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ISSN 3030-3907

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ISSN 3030-3907

DEVELOPMENT OF A DIGITAL TWIN BASED ON ARTIFICIAL INTELLIGENCE TO INCREASE THE EFFICIENCY OF EXCAVATOR-DUMP TRUCK COMPLEXES IN OPEN PITS

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Annotatsiya. Konchilik sanoatini raqamlashtirish sharoitida ochiq konlarda yuk tashish ishlarining asosiy qismini bajaruvchi ekskavator-avtosamosval majmualari samaradorligini oshirish dolzarb masalalardan biri hisoblanadi. Mavjud dispetcherlik va avtopark boshqaruv tizimlari asosan GPS monitoringi hamda telemetriya ma'lumotlariga tayanganligi sababli ishlab chiqarish jarayonlarini real vaqt rejimida chuqur tahlil qilish va prognozlash imkoniyatlari cheklangan. Shu sababli raqamli egizak texnologiyalari hamda sun'iy intellekt usullarini joriy etish kon transport tizimlarini intellektual boshqarishning istiqbolli yo'nalishi sifatida qaralmoqda. Mazkur maqolada ochiq kon sharoitida ekskavator-avtosamosval majmuasining ishlab chiqarish jarayonlarini real vaqt rejimida monitoring qilish, modellashtirish va tahlil qilish imkonini beruvchi raqamli egizak modeli ishlab chiqilishi ko'rib chiqilgan. Uskunalarning bekor turib qolish vaqtlarini prognozlash, avtosamosvallarni optimal taqsimlash hamda kon transporti ishlarining samaradorligini oshirish maqsadida sun'iy intellekt texnologiyalarini integratsiyalash konsepsiyasi taklif etilgan. Taklif etilayotgan tizimni joriy etish natijasida uskunalarning samarasiz bekor turish vaqtlarini kamaytirish, texnikalardan foydalanish koeffitsientini oshirish hamda kon transport tizimi unumdorligini yaxshilash kutilmoqda.

Kalit so'zlar: raqamli egizak, sun'iy intellekt, ochiq kon, ekskavator-avtosamosval majmuasi, kon transporti, optimallashtirish, dispetcherlik boshqaruvi.

Аннотация. В условиях цифровой трансформации горнодобывающей промышленности повышение эффективности экскаваторно-автосамосвальных комплексов, выполняющих основную часть

ISSN 3030-3907

транспортных операций на открытых горных работах, является одной из актуальных задач. Традиционные системы диспетчеризации и управления парком техники в основном основаны на данных GPS-мониторинга и телеметрии, что ограничивает возможности оперативного анализа и прогнозирования производственных процессов в режиме реального времени. В связи с этим внедрение технологий цифровых двойников и методов искусственного интеллекта рассматривается как перспективное направление интеллектуального управления горнотранспортными системами. В статье рассматривается разработка цифрового двойника экскаваторно-автосамосвального комплекса открытого карьера, обеспечивающего мониторинг, моделирование и анализ производственных процессов в режиме реального времени. Предложена концепция интеграции технологий искусственного интеллекта для прогнозирования простоев оборудования, оптимизации распределения автосамосвалов и повышения эффективности горнотранспортных работ. Ожидаемыми результатами внедрения предлагаемой системы являются снижение непроизводительных простоев оборудования, повышение коэффициента использования техники и увеличение производительности горнотранспортной системы.

Ключевые слова: цифровой двойник, искусственный интеллект, открытые горные работы, экскаваторно-автосамосвальный комплекс, карьерный транспорт, оптимизация, диспетчеризация.

Abstract. In the context of the digital transformation of the mining industry, improving the efficiency of excavator-truck complexes, which perform the majority of open-pit haulage operations, has become increasingly important. Traditional dispatching and fleet management systems are primarily based on GPS monitoring and telemetry data, which limits the possibilities for real-time analysis and forecasting of production processes. Therefore, the implementation of digital twin technologies and artificial intelligence methods is considered a promising approach for the intelligent management of mining transportation systems. This paper considers the development of a digital twin of an excavator-truck complex for an open-pit mine, enabling real-time monitoring, modeling, and analysis of production processes. A concept for integrating artificial intelligence technologies is proposed to predict equipment downtime, optimize truck allocation, and improve the efficiency of mine haulage operations. The expected outcomes of implementing the proposed system include a reduction in unproductive equipment downtime, an increase in equipment utilization rates, and improved productivity of the mining transportation system.

Keywords: digital twin, artificial intelligence, open-pit mining, excavator-truck complex, mine haulage, optimization, dispatching.

ISSN 3030-3907

INTRODUCTION.

The modern development of the mining industry is characterized by the active implementation of digital technologies aimed at improving production efficiency, reducing operating costs, and ensuring the sustainable operation of mining enterprises. In the context of increasing mineral extraction volumes, particular importance is attached to improving the performance of excavator–truck complexes, which represent the primary component of the transportation system in open-pit mining operations [1–6].

The efficiency of excavator–truck complexes directly affects mine productivity, the cost of mineral extraction, and the utilization rate of mining and haulage equipment. At the same time, various factors arise during operation that reduce equipment efficiency, including excavator and haul truck downtime, uneven distribution of transportation resources, deviations from production schedules, and insufficient responsiveness of dispatching decisions.

Currently, many mining enterprises employ dispatching and fleet monitoring systems based on GPS positioning, telemetry, and automated production data collection technologies [7–10]. However, existing systems are mainly focused on monitoring the current state of equipment and do not provide comprehensive forecasting of production processes or intelligent optimization of equipment operation in real time.

One of the most promising directions in the development of digital technologies in the mining industry is the application of the Digital Twin concept, which represents a virtual model of a real production asset operating through continuous data exchange between physical and digital environments. The use of digital twins enables monitoring, simulation, and forecasting of equipment performance, as well as the evaluation of management decisions before their practical implementation.

Additional opportunities for improving the efficiency of mining transportation systems are provided by the application of artificial intelligence methods. Modern machine learning algorithms are capable of analyzing large volumes of production data, identifying operational patterns, predicting equipment downtime, and generating recommendations for the optimal allocation of transportation resources [11–12]. The integration of artificial intelligence and digital twin technologies forms the foundation for the development of next-generation intelligent mine haulage management systems.

The objective of this study is to develop a digital twin of an excavator–truck complex for an open-pit mine and to investigate the potential of artificial intelligence methods for improving the efficiency of mine haulage operations,

ISSN 3030-3907

reducing equipment downtime, and optimizing the utilization of mining transportation equipment [13–15].

Analysis of Existing Research and Technologies

In recent years, the digitalization of the mining industry has become one of the key directions for improving the efficiency of open-pit mining operations. The development of Industrial Internet of Things (IIoT), artificial intelligence, big data analytics, and digital twin technologies has contributed to the creation of intelligent mining management systems that provide a higher level of automation and operational decision-making.

One of the most important components of open-pit mining operations is the excavator–truck complex, which accounts for a significant share of the costs associated with the extraction and transportation of rock mass. The productivity of this complex depends on the coordinated operation of excavators and haul trucks, the condition of haul roads, the effectiveness of dispatching systems, and the ability to respond promptly to changes in production conditions.

To manage mine transportation systems, modern mining enterprises widely employ Fleet Management Systems (FMS) based on GPS navigation, telemetry, and automated data collection technologies. These systems make it possible to track equipment locations, monitor production performance, record equipment downtime, and generate operational reports. Despite their effectiveness in monitoring, most existing FMS solutions do not provide advanced forecasting capabilities or intelligent optimization of haulage processes.

In international mining practice, significant attention has been devoted to the implementation of digital twin technologies. A digital twin is a dynamic virtual representation of a physical asset that is continuously updated using real-time data obtained from operational equipment. In the mining industry, digital twins are applied to simulate equipment performance, predict production indicators, analyze operational scenarios, and improve the quality of management decisions.

ISSN 3030-3907



Fig. 1. Excavator-truck complex in an open-pit mine



Fig. 2. Architecture of the digital twin of the excavator-truck complex

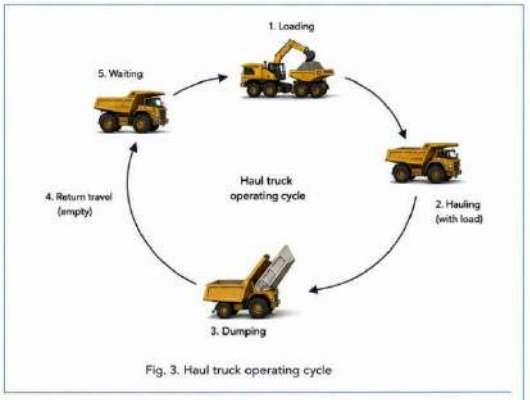


Fig. 3. Haul truck operating cycle

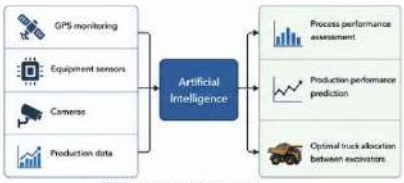


Fig. 4. Use of artificial intelligence for dispatching

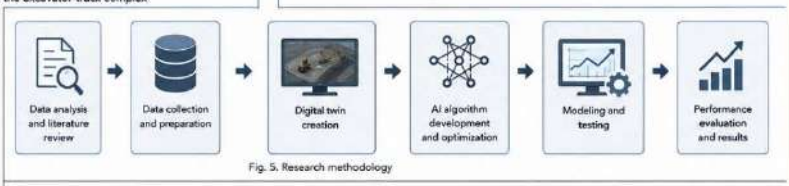


Fig. 5. Research methodology

Table 1 – Comparison of complex operational efficiency

Indicator	Conventional system	System with Digital Twin and AI	Change, %
Excavator downtime, %	18	9	-50
Haul truck downtime, %	22	11	-50
Equipment utilization rate, %	72	85	+18
Complex productivity, %	100	115	+15
Fuel consumption, L/h	100	92	-8



Alongside the development of digital twins, artificial intelligence technologies are increasingly being integrated into mining operations. Machine learning and intelligent data analysis algorithms enable the identification of hidden patterns in production processes, prediction of equipment failures, determination of optimal haulage routes, and minimization of non-productive downtime.



ISSN 3030-3907

A review of existing scientific studies indicates that most research considers digital twins and artificial intelligence as separate technological solutions. However, the comprehensive integration of these technologies for the management of excavator–truck complexes in open-pit mining remains insufficiently explored. Therefore, the development of a digital twin of an excavator–truck complex incorporating artificial intelligence elements represents a relevant scientific and technical challenge aimed at improving the efficiency of mine haulage operations and advancing intelligent mining management systems.

CONCLUSION.

As a result of this study, a concept of a digital twin for an open-pit excavator–truck complex was developed to improve the efficiency of mine haulage operations through the application of artificial intelligence methods. An analysis of modern approaches to mining transportation management systems was conducted, revealing that traditional dispatching systems based on GPS monitoring and telemetry have limited capabilities in terms of production process forecasting and intelligent decision-making.

The proposed digital twin architecture provides continuous real-time collection, processing, and analysis of operational data obtained from mining equipment. The integration of artificial intelligence technologies enables the prediction of equipment downtime, analysis of production performance indicators, and generation of recommendations for the optimal allocation of haul trucks among excavators.

The developed model contributes to reducing non-productive equipment downtime, increasing equipment utilization rates, and improving the organization of mine haulage operations. The simulation results demonstrate that the implementation of a digital twin combined with intelligent control algorithms can reduce equipment waiting times, enhance the productivity of the excavator–truck complex, and ensure more efficient utilization of mining enterprise resources.

The practical significance of the research lies in the possibility of applying the proposed solutions to the development of intelligent management systems for open-pit mining operations within the framework of the Digital Mine and Mining 4.0 concepts. The obtained results may serve as a foundation for the further development of automated dispatching, forecasting, and optimization systems for production processes in mining enterprises.

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ISSN 3030-3907

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