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TECHNOLOGICAL MECHANISMS AND TECHNICAL EFFICIENCY OF OPEN-PIT MINING

Jumabayeva Guljaxan Jaksilikovna
Senior Lecturer, Department of Mining and Metallurgy, Nukus State Technical University

Abstract. This scientific article provides a comprehensive analysis of the modern technological mechanisms for open-pit mining of mineral deposits, their principles of operation, and methods for increasing technical efficiency. The research deeply explores drilling and blasting operations, loading and hauling systems, conveyor technologies, IPCC systems, and digital control and automation processes. It also highlights issues of ensuring geomechanical stability, selective mining, energy efficiency, water resource management, environmental safety, and reclamation. The article substantiates the potential for increasing production efficiency based on modern innovative approaches, big data analysis, digital twin technologies, and the "smart mine" concept. The results obtained are of great importance for the rational use of resources, cost reduction, and ensuring sustainable development in open-pit mining.

Keywords: Mining enterprises, open-pit mining, minerals, technological mechanisms, drilling and blasting processes, excavator efficiency, digital mine project, technical efficiency, mine management mechanism.

Annotatsiya. Ushbu ilmiy maqolada foydali qazilma konlarini ochiq usulda qazib olishning zamonaviy texnologik mexanizmlari, ularning ishlash prinsiplari va texnik samaradorlikni oshirish usullari har tomonlama tahlil qilingan. Tadqiqotda burg‘ilash-portlatish ishlari, yuklash-tashish tizimlari, konveyer texnologiyalari, IPCC tizimlari hamda raqamli boshqaruv va avtomatlashtirish jarayonlari chuqur o‘rganilgan. Shuningdek, geomexanik barqarorlikni ta’minlash, tanlab qazib olish, energiya tejamkorligi, suv resurslarini boshqarish, ekologik xavfsizlik va rekultivatsiya masalalariga ham e’tibor qaratilgan. Maqolada zamonaviy innovatsion yondashuvlar, katta hajmli ma’lumotlar tahlili, raqamli egizak texnologiyalari va “aqlli kon tizimi” konsepsiyasi asosida ishlab chiqarish samaradorligini oshirish imkoniyatlari asoslab berilgan. Olingan natijalar ochiq usulda kon qazishda resurslardan oqilona foydalanish, tannarxni pasaytirish va barqaror rivojlanishni ta’minlash uchun katta ahamiyatga ega.

Kalit so‘zlar: Konchilik korxonalari, ochiq usulda kon qazish, foydali qazilmalar, texnologik mexanizmlar, burg‘ilash-portlatish jarayonlari, ekskavator samaradorligi, raqamli kon loyihasi, texnik samaradorlik, konni boshqarish mexanizmi.

Аннотация. В данной научной статье всесторонне проанализированы современные технологические схемы разработки месторождений полезных

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ископаемых открытым способом, принципы их функционирования и методы повышения технической эффективности. В исследовании глубоко изучены буровзрывные работы, погрузочно-транспортные комплексы, конвейерные технологии, системы ЦПТ (циклично-поточной технологии), а также процессы цифрового управления и автоматизации. Также уделено внимание вопросам обеспечения геомеханической устойчивости, селективной выемки, энергосбережения, управления водными ресурсами, экологической безопасности и рекультивации. В статье обосновываются возможности повышения эффективности производства на основе современных инновационных подходов, анализа больших данных, технологий цифровых двойников и концепции "умного карьера." Полученные результаты имеют большое значение для рационального использования ресурсов при добыче открытым способом, снижения себестоимости и обеспечения устойчивого развития.

Ключевые слова: Горнодобывающие предприятия, разработка открытым способом, полезные ископаемые, технологические схемы, буровзрывные работы, производительность экскаватора, цифровой проект карьера, техническая эффективность, система управления горными работами.

INTRODUCTION.

Open-pit mining of mineral deposits is one of the most widespread and economically efficient sectors of the modern mining industry. This method allows for the extraction of minerals near the Earth's surface in large volumes, with high productivity and at relatively low costs. Open-pit mining technology is a complex, multi-stage process in which all operations, from geological exploration to mine reclamation, are organized within a unified technological system. In this system, the primary role is occupied by technological mechanisms and technical solutions that ensure its effective operation. The extraction process in open-pit mines typically begins with drilling and blasting operations. In this process, the rock mass is drilled using special rigs, explosives are placed, and the rock is fragmented. Modern drilling rigs are distinguished by their high precision, automated control systems, and energy efficiency. Blasting operations are carried out based on computer modeling, which ensures optimal rock fragmentation and minimizes vibration and other adverse effects. In the next stage, the extracted rock mass is transferred to loading and hauling operations. Excavators, loaders, and haul trucks play a key role here. High-capacity hydraulic excavators and electric draglines are characterized by their high productivity. Their technical efficiency is determined by the short duration of their work cycle, great digging depth, and large loading capacity. Additionally, modern loading machines are equipped with automatic control systems that increase safety and precision by reducing the

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human factor. In open-pit mines, the largest share of costs is attributed to transport systems. Therefore, optimizing the transport system is crucial for increasing technical efficiency. Although haul trucks are widely used, conveyor systems and railway transport are also effective in large-scale mines. In recent years, the introduction of autonomous trucks has enabled a reduction in transportation costs, optimization of fuel consumption, and an increase in safety. These technologies operate based on real-time data exchange and serve to ensure continuous control over the production process. Digital technologies and management systems based on mining‘s technical efficiency hold a special place in enhancing the effectiveness of technological mechanisms. Processes such as mine planning, determining the excavation sequence, optimizing transport routes, and forecasting maintenance are carried out using specialized software. This increases production efficiency and reduces excess costs. Furthermore, the condition of the equipment is constantly monitored through sensors and monitoring systems, which helps prevent malfunctions and lower maintenance costs. Energy efficiency is also a crucial indicator in open-pit mines. Modern equipment is designed to provide high productivity while consuming minimal energy. The use of electric vehicles, hybrid engines, and renewable energy sources can lessen the environmental impact and reduce production costs. At the same time, waste recycling and the efficient use of water resources are integral components of the technological system. Another important direction for increasing technical efficiency in open-pit mining is the comprehensive mechanization and automation of production processes[1]. This minimizes human intervention, resulting in increased labor productivity and safety. Innovative approaches, such as remote-controlled equipment, drone surveillance, and geodetic surveys, further enhance the mining process. Moreover, the proper design of the mine's geometry also has a direct impact on technical efficiency. Factors such as the height of excavation benches, slope angles, and the structure of haul roads affect both the efficient operation of machinery and the level of safety. Optimal design solutions make it possible to increase production volumes, reduce losses, and maximize equipment efficiency. In the open-pit mining of mineral deposits, technological mechanisms and technical efficiency are inextricably linked, and the implementation of modern innovations allows for the achievement of significant results in this field. Automation, digitalization, energy efficiency, and the use of advanced technical equipment ensure the sustainable development of the mining industry and increase its economic effectiveness. One of the key directions for further improving open-pit mining processes is the in-depth study and monitoring of geomechanical stability. Ensuring the stability of pit walls directly affects not only safety but also technical and economic efficiency. To predict quarry wall

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displacement and hazardous zones, modern geotechnical monitoring systems are employed, including inclinometers, radar monitoring equipment, and satellite-based interferometric technologies. This serves to prevent accidents and work stoppages, thereby reducing additional costs. Managing the quality of minerals is also particularly important for increasing extraction efficiency. In open-pit mines, ore quality indicators can vary significantly between layers, necessitating the implementation of selective mining technologies. This involves using high-precision geological modeling, real-time analyzers, and GPS-based control systems. As a result, it becomes possible to accurately separate ore from waste rock, which enhances the efficiency of the processing stage and increases overall economic benefit. Managing water-related issues in mines is also a critical component of the technological system. The ingress of groundwater into a mine can negatively affect excavation work; therefore, the proper design of drainage systems and the effective use of dewatering mechanisms are essential. Modern pumping stations are distinguished by their high efficiency and energy conservation. Furthermore, implementing water resource reuse systems is economically beneficial and also ensures environmental sustainability. The digitalization of transport and logistics systems can optimize movement within the mine. Special dispatching systems monitor the movement of all equipment in real-time and efficiently distribute cargo flows. This reduces downtime, lowers fuel consumption, and increases production efficiency. At the same time, regularly improving the technical condition of roads, enhancing pavement quality, and selecting optimal routes also significantly impact the efficiency of the transport system. Waste management and reclamation are also important technological stages in open-pit mining[2]. The disposal of waste rock generated during the excavation process is carried out in specially planned landfills. In this process, environmental requirements are strictly considered, and measures are taken to reduce dust and protect water and soil from contamination. After mining operations are completed, reclamation work is aimed at restoring the area, transforming it into a green zone, and re-establishing the natural balance. By introducing innovative technologies, the production process in open-pit mines can be organized more effectively. This extends the service life of the equipment and prevents unexpected shutdowns. Furthermore, within the "smart mine" concept, all technological processes are managed through a single digital platform, which accelerates decision-making and reduces the human factor. Continuous professional development of personnel is also one of the most important factors in increasing labor productivity. Highly qualified specialists are required to work with modern equipment and software. For this reason, mining enterprises regularly organize training programs, seminars, and practical workshops. This

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ensures the correct and efficient execution of technological processes. To increase economic efficiency, a thorough analysis and optimization of production costs are crucial. It is necessary to develop measures for cost control and the rational use of resources for each technological stage. For instance, significant economic results can be achieved by reducing fuel consumption, making efficient use of spare parts, and implementing energy-saving technologies. At the same time, adherence to the principles of sustainable development is becoming increasingly important in the global mining industry. Minimizing environmental impact, increasing social responsibility, and balancing economic efficiency have become the primary strategic goals of modern mining enterprises. Consequently, open-pit mining is a complex, multi-component, and constantly evolving process in which the integration of technological mechanisms, innovative solutions, and effective management methods enables the achievement of high performance. In the subsequent stages of development for open-pit mining systems, the principle of integrated resource utilization is gaining significance; that is, technologies for the economically viable extraction of associated components alongside the primary mineral are being widely implemented. Such an approach not only increases the overall value of the mine but also reduces the volume of waste and significantly mitigates the negative impact on the environment. In this context, mines that operate in close integration with modern processing plants achieve high efficiency, as the technological properties of the ore are considered during the extraction process itself, and optimal processing regimes are determined[3].



MATERIALS AND METHODS.

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Furthermore, the application of long-term strategic models in mine planning is an important tool for enhancing technical and economic efficiency. Digital mine plans, developed based on three-dimensional geological models, allow for the optimization of extraction sequences, the reduction of mineral losses, and the effective allocation of capital investments. Using these models, various scenarios are tested and the most optimal option is selected, which reduces risks and increases investment attractiveness. Modernizing maintenance systems also plays an important role in ensuring the stable operation of technological processes. Unlike traditional scheduled maintenance, modern mines utilize condition-based and predictive maintenance systems. These systems analyze data collected through sensors to determine the actual technical condition of the equipment and allow for necessary measures to be taken before a malfunction occurs. As a result, equipment reliability is enhanced, repair costs are reduced, and production continuity is ensured. The use of mathematical modeling and operations research methods in optimizing production processes is also becoming increasingly widespread. The challenges of managing complex logistics chains, balancing technical loads, and efficiently allocating time resources are solved using specialized algorithms. This approach minimizes human error and increases the accuracy of managerial decisions, leading to significant economic benefits, especially in large-scale mines[4]. The development of energy infrastructure in open-pit mines is another critical area, with the stability and efficiency of the power supply being key criteria. High-voltage power grids, transformer substations, and electricity distribution systems are being upgraded with modern technologies. In parallel, the use of alternative sources like solar and wind energy enhances the energy independence of mining enterprises and reduces carbon emissions. As part of the digital transformation, "digital twin" technology is also being implemented, creating a virtual model of a real mine where all technological processes can be tested. This allows for the early detection of potential real-world problems, the optimization of production processes, and the acceleration of decision-making. Such a method provides for high-precision forecasting and effective management. Furthermore, improving safety systems in open-pit mines remains a priority. The level of safety in production areas is carefully monitored using modern monitoring tools, video surveillance systems, and automatic alarm devices. Additionally, systematic work is underway to foster a safety culture among employees, ensure strict adherence to occupational safety regulations, and prepare for emergencies. Socio-economic factors also directly impact the efficiency of mining operations. By developing local infrastructure, creating new jobs, and positively influencing the regional economy, mining enterprises contribute to sustainable development. At the same time, effective cooperation

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with local communities and the preservation of ecological balance ensure the long-term success of mining projects. Thus, open-pit mining reveals itself as a complex system that evolves through constant innovation, a scientific approach, and technological progress. High efficiency and global competitiveness in the mining industry are achievable by refining technological mechanisms, ensuring the rational use of resources, and improving management systems. The further development of open-pit mining is linked to the deepening of mining operations, a process in which the increasing complexity of geological and technical conditions demands new technological approaches. In particularly deep quarries, factors such as increased transportation distances, the need to ensure quarry wall stability, and rising energy consumption directly affect efficiency. For this reason, modern mining practices widely implement cyclical-continuous technologies, which integrate traditional transport systems with conveyors, crushing stations, and continuous transport systems. This approach serves to reduce fuel consumption, increase transport speed, and lower overall operational costs. The optimization of drilling and blasting parameters is also becoming increasingly important for enhancing production efficiency. The granulometric composition of rock can be controlled by correctly selecting the explosive composition, optimizing the charging pattern, and applying delayed blasting technologies. This, in turn, increases the efficiency of subsequent loading and crushing processes[5].

RESULTS AND DISCUSSION.

Concurrently, reducing the amount of dust and gas generated by blasting is a crucial factor in ensuring environmental safety. Another important direction is the introduction of in-pit crushing and sorting complexes in mines. With In-Pit Crushing and Conveying (IPCC) systems, the extracted rock mass is crushed directly in the quarry and transported via a conveyor. This technology is considerably more cost-effective and energy-efficient for transporting large volumes over long distances compared to traditional vehicles. Furthermore, IPCC systems mitigate negative environmental impacts by significantly reducing exhaust emissions and noise levels. Time management and the shortening of production cycles are also vital in mining processes. Overall efficiency can be increased by precisely planning the duration of each operation, establishing a coordinated work schedule between equipment, and eliminating redundant operations. To this end, the principles of "lean mining" are being implemented in modern mines to reduce excessive resource consumption and achieve maximum results. In addition, data analytics and big data technologies are opening up new opportunities in the mining industry. By analyzing the large volumes of data collected during the production process, hidden patterns can be identified, and the decision-making process can be conducted on a scientific basis. This helps in the

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efficient use of resources, improves production indicators, and reduces risks. Innovations in materials and equipment manufacturing also have a significant impact on the efficiency of open-pit mines. A new generation of high-strength steels, wear-resistant coatings, and composite materials extends the service life of mining equipment and reduces operational costs. At the same time, equipment based on a modular design allows for rapid repair and component replacement. The implementation of technologies adapted to climatic conditions is also of great importance. Special protection systems and adapted operating modes are used to ensure the stable operation of machinery in conditions of extreme temperatures, strong winds, or heavy precipitation. This ensures the continuity of the production process throughout the year and reduces seasonal losses. Another important factor in increasing economic efficiency in quarries is the implementation of risk management systems. Starting from the design stage, all potential risks are identified, their level of impact is assessed, and mitigation measures are developed. This approach ensures investment security and increases the sustainability of mining operations. As a result, open-pit mining is evolving into a system that incorporates the most advanced achievements of modern science and technology[6]. In this field, opportunities are expanding to achieve high efficiency, reduce production costs, and maintain ecological balance through the continuous improvement of technological mechanisms, the introduction of innovative solutions, and the application of integrated management approaches. Another promising direction for increasing production efficiency in open-pit mines is the optimization of pit boundaries and the scientific determination of the final pit limit. By correctly defining the mine's boundaries, the amount of waste rock to be extracted is reduced, and the recovery rate of minerals is maximized. To this end, optimization methods, such as the Lerch-Grossmann algorithm and modern mine design software, are used to determine the most economically viable pit limits. As a result, an optimal balance between capital and operating expenses is achieved. Furthermore, the synchronization of technological flows within the mine is of great importance. The coordination of drilling, blasting, loading, and hauling operations determines the production rhythm. If a discrepancy arises between these processes, equipment downtime increases and overall efficiency decreases. The introduction of high-precision navigation and positioning systems is also one of the most important technological advancements in open-pit mining. Using GPS and GNSS technologies, the location of mining equipment is determined with centimeter-level accuracy, which increases the precision of excavation work and prevents over-excavation and losses. Such precision yields a significant economic benefit, especially during selective mining processes. Optimizing the ore preparation process at the mine stage also enhances efficiency.

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The quality of raw material entering the processing plant is improved through primary crushing, screening, and moisture control. This, in turn, reduces the energy consumption of subsequent metallurgical processes and increases the efficiency of the entire production chain. At the same time, identifying and eliminating bottlenecks in technological flows allows for the full utilization of production capacity. Reducing problems related to dust and noise in mines also has an indirect effect on technical efficiency. Water spray systems, chemical stabilizers, and enclosed conveyor systems are used for dust suppression. Noise reduction is achieved by improving equipment design and using special protective gear. These measures improve the working environment and increase labor productivity[7]. External elements of the logistics chain also play a critical role in mining. The system for delivering the extracted product to the consumer—that is, processes related to rail, port infrastructure, or processing plants—affects overall efficiency. For this reason, issues of integration with logistics infrastructure are also studied in depth when developing mining projects. Furthermore, improving corporate governance systems at mining enterprises has a significant impact on efficiency. Production results are improved through transparent management, clear KPIs, and effective planning and control systems. This leads to an increase in not only technical but also economic performance indicators.

CONCLUSION.

In conclusion, open-pit mining has become one of the most efficient and technologically advanced sectors of the modern mining industry. Research findings show that it is possible to significantly increase the productivity of mining operations by improving technological mechanisms and by automating and digitalizing production processes. In particular, optimizing transport systems, introducing continuous technologies such as IPCC, developing selective mining, and improving geomechanical control are key factors that ensure technical and economic efficiency. At the same time, the use of energy-efficient technologies, waste reduction, and compliance with environmental requirements ensure the sustainability of mining operations.

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