduced labour costs, and minimisation of risks for workers. However, this is only the initial step in the adoption of digital technologies. In the second stage, the mining enterprise transitions to broader use of digital technologies, which includes converting analogue information into digital format. The use of sensors, IoT technologies, data analytics, and cloud services allows for the collection and processing of large volumes of information in real-time. Digitisation enables the enterprise to gain a deeper understanding of its operations, react to changes in real-time, and improve decision-making strategies. The final stage is digital transformation, where the mining enterprise changes its philosophy, business model, and culture, using advanced digital technologies. This includes the adoption of artificial intelligence (AI), blockchain technologies, big data analytics, and other innovations. Digital transformation enables the enterprise to move from reactive management to forecasting and strategic planning. It also improves interaction with customers, ensures sustainability, and addresses environmental challenges.

The evolution of digital transformation in the mining industry is a process that reflects the transition from automation to deep digital transformation. Each stage aims to improve efficiency, ensure safety, and environmental responsibility, making mining enterprises more competitive and resilient in the modern world of technology. In the modern world of technology, virtual and augmented realities (VR/AR) become integral parts of the industry, especially in resource extraction. One of the key applications of VR/AR in the mining sector is the use of virtual environments for training operators and personnel. Virtual simulators allow for the creation of realistic scenarios where personnel can learn to work efficiently and safely with equipment. This is particularly relevant in cases where work requires a high level of skill and safety, such as operating heavy machinery or robots in extraction sites. Virtual simulations also allow personnel to adapt to unforeseen situations and emergencies, making training more realistic and effective, leading to improved employee readiness and risk reduction.

VR/AR is also widely used to optimise design and planning processes in the mining industry. Virtual environments allow engineers and designers to interact with extraction objects and examine them under real conditions. Work planning may include the use of AR for overlaying virtual models onto real objects, allowing for precise marking of work areas, equipment placement, and infrastructure layout. This approach improves planning efficiency and reduces errors in project implementation. The use of VR/AR in the mining industry not only ensures safety and high levels of personnel training,

but also greatly facilitates project planning and design (Xie *et al.*, 2022). These technologies bring innovation to the industry, contributing to its development and increasing overall productivity. AI and machine learning (ML) address a wide range of tasks in the industrial sector, including resource extraction (Sircar *et al.*, 2021).

The use of ML algorithms enables the analysis of large volumes of data to forecast various parameters in the extraction field. AI systems can analyse data on extraction, energy consumption, and other key indicators to provide accurate and predictive results. For example, algorithms can forecast extraction volumes based on historical data, climatic conditions, and equipment technical parameters. This allows companies to plan production processes, optimise resource utilisation, and reduce costs. The implementation of visual surveillance and object recognition systems ensures a high level of safety and efficiency at extraction sites. AI systems can recognise objects, detect anomalies, and take action in real-time. For example, recognition systems can detect hazardous situations, such as gas leaks or transportation accidents, and send automatic signals for evacuation or other safety measures. The use of AI and ML in resource extraction contributes to increased productivity and provides significant advantages in forecasting and labour safety (Waltersmann *et al.*, 2021). These technologies open up new opportunities for efficient resource utilisation and industrial process optimisation, making a significant contribution to the modern industry. Digital technologies play a crucial role in improving processes and optimising management across various sectors of industry.

The application of blockchain technology in supply chains is intended to enhance transparency and trust in this crucial aspect of industry. The Blockchain enables the creation of a continuous and immutable registry of transactions that can be easily tracked and verified. Through blockchain, accuracy, and reliability of information regarding the sources of resources, their movement, and processing at various stages of the supply chain can be ensured. This provides parties with the ability to verify conditions of extraction, storage, and transportation, thereby contributing to the improvement of product quality and safety.

The use of digital technologies for automating the processing and storage of documentation is another important part of digital transformation. Electronic document management systems replace traditional paper-based processes with efficient and environmentally friendly solutions. These systems automate the processes of document creation, processing, signing, and storage, ensuring their availability, integrity, and security. This reduces time, costs, and the likelihood of errors associated with manual operations. Digital technologies make a significant contribution to modern industry, particularly in the resource extraction sector (Calvão & Archer, 2021). The use of blockchain for supply chains and electronic document management systems contributes to enhancing transparency, security, and efficiency in various aspects of industrial processes. The implementation of digital solutions in resource extraction allows for the efficient use of energy and water while reducing emissions into the atmosphere and water bodies. The use of modern technologies for monitoring and controlling processes enables companies to accurately regulate resource consumption while considering production needs and environmental standards. For example, the use of sensors and IoT technologies allows for real-time monitoring and optimisation of energy usage in equipment. Data analysis also helps identify effective ways to reduce costs and environmental impact.

The use of models to forecast the ecological consequences of mining operations is a key step in ensuring sustainable development. These models allow scientists and engineers to understand the potential impact of actions on the natural environment. Developing strategies to mitigate negative environmental impacts is based on modelling results. These strategies may include implementing technologies for wastewater treatment, implementing measures to restore soil fertility, and using environmentally friendly mining methods. The introduction of digital technologies in the mining sector promotes more efficient resource utilisation and reduces negative environmental impact. Combining optimisation and modelling of environmental consequences makes the industry more sustainable and responsible towards nature (Xiong *et al.*, 2022). Digital modelling technologies can significantly increase the productivity and resilience of mining enterprises while reducing their environmental impacts, creating more efficient and environmentally sustainable working conditions.

DISCUSSION

In the modern world, open-pit mining enterprises are taking the forefront of digital transformation, implementing new modelling technologies to optimise and enhance production processes. This trend creates new opportunities and challenges for the industry that should be carefully considered. Digital modelling technologies allow miners to precisely calculate and forecast mining processes. The use of virtual models enables the optimisation of open-pit mining operations, managing extraction, resources, and minimising time and resource losses. Digital technologies facilitate the implementation of automation and robotics in open-pit mining enterprises. The use of drones, autonomous vehicles, and other automated systems simplifies and accelerates production processes, reducing labour costs and increasing safety. Digital technologies enable more efficient use of natural resources and minimise negative environmental impact. Modelling allows for deeper analysis of energy, water, and other resource usage, contributing to the creation of more environmentally friendly and sustainable mining activities.

The growth of digitisation demands new skills and competencies from workers in the mining industry. Ensuring cybersecurity and compliance with standards are critical tasks. The implementation of digital technologies may change the employment profile and require retraining of workers. Simultaneously, this may create new opportunities for development and skill enhancement. Digital modelling technologies open new horizons for open-pit mining enterprises. Their efficiency, contribution to sustainable development, and increased worker safety make this digital transformation crucial for the future of the mining industry. However, it is important to manage this process wisely, considering social, ethical, and environmental aspects, to achieve a balance between innovation and sustainability.

According to recent research by J. Duarte *et al*. (2021), the digitisation of open-pit mining operations is marked by significant advantages, particularly in the implementation of a new approach to monitoring and controlling rock fragmentation. The use of advanced digital technologies enables precise and efficient tracking of rock fragmentation processes, defining the direct importance of digital monitoring in mining. One key advantage is the use of modern sensors and IoT technologies for continuous real-time monitoring of mining parameters. This provides operators and engineers with access to real-time data on fragmentation, allowing timely responses to any changes in rock conditions. The use of digital systems also facilitates automated data collection and analysis, ultimately improving the accuracy and timeliness of decision-making. These findings align with the themes presented in the previous section. An important aspect of digitisation in this context is the implementation of AI technologies for forecasting fragmentation implications and optimising material removal processes. This allows not only reacting to current conditions but also planning future operations based on trends and historical data. This new approach to monitoring and controlling rock fragmentation ensures high levels of efficiency, safety, and stability in mining operations.

One can refer to the definition by G. Wang (2022) that the new technological progress in coal exploration is characterised by significant achievements, yet certain problems arise that require attention and solutions. One key advantage is the use of advanced geoinformation systems and modern satellite probing technologies for accurately determining coal deposit locations. This ensures high accuracy in determining the locations of coal reserves, allowing for effective planning of extraction and optimisation of work processes. However, against the backdrop of technological progress, environmental and social problems arise. Coal mining is often associated with a significant impact on the environment and the health of local residents. Air, water, and soil pollution, gas emissions, as well as ecosystem degradation, can have serious consequences. Additionally, social aspects such as preserving the health and safety of workers, adequate living conditions for local populations, are necessary requirements in the development of the coal industry. It is worth noting that these mentioned problems require a comprehensive approach and the search for innovative solutions to balance technological development with environmental preservation and socio-economic well-being in coal regions.

Researchers P.V. Hartlieb-Wallthor *et al*. (2022) have identified that sustainable intelligent mineral extraction defines the modern approach to mining, focusing on ensuring safety, economic efficiency, environmental cleanliness, and digital enhancement. One of the key characteristics of this approach is the application of advanced technologies and intelligent systems to enhance worker safety in mining sites. Monitoring and forecasting systems help prevent accidents and incidents, while artificial intelligence can analyse data to anticipate potential risks. Economic efficiency is ensured through optimisation of extraction processes, use of autonomous technical means, and improved resource management. Digital technologies, such as blockchain, can enhance the transparency and reliability of supply chains, crucial for the sustainable economic activities of mining enterprises. The environmental cleanliness of sustainable intelligent extraction is determined by the use of environmentally friendly technologies, implementation of measures for restoring natural resources, and minimisation of emissions. This includes the adoption of energy-efficient solutions and the use of renewable energy sources. These results confirm the aforementioned research, as sustainable intelligent mineral extraction promotes the harmonious combination of industrial development with nature preservation and improvement of the quality of life for communities involved in mining activities.

Researchers Q. Qi *et al.* (2021) demonstrated in their work that the use of technologies and tools for Digital Twins is marked by revolutionary capabilities in many fields – from industry and infrastructure to science and medicine. A digital twin is a virtual model of a real object or system that reflects its state, parameters, and interaction with the surrounding environment in real-time. In industry, digital twins can be used for monitoring and managing equipment, predicting potential breakdowns, optimising production processes, and increasing manufacturing efficiency. In infrastructure, this may involve creating virtual models of cities to manage traffic, water supply, and other municipal systems. However, along with the benefits, there are also challenges. Ensuring high accuracy and truthfulness of data, ensuring cybersecurity, and addressing confidentiality issues are key tasks in the use of digital twins. It is also important to consider the cost of implementation and maintenance of such technologies. With this view, one can

agree, more specifically, that governments, businesses, and scientific sectors should work together to develop standards, regulations, and ethical norms to ensure successful integration of digital twins into various spheres and make them safe and beneficial for society.

As noted by Y. Uteshov *et al*. (2021), the use of digitisation and advanced analytics in the field of designing and developing solid mineral deposits opens up wide opportunities for improving process efficiency. One of the key advantages is the use of digital twins of mining objects, which virtualise the entire geological structure and resource locations. This allows geologists and engineers to conduct more precise modelling and analysis of potential deposits, contributing to the study of geological conditions and optimisation of extraction design. Advanced analytics involves the use of intelligent algorithms and AI to process large volumes of data collected during geological surveys and drilling. This contributes to improving forecasts regarding ore presence, depth of mineralisation, and other important parameters that determine the profitability of deposit development. Additionally, digital technologies enable the implementation of real-time monitoring systems on mining objects. This provides a continuous flow of data on equipment conditions, ore reserves, and other factors, facilitating prompt response to changes in production processes. Analysing the results and conclusions obtained, it can be concluded that digitisation and advanced analytics in the mining industry create prospects for improving development strategies and increasing production efficiency, while reducing risks and optimising resource utilisation. Researchers T. Li *et al*. (2022) identified that thematic research on the effectiveness of technological innovations in enterprises is influenced by digital transformation. This process significantly changes approaches to production, management, and customer interaction. One of the main advantages of digital transformation is the ability to quickly integrate cutting-edge technologies, leading to increased innovation within the enterprise. This allows companies to improve the quality of their products and services, as well as to respond more promptly to changes in market conditions.

Technological innovations driven by digital transformation can encompass various areas, including production processes, logistics, marketing, and customer service. Automation of production lines, implementation of AI systems for data analysis, and the use of IoT for equipment monitoring are just a few directions that can improve enterprise productivity. It is worth noting that companies can quickly adopt and adapt to advanced innovations, which becomes a key factor in a changing business environment. This ability to rapidly integrate allows enterprises to leverage the latest technological solutions, leading to increased levels of innovation.

CONCLUSIONS

In the conclusions, it is expedient to emphasise the significance of digital modelling technologies in the mining industry, as well as to identify their potential benefits and prospects for open-pit mining enterprises. For successful implementation of digital technologies into the business model of a mining enterprise, it is necessary to overcome traditional conservative approaches in the mining industry, activate systematic training and skill enhancement of employees, taking into account industry-specific features and organisational-technological aspects of the enterprise. Another important element is the creation of an industry innovation system aimed at intensifying technology transfer.

Digital modelling technologies applied in the mining industry define a new level of efficiency and management of production processes in open-pit mining enterprises. They enable accurate forecasting and optimisation of mining operations, ensuring optimal resource utilisation and maximising production productivity. The efficiency of digital technologies lies in their ability to enhance decision-making quality, minimise risks, and ensure workplace safety. Implementation of automated systems, remote monitoring, and other innovative solutions simplifies tasks and enables flexible response to changing conditions in mining activities. The prospects of digitisation for open-pit mining enterprises include productivity growth, resource loss reduction, increased worker safety, and reduced environmental impact. It is noted that these technologies open up new opportunities for industry development and contribute to its sustainable growth.

Digitisation in the mining industry not only transforms technological processes but also contributes to the formation of the concept of a "green" mining enterprise. This process involves the implementation of environmentally friendly technologies, optimisation of resource use, and reduction of atmospheric emissions, leading to the creation of environmentally safe and economically efficient production. This direction is characterised not only by the use of advanced technologies to increase productivity but also by active implementation of energy-efficient and environmentally friendly solutions. However, it is important to consider challenges such as staff training, ensuring cybersecurity, and addressing social and ethical issues. Overall, digital modelling technologies are a key factor in transforming open-pit mining enterprises into high-tech, productive, and environmentally friendly complexes.

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CONFLICT OF INTEREST

None.

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Цифрові технології моделювання в гірничій індустрії: ефективність та перспективи цифровізації відкритих гірничих підприємств

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Анотація. У зв'язку зі стрімким розвитком гірничої індустрії та необхідністю підвищення її конкурентоспроможності, цифрові технології моделювання відкритих гірничих підприємств стають актуальним і важливим напрямком дослідження. Метою даного дослідження є аналіз інтегрованих цифрових моделей для оптимізації відкритих гірничих підприємств, спрямованих на підвищення продуктивності, забезпечення безпеки та зменшення впливу на навколишнє середовище. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. У ході дослідження був проведений аналіз інтегрованих цифрових моделей для оптимізації функціонування відкритих гірничих підприємств. Впровадження інтегрованих цифрових моделей в гірничі підприємства призвело до значного зростання рівня продуктивності в видобутку ресурсів, забезпечивши ефективнішу організацію робочих процесів. Також виявлено покращення в системі безпеки, де ці моделі дозволили вчасно виявляти та управляти потенційними ризиками. Крім того, застосування цифрових технологій моделювання сприяло значному зменшенню негативного впливу на природне середовище, реалізуючи більш екологічно сталі методи видобутку та обробки ресурсів. Інтеграція цифрових технологій дозволила оптимізувати робочі процеси, роблячи їх більш ефективними та стійкими. Дослідження також підкреслило значення використання цифрових моделей у контексті прогностичного аналізу та прийняття рішень. Загальний висновок полягає в тому, що цифрові технології моделювання є ключовим інструментом для досягнення оптимального функціонування сучасних гірничих підприємств. Детальне вивчення сучасних шляхів оптимізації гірничих підприємств дозволить оптимізувати робочі процеси, підвищить ефективність та зменшувати негативний вплив на довкілля

Ключові слова: конкурентоспроможність; вплив на навколишнє середовище; робочі процеси; стратегія; моделювання; цифровізація