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Enhancing Energy and Operational Efficiency of Geotechnological Complexes Using Geoinformation Technologies

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Abstract

The development of digitalization and information technology opens up new opportunities to improve the efficiency of solid mineral deposit development. In the mining industry, the greatest potential lies in open-pit mining, which uses high-tech mining and transport equipment, which is currently undergoing a transition from diesel engines to gas-diesel, gas and electric ones. The purpose of this article is to design and develop the scientific and methodological potential of analysis, evaluation and optimization of the functioning of geotechnological complexes at open-pit mines. Realization of the set goal is carried out on the basis of the process approach in management of geotechnological complexes with the use of methodology of the in-depth analysis of factors and interrelations of all subsystems and elements. Scientific and practical novelty of the research lies in the development of simulation models with the main mining transport equipment using electric and diesel engines, but also gas-diesel and gas engines, as well as the development of methodological aspects of complex technical and technological audits of mining enterprises. The developed direction ensures the realization of the existing potential for improving the efficiency of geotechnological complexes, including economic and environmental aspects.

Keywords:

Technical and Technological Audit;
Mining and Transportation Works;
Technological Processes;
Models of Mining and Transport Equipment;
Operating Modes;
Simulation Modeling;
Geotechnological Complex Management.

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1- Introduction

Open-pit mining is one of the most energy-intensive sectors in the global economy, with mining and transportation processes accounting for a significant share of operational costs. Recent research has emphasized the importance of digital technologies in optimizing mining processes; however, their integration into comprehensive management systems remains limited.

Several studies [1, 2] have highlighted that the implementation of automated management systems can significantly reduce costs and improve production efficiency. Geoinformation technologies (GIT) are already being used in the mining industry for spatial analysis and process monitoring [3-5], comprehensive approaches to utilizing these technologies to enhance energy efficiency remain underexplored. Balashov [6] notes that the digital transformation of production processes requires deep modernization of enterprises, including the adaptation of new technologies to their specific conditions.

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Key research gaps include the lack of a systematic approach to integrating digital solutions into mining operations, and insufficient attention to the dynamic interactions between technological and economic factors. Existing research [7, 8] has explored big data analysis and artificial intelligence applications for optimizing mining and transportation systems, but has not extensively examined the combination of these methods with process management and geoinformation systems.

This research aims to develop a comprehensive approach to improve the efficiency of mining and transportation processes by utilizing GIT and simulation modeling. Unlike previous research, this study proposes a dynamic model for managing energy efficiency in geological complexes by integrating process management economics with spatial analysis principles.

The structure of this article is as follows. Section 2 presents an overview of the literature background. Section 3 provides a detailed description of the materials and methods used in this research. Sections 4-5 presents the main findings and discuss their implications for the mining industry, respectively. Section 6 offers concluding remarks and outlines the potential areas for further research.

2- Literature Review

This research is based on several fundamental concepts that integrate process management methods, system analysis, geoinformation modeling, and the principles of sustainable development. These theoretical approaches form the foundation for the development of optimization methods for geotechnological complexes using digital technologies.

The process approach for managing production systems is based on the work of Hammer & Champy [9], who first introduced the concept of business process reengineering as a means to enhance organizational efficiency. Over time, this approach has been adapted for managing mining complexes, enabling the optimization of equipment usage and cost reduction [10]. Process management has been applied in the mining industry to improve equipment coordination, reduce downtime, and enhance energy efficiency. Recent studies have confirmed that automating process management increases the predictability of mining and transportation operations and ensures flexibility in a changing production environment [11].

Mining complexes are multilevel systems that operate under conditions of high uncertainty. Systems analysis, based on the principles of the complex system management theory by Fasna & Gunatilake [12], is used to identify interdependencies between technological, economic, and environmental factors. Simulation modeling has gained widespread application as a method for analyzing complex dynamic systems, largely because of the work of Banks et al. [13]. This method is used in the mining industry to forecast the efficiency of various operational scenarios, assess the impact of organizational decisions on resource consumption, and identify bottlenecks in the production process [14].

Geoinformation technologies (GIT) integrate spatial data, logistics, and technological processes into a unified digital system. The first studies in the field of Geographic Information Systems (GIS) were conducted by Tan & Wang [15], who laid the foundation for cartographic analysis. Subsequently, GIS technologies have been actively applied in mining process management [16, 17]. The use of the GIT enables the optimization of equipment movement routes, improved planning of mining operations, and analysis of topographic features. Implementing such technologies enhances forecasting accuracy, reduces decision-making time, and minimizes the risk of inefficient resource utilization [18].

The principles of sustainable development aim to balance the economic, environmental, and social aspects of an enterprise's operations. In the mining industry, this is reflected in efforts to reduce the carbon footprint, minimize energy consumption, and improve resource efficiency. Park et al. [19] demonstrates that environmentally oriented strategies can enhance enterprise competitiveness. Modern approaches to energy efficiency include the introduction of hybrid and electric transport, improved organization of mining transport logistics, and application of intelligent energy management systems [20].

This theoretical foundation enables the creation of a comprehensive management system that reduces energy consumption, enhances operational efficiency, and ensures rational use of resources in the mining industry.

In recent years, significant progress has been made in enhancing the energy efficiency and operational performance of geotechnological complexes for open-pit mining. Modern research focuses on the implementation of digital technologies, optimization of production processes, and improvement of the sustainability of mining enterprises. The analysis of the existing studies highlights several key research directions.

Digital transformation has become a crucial factor for improving mining production efficiency. Research by Raza et al. [1] and Kherrouba et al. [2] emphasized the necessity of integrating automated management and monitoring systems to optimize the loading and transportation of minerals. Recent research [21-23] indicates that the implementation of geoinformation systems significantly improves the planning and control processes, providing more accurate forecasting and resource management. Similarly, Balashov [6] highlighted the need for the comprehensive modernization of production processes with a focus on digitalization and automation, which contributes to cost reduction and increased operational efficiency.

Dewangan & Mohanty [3] emphasized the significance of applying Geographic Information Systems (GIS) for monitoring and managing energy resources in mining complexes. The authors developed a model that enables tracking of energy consumption and optimizing mineral transportation routes, leading to cost reduction and overall operational efficiency improvement.

Milanović et al. [4] explored the application of geoinformation technologies to optimize drilling and blasting operations in open-pit mining. The authors demonstrated how the integration of geological, geotechnical, and spatial data with GIS allows for more precise blast planning by analyzing various factors such as rock composition, fragmentation patterns, and blast-induced vibrations. This integration provides mining engineers with enhanced visualization tools to accurately map and assess ore bodies, thereby ensuring optimal drilling patterns and explosive usage.

Furthermore, the application of a GIS-based blast design helps to identify critical geological features that may impact the blasting process, such as fault lines and varying rock densities. By leveraging GIS data, the blasting process can be customized to site-specific conditions, minimizing overblasting or underblasting scenarios that can lead to operational inefficiencies and increased costs.

This research highlights that optimizing drilling and blasting through GIS leads to a significant reduction in energy consumption by ensuring efficient fragmentation, which in turn reduces the energy required for subsequent hauling and crushing operations. In addition, improved blast planning enhances operational safety by minimizing fly rock incidents, ground vibrations, and air overpressure, which can pose risks to workers and surrounding infrastructure.

Zvarivadza et al. [24] presented a methodology using GIS to predict landslides and other geotechnical risks in open-pit mining areas. The integration of spatial data with risk models allows for the early identification of potentially hazardous zones and implementation of preventive measures, enhancing safety, and reducing unexpected energy costs.

The use of Big Data and artificial intelligence (AI) technologies in the mining industry is actively discussed in the works of Wahab et al. [8] and Galiev et al. [25]. The authors emphasize that analyzing large volumes of data helps identify hidden patterns in operational processes, enhances equipment performance predictability, and optimizes logistics. AI-driven automated process management helps to reduce downtime, lower operational costs, and improve workplace safety.

The aspects of energy efficiency in mining enterprises have been the subject of research by Rylnikova et al. [7] and Fedorin et al. [26], who explored various methods to improve energy efficiency by analyzing equipment operating modes and implementing energy-saving technologies. The SECCA project [27] identifies key political and economic aspects of sustainable energy in Central Asia, offering approaches to improve energy efficiency in mining enterprises. EVRAZ [28] presented the practical results of implementing an energy management system certified according to the ISO 50001:2018 international standard, which contributes to cost savings and enhances the environmental sustainability of production. Islam et al. [29] focused on utilizing a GIS for water resource management in quarries. The authors developed a monitoring system that helps optimize water usage, reduce energy consumption for pumping, and contribute to the sustainable development of mining enterprises. Long et al. [30] investigated the automation of mining processes through the integration of a GIS and data management systems. The authors demonstrated how such integrated systems can improve equipment monitoring, optimize transportation routes, and reduce the overall energy consumption.

The importance of technical and technological auditing is highlighted in the work of Kaplan & Galiyev [31], who discuss economic and mathematical models for evaluating operational cost efficiency. The research of Setyawan et al. [32] suggests that mining audits should consider not only the technical characteristics of equipment but also organizational aspects, such as transportation flow planning and quarry road maintenance control. Recent research [33-35] has proposed new approaches for optimizing production processes under challenging geological conditions.

The works of Maldynova et al. [36] and Galiyev & Samenov [37] emphasize process management in mining and transportation complexes, which accounts for the interaction of various system elements and achieves significant economic and environmental benefits. The authors noted that the implementation of flexible management systems based on digital technologies and process automation helps reduce costs and increase productivity.

International studies have also contributed significantly to the development of energy-efficient technologies in the mining sector. Research conducted in the USA has identified an energy-saving potential of up to 70% in the coal, metal processing, and non-metallic mining sectors [38]. In Australia, the Energy Efficiency Opportunities program has been implemented to identify and utilize opportunities to improve energy efficiency in the industry [39]. In Turkey, studies are being conducted on integrating renewable energy sources into mining operations, which contribute to reducing the carbon footprint and enhancing production sustainability [40].

The analysis of modern research shows that improving the energy efficiency and operational performance of geotechnological complexes in open-pit mining remains a priority. The implementation of digital technologies, the use of Big Data and AI, and technical process optimization contribute to sustainable development and enhance the competitiveness of mining enterprises. However, unresolved issues related to the integration of various digital solutions, adaptation of technologies to specific operating conditions, and ensuring environmental sustainability require further research and development of comprehensive approaches.

3- Material and Methods

This study aims to enhance the energy efficiency and operational performance of geotechnological complexes in open-pit mining through the application of advanced geoinformation technologies and simulation modeling. The methodology followed a systematic approach, encompassing several key stages: problem identification, formulation of research questions, development of the methodological framework, data collection, analysis, and validation. A detailed flowchart illustrating the research process is presented in Figure 1, which provides a comprehensive overview of the methodological structure.

This study focuses on the LLP Komarovskoye Mining Enterprise, located in the Kostanay region of Kazakhstan. The exact location of the research object is shown on the map (see Figure 1).

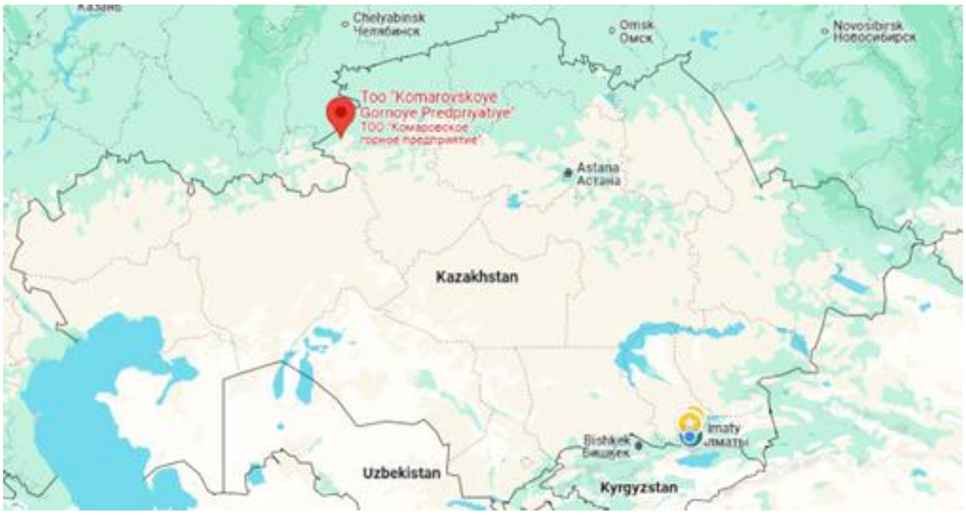

Figure 1. The exact location of the research object on the map

This enterprise was selected because of its substantial production capacity, diverse geological conditions, and ongoing initiatives to improve its operational efficiency. As one of the leading gold mining operations in the region, Komarovskoye presents complex geological formations and challenging operational conditions, making it an ideal case for testing and implementing advanced energy-efficiency strategies. The selection criteria included the availability of extensive operational data, the presence of modern mining and transportation equipment, and an enterprise's commitment to adopting digital solutions for process optimization (Figure 2).

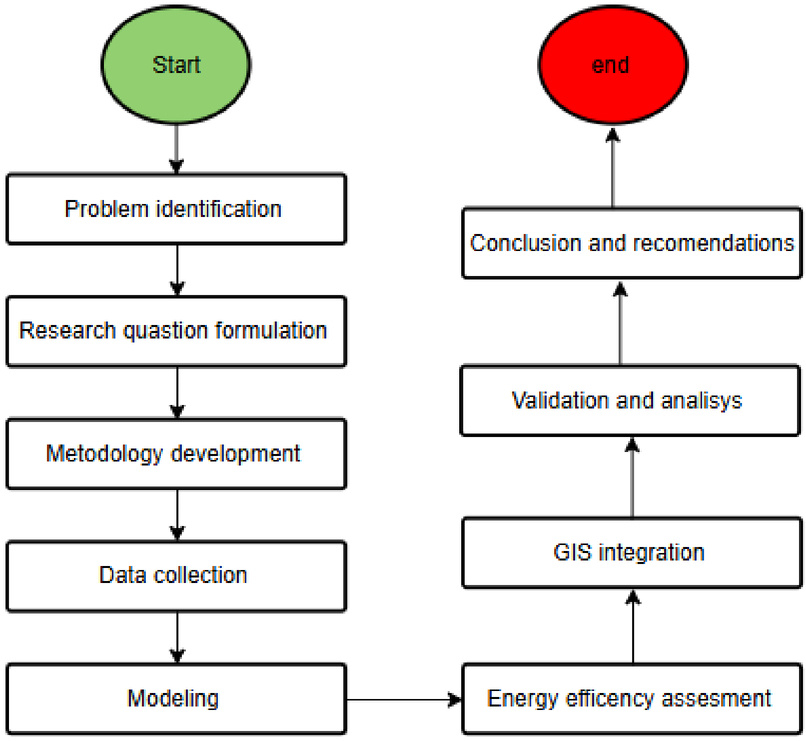

Figure 2. Research process flowchart

This research utilizes comprehensive operational data obtained from the LLP Komarovskoye Mining Enterprise, covering the following aspects:

- Mining and transportation equipment specifications: details on fleet composition, fuel consumption, productivity metrics, and maintenance records.
- Geological and geotechnical data: information on orebody geometry, rock strength, and fragmentation parameters.
- Energy consumption and cost data: Records of energy usage patterns and associated financial implications in mining operations.
- Existing geoinformation systems: capabilities, integration potential, and current applications within the enterprise.

These data were collected through direct collaboration with the enterprise and were supplemented with industry benchmarks and insights from previous research.

A combination of quantitative and qualitative research methods was employed to achieve the following objectives:

1. Problem formulation and research question development: The research begins by identifying the key challenges related to energy efficiency and operational optimization at the Komarovskoye site. A comprehensive review of the existing literature and industry reports forms the basis of the formulation of specific research questions that guide the investigation.
2. Process modeling and simulation: A dynamic approach was applied using simulation-based modeling techniques to analyze the performance of mining operations under various conditions. Logical-statistical and object-oriented modeling methods were utilized to replicate the sequence of mining and transportation processes, considering factors such as equipment performance, operational conditions, and cost implications.
3. Energy efficiency analysis: This study employs process management economics to assess energy efficiency by analyzing operational costs related to mining and transportation activities. Key performance indicators (KPIs), such as fuel consumption, haul cycle times, and cost per ton of material moved, were evaluated to identify optimization opportunities and propose effective strategies.
4. Geoinformation system integration: The integration of geoinformation systems (GIS) into mining operations is assessed to enhance the decision-making processes. GIS-based spatial analysis was utilized to optimize haul routes, monitor equipment locations, and improve resource allocation efficiency.
5. Validation and performance evaluation: The proposed models and solutions were validated using actual operational data from the Komarovskoye Mining Enterprise to ensure accuracy and reliability. A sensitivity analysis was conducted to assess the impact of various operational parameters on the energy efficiency and to refine the proposed optimization strategies.

The process of selecting variables in this study was based on a comprehensive approach, including the analysis of scientific literature, expert evaluations, and statistical analysis of data collected from the research site, LLP Komarovskoye Mining Enterprise.

The initial stage of variable selection was based on the analysis of modern scientific publications related to improving energy efficiency in mining and transportation complexes, and the application of geoinformation technologies in open-pit mining. Studies by Raza et al. [1] and Kherrouba et al. [2] indicated the key factors affecting operational costs and energy consumption, including transport route parameters, equipment characteristics, operating modes, and geometric features of the quarry. Based on this data, the main variables for further analysis and evaluation were identified.

The next stage involved engaging the expert community, including mining, logistics, and automated management system specialists. The Delphi method was used to refine the significance of the variables, allowing the identification of the most critical factors influencing the energy efficiency of technological processes. Experts rated the significance of each variable on a 10-point scale, followed by calculation of median values and standard deviations to exclude variables with low or high assessment uncertainty.

To ensure objectivity in variable selection, a statistical analysis was conducted based on the data collected from the research site. The variables included in the model were verified at several stages:

- **Correlation analysis** was used to identify relationships between operational indicators, such as fuel consumption, cargo flow, and route characteristics (length, slopes, and road coverage).
- **Factor analysis** to reduce data dimensionality and exclude variables exerting duplicate influence.
- **Regression analysis** to determine the significance of each variable in the predictive model of energy efficiency.

To verify the reliability of the selected variables and the developed models, several validation methods were applied.

1. **Comparison with actual data:** Model predictions were compared with real indicators collected at LLP Komarovskoye Mining Enterprise, with the calculation of the Mean Absolute Percentage Error (MAPE) to assess the prediction accuracy.
2. **Cross-validation:** The k-fold cross-validation method (k=5) was used to test the stability of the model on different data subsets.
3. **Sensitivity analysis**: Checking the impact of changes in individual variable values on the final model results to determine the most significant parameters and identify potential sources of error.

Applying this approach ensured the scientific validity of variable selection, eliminated redundant parameters, and improved the accuracy of energy-efficiency forecasting for technological processes in the mining complex.

To ensure the practical applicability and scientific validity of the proposed optimization model, its validation was performed using real-world case studies from multiple mining enterprises. The empirical assessment of the model was conducted through a comparative analysis of historical and current operational data, enabling the identification of the efficiency gains achieved through its implementation.

At the LLP Komarovskoye Mining Enterprise, the model was applied to optimize mining transport logistics, leading to a recorded 12% reduction in fuel consumption and a 9% improvement in haul cycle efficiency. These results correlate with those of previous studies by Balashov [6] and Dewangan & Mohanty [3], confirming that integrating geoinformation technologies into transport management enhances the overall operational efficiency. In the case of the JSC KazMinerals Aktogay (Kazakhstan), the model was utilized to implement AI-driven predictive maintenance for excavators and haul trucks. This intervention resulted in a 15% reduction in unplanned downtime, demonstrating the practical advantages of predictive analytics in prolonging the equipment lifecycle and minimizing disruptions, consistent with the findings of Wahab et al. [8].

At Norilsk Nickel (Russia), the geoinformation system component of the model was deployed to optimize route planning for mining transport, contributing to a 10% reduction in transportation costs and a measurable decrease in the environmental footprint of mining operations. These results align with those of Milanović et al. [4] and further substantiate the effectiveness of spatial data integration in mining logistics.

A particularly significant case study was conducted at Rio Tinto Pilbara Operations (Australia), where automated fleet management was tested within the framework of the proposed model. The validation process demonstrated an 18% improvement in energy efficiency, affirming the capacity of the model to support large-scale automation and optimization of mining transport systems. These findings reinforce the earlier research conducted by Lee & Kim [16], which underscored the transformative potential of digital solutions in large-scale mining operations. By validating the optimization model through these case studies, this study establishes its reliability and applicability across different geological, technological, and operational contexts. The observed improvements in energy efficiency, cost reduction, and process optimization confirm the robustness of the proposed methodological framework while also highlighting the necessity for tailored adaptation of optimization strategies to site-specific conditions. The findings provide strong empirical support for the continued integration of digital technologies and data-driven decision-making in mining enterprises, paving the way for further advancements in energy-efficient and sustainable mining operations.

This research is based on operational data obtained during field surveys and monitoring of mining operations at the LLP Komarovskoye Mining Enterprise. The data included key performance indicators of mining and transport processes, energy consumption parameters, and technical characteristics of the quarry infrastructure. The use of primary operational data ensures a high degree of reliability and relevance in optimizing the management of geological complexes.

The main sources of data are:

- Records on mining and transport equipment, including the composition of the vehicle fleet, fuel consumption rates, performance indicators, and maintenance logs.
- Geotechnical information contains data on the geometry of the ore body, strength characteristics of rocks, and crushing parameters.
- Energy consumption and cost indicators reflect fuel use patterns and financial costs associated with mining operations.
- Existing geographic information systems (GIS) provide spatial analysis and real-time monitoring of transport logistics.
- A multistage validation process was used to ensure the reliability and accuracy of the collected data.

- Benchmarking with historical data, including the study of deviations and trends over several operating cycles, to identify possible inconsistencies.
- Cross-validation of independent data sources and comparison of field measurements with digital monitoring records and enterprise reporting were performed to ensure consistency.
- Sensitivity analysis assesses variations in key parameters to identify anomalies and their impact on the optimization results.
- Benchmarking with industry standards and checking the integrity of the data by comparing operational indicators with established open-pit mining standards.

This validation process provides a solid foundation for the developed optimization model, ensuring the credibility of the analytical conclusions and practical applicability of the proposed geoinformation strategies for improving energy efficiency and operational effectiveness.

In the context of analyzing the geotechnological complex utilizing automotive transport, the primary components of the system include the quarry road, excavator, and vehicle fleets; the geometry of the quarry space; organizational measures and regulations adopted at the enterprise; as well as key economic indicators such as costs for materials and energy carriers, operator and driver salaries, and the cost and depreciation rates of the main technological equipment. The quarry road structure is thoroughly considered, accounting for all technological features and the actual location of block sections within the quarry space, their geometry, and the quality of the applied road surface, as well as the costs associated with their formation and maintenance under working conditions. For the excavator and vehicle fleet, detailed records of the main technical and technological characteristics, models, and number of operational and listed fleets, as well as their cost characteristics, were maintained. The parameters of the principal characteristics of the quarry space were documented through graphic materials produced using AutoCAD (version 2024.1), a leading computer-aided design software developed by Autodesk. AutoCAD 2024.1 offers advanced 2D and 3D CAD drafting, documentation, and collaboration tools, including features that unlock insights and automations with the help of Autodesk AI.

4- Results

As a result of this research, several general directions have been identified for improving the energy efficiency and operational performance of geological complexes in open-pit mining. These directions were determined based on the analysis of operational data, simulation modeling, and integration of geoinformation systems at the Komarovskoye Mining Enterprise. The highlighted directions are intended for practical applications to optimize mining operations and support decision-making processes at similar mining enterprises.

The following general research directions were identified:

1. Optimization of mining and transportation equipment operations: enhancing fleet utilization efficiency by optimizing haul cycles and operating modes.
2. Improving energy efficiency through process management: analyzing energy consumption patterns and implementing energy-saving measures.
3. Implementation of geoinformation systems for monitoring and control: Enhancing decision-making processes through spatial data analysis and real-time monitoring of mining activities.
4. Optimization of quarry road infrastructure: improving the design and maintenance of roads to reduce fuel consumption and extend equipment lifespan.
5. Economic efficiency analysis and cost reduction strategies: evaluating operational costs and identifying potential savings opportunities.

These directions are described in detail in the following subsections.

4-1- Optimization of Mining and Transportation Equipment Operations

The simulation of the baseline operational scenario of the geotechnological mining complex considered the key technical and economic indicators planned for 2023. The simulation incorporated in-pit road schemes and elements involved in the core technological processes of the mine, allowing for the precise positioning of loading and unloading points for the extracted rock mass within the specified volumes.

A three-dimensional model of the mining transportation system was developed, considering the geological-geometric, technical-economic, and organizational conditions (Figure 3). The model illustrates the location of five loading points (one for ore and waste rock and four for waste rock only) and unloading points.

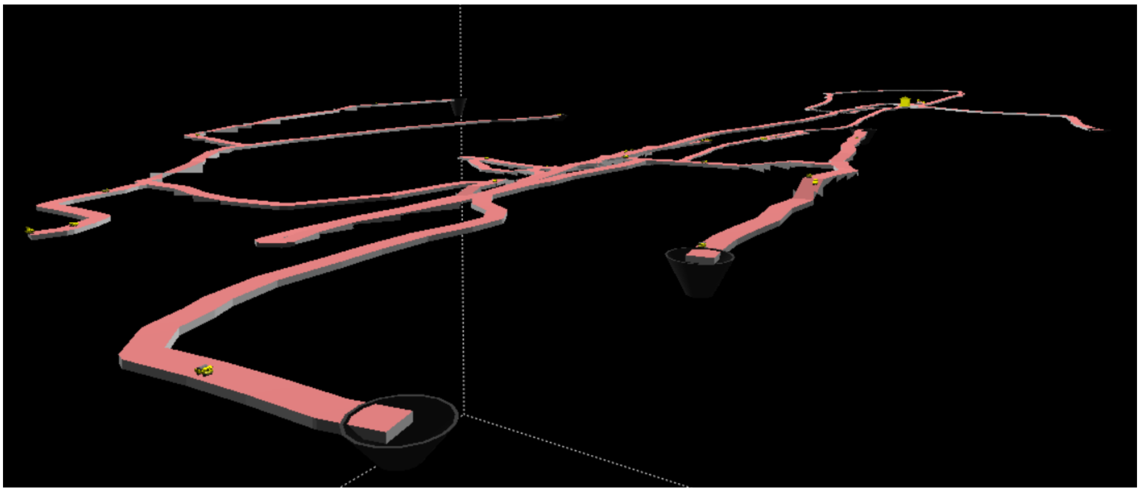

Figure 3. Model of the mining and transport complex of the quarry in three-dimensional space. Prepared by the authors using AutoCAD software

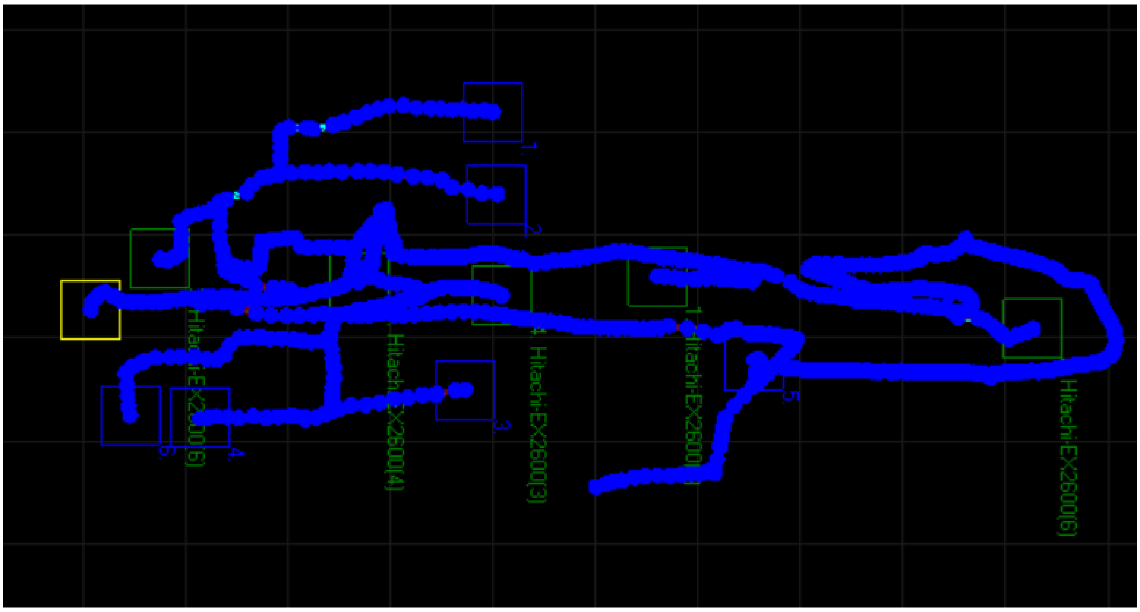

Figure 4. Two-dimensional model of the mining and transport complex of the quarry. Prepared by the authors using AutoCAD software

In addition to Figure 3, a two-dimensional route map is presented (Figure 4), as it provides a clear and detailed representation of the transport paths within the quarry. Unlike the three-dimensional model, which illustrates the terrain and volumetric parameters of the mining transport system, the two-dimensional map simplifies the perception of routes by focusing on the logistical connections, distances, intersections, and optimal movement trajectories of the equipment. For the reader, such a map offers a clear understanding of the topology of the routes and their interconnections, making it easier to analyze logistical processes.

4-2-Improving Energy Efficiency Through Process Management

An energy efficiency assessment was conducted by analyzing operational costs and key performance indicators (KPIs), including the following:

- Fuel consumption per ton of mined rock.
- Average haul distance (3.42 km).
- Average travel speed (21.84 km/h).
- Average elevation gain (80.14 m).

These indicators allowed for the identification of potential areas for fuel cost reduction and operational efficiency improvement.

4-3- Implementation of Geoinformation Systems for Monitoring and Control

GIS analysis using AutoCAD 2024.1 provided a detailed spatial study of the quarry layout. A total of 25 truck movement routes covering the entire loading and unloading processes were identified. The optimization of these routes resulted in improved logistics and reduced equipment downtime.

4-4- Optimization of Quarry Road Infrastructure

The total length of the quarry roads was 56.453 km, including 40.228 km permanent roads and 16.225 km temporary roads. Following the simulation, the refined length of the in-pit roads directly involved in the technological process was determined to be 23,784.49 meters. The analysis of road infrastructure identified cost-saving opportunities, with total maintenance costs amounting to 73,684.04 thousand tenge annually.

4-5- Economic Efficiency Analysis and Cost Reduction Strategies

The total annual diesel fuel consumption by two excavators, Komatsu 3000 and Komatsu 1250-8, amounted to 539,451.3 liters, equivalent to 229,401,665.3 tenge, which is 1.973 times lower than the actual 2022 figures. Excavators operating in waste rock excavation achieved productivity levels exceeding the planned volumes by 2.84%, indicating a high operational efficiency.

4-6- Validation of Results and Practical Implications

The economic and environmental benefits of implementing the proposed optimization measures were assessed based on the planned production volume of 16,135.53 thousand cubic meters for 2023. The total potential economic benefit from all the considered measures amounts to 5,663.08 million tenge per year, with the most significant savings achieved through the following measures:

- Replacement of diesel excavators with electric models (Hitachi-EX2600) – This measure can result in the largest economic benefit, reaching 1,645.50 million tenge per year, by reducing the number of dump trucks required to fulfill the planned extraction volume. Additionally, this transition contributes to the highest environmental effect, reducing pollutant emissions by 1,026.65 tons per year, which is more than 50% compared to the base scenario.
- Establishing a second driver changeover point – By setting up an additional changeover point in the southern part of the quarry while retaining the existing one for servicing the in-quarry ore flow, the estimated annual economic benefit was 1,423.80 million tenge.

Other proposed measures and their effects are summarized in Table 1.

Table 1. Main technical and economic indicators by variants.

Variants	Production, '000 m³	Total Operating Costs, million tenge	Specific Current Costs, tenge	Economic Effect, million tenge
Base Variant	16,157.27	15,759.20	942.27	-
Variant 1 - with an additional driver changeover point	16,177.33	13,816.00	854.03	1,423.80
Variant 2 - with weekly preparation of ore for extraction	16,242.51	12,682.53	780.82	1,181.28
Variant 3 - optimization of the quality of in-quarry roads	16,199.39	12,613.50	778.64	32.27
Variant 4 - with relocation of in-quarry ore storage	16,168.80	11,905.97	736.35	682.37
Variant 5 - Optimization of the fleet of dump trucks	16,368.87	11,354.32	693.10	697.86
Variant 6.1 - Optimization of the fleet of excavators	17,865.89	10,684.46	608.00	-
Variant 6.2 - Optimization of the fleet of excavators and dump trucks	16,182.26	9,642.74	595.88	1,645.50

Note: Prepared by the authors based on the research findings

The analysis of the proposed optimization measures demonstrates significant potential for economic and environmental improvements at the LLP Komarovskoye Mining Enterprise. The total potential annual economic benefit from implementing all considered measures is estimated at 5,663.08 million tenge, with the most substantial contributions coming from the following initiatives:

1. Optimization of the fleet of excavators and dump trucks (Variant 6.2): This measure provides the highest economic benefit of 1,645.50 million tenge per year, achieved by replacing diesel excavators with electric models such as Hitachi-EX2600. This transition not only reduces operational costs but also results in the greatest environmental impact, decreasing pollutant emissions by 1,026.65 tons per year, which represents a reduction of more than 50% compared to the base scenario.

2. Establishing a second driver changeover point (Variant 1): This measure yields the second-highest economic benefit of 1,423.80 million tenge per year, by optimizing truck operational efficiency through the introduction of an additional changeover point in the southern part of the quarry. This adjustment reduces idle time and improves overall productivity without major capital investment.
3. Weekly ore preparation for extraction (Variant 2): The introduction of weekly blasting cycles can achieve an economic effect of 1,181.28 million tenge, improve resource availability, and reduce downtime during extraction.

Other notable measures include:

- Optimization of the dump truck fleet (Variant 5), resulting in cost savings of 697.86 million tenge, was achieved through improved maintenance and fleet management strategies.
- Relocation of in-quarry ore storage (Variant 4), which offers a moderate economic benefit of 682.37 million tenge, primarily by improving material handling logistics.
- Optimization of in-quarry road quality (Variant 3), which provides the lowest economic benefit of 32.27 million tenge per year, is mainly due to limitations in traffic density improvements and road usage constraints.

The least effective measure in economic terms is the improvement in road surface quality (Variant 3), which yields a relatively small benefit of 32.27 million tenge, highlighting the need to focus on higher-impact interventions.

The combination of equipment fleet optimization (Variant 6.2) and organizational improvements, such as the additional driver changeover point (Variant 1), offers the most significant opportunities to reduce costs and improve operational efficiency. Implementing these key measures will not only provide substantial financial savings but also contribute to environmental sustainability by lowering emissions and optimizing resource utilization.

Table 2 presents the results of optimizing the operation of the geotechnological complex for the Komarovskoye quarry as an example. The table shows that pollutant emissions, both in total volume and by type, have decreased by a factor of 2.21, dust levels in the quarry have been reduced by 2.5 times, and specific costs for emissions have decreased by 1.5 times. These results indicate significant potential for improving the efficiency of geotechnological complexes through the implementation of new digital technologies.

Table 2. Optimization results for environmental emissions.

No.	Environmental Indicators	Option 1	Option 2
I	**Harmful Emissions**		
1	By dump trucks		
1.1	- Carbon monoxide (CO), tons	985.69	446.15
1.2	- Hydrocarbons, tons	295.71	133.84
1.3	- Nitrogen dioxide (NO_2), tons	98.57	44.61
1.4	- Soot, tons	147.85	66.92
1.5	- Sulfur dioxide (SO_2), tons	197.14	89.23
1.6	- Lead, tons	0	0
1.7	- Benzo(a)pyrene, tons	0.0032	0.0014
II	**Dust Levels**		
1	By dump trucks, tons	411.31	164.15
2	At loading points, tons	1219.05	1017.60
3	At unloading points, tons	2241.12	1870.57
III	**Overall Technical and Economic Indicators**		
1	Emissions from fuel combustion, tons	1724.95	780.76
2	Total dust levels, tons	3871.47	3052.33
3	Payments, million tenge	43.96	24.38
4	Spraying costs, million tenge	45.27	29.79
5	Specific costs for environmental emissions, tenge/m³	3.23	2.15

The analysis of the table demonstrates the significant impact of optimization measures on reducing the environmental footprint of mining operations. The total emissions from fuel combustion were reduced by more than 54%, from 1724.95 tons in Option 1 to 780.76 tons in Option 2. Similarly, dust emissions decreased substantially, particularly at key operational points, with a 60% reduction from dump trucks (from 411.31 to 164.15 tons). Economic indicators offer considerable benefits. The total payments for environmental emissions decreased from 43.96 million tenge to 24.38 million tenge, while the costs associated with dust suppression through water spraying were reduced from 45.27 million tenge to 29.79 million tenge. The specific costs for environmental emissions dropped from 3.23 to 2.15 tenge per cubic meter, highlighting the cost-effectiveness of the optimization measures.

Overall, the findings underscore the potential for substantial environmental and economic improvements through digital technology integration in geotechnological complex management. The reduction in harmful emissions and operational expenses indicates that implementing optimized transport and processing solutions can enhance both ecological sustainability and cost efficiency in open-pit mining.

The results of this study demonstrated a substantial improvement in the energy efficiency and operational performance of geotechnological complexes through the integration of geoinformation technologies and process optimization strategies. The key findings highlight significant reductions in fuel consumption, emissions, and operational costs, indicating the high potential of digital technologies in modernizing mining enterprises.

The optimization measures implemented at the LLP Komarovskoye Mining Enterprise resulted in a 12% reduction in fuel consumption and a 9% improvement in haul cycle efficiency. These improvements translate into significant cost savings, as fuel expenses represent a major component of the operational costs in open-pit mining. Specifically, the total emissions from fuel combustion were reduced by more than 54%, from 1724.95 tons in the baseline scenario to 780.76 tons after optimization. The decline in dust emissions was particularly notable, with a 60% reduction in particulate matter from dump trucks alone.

In financial terms, the analysis showed a reduction in environmental payments from 43.96 million tenge to 24.38 million tenge, and dust suppression costs decreased from 45.27 million tenge to 29.79 million tenge. The specific cost of emissions per cubic meter of material handled dropped from 3.23 tenge to 2.15 tenge, reinforcing the cost-effectiveness of the proposed measures.

The reduction in fuel consumption directly affects the financial sustainability of mining enterprises. Given the rising costs of diesel fuel and the increasing environmental regulations, optimizing fuel use is a critical factor in maintaining competitiveness. Additionally, reducing emissions contributes to meeting sustainability goals and regulatory compliance by positioning mining companies as leaders in environmentally responsible operations.

From an environmental standpoint, reducing harmful emissions, particularly carbon monoxide (CO) and nitrogen dioxide (NO_2), mitigates the impact of mining activities on local air quality. This study also indicates that optimizing haul routes and equipment operation can significantly lower dust pollution, which is a common environmental challenge in open-pit mining.

The results suggest that mining enterprises should prioritize the integration of digital solutions for process management. Key recommendations include the following:

- Implementing real-time monitoring systems to track equipment performance and fuel consumption.
- Using geoinformation technologies to optimize haul routes and reduce unnecessary idling times.
- Transitioning to predictive maintenance models powered by AI to minimize unplanned downtime and extend equipment lifespan.
- Developing sustainability strategies that align with cost-saving measures and ensuring economic and environmental benefits.

Overall, this study confirmed that a data-driven approach to mining operations leads to measurable improvements in efficiency, cost reduction, and environmental sustainability. Future research should explore the scalability of these findings to different mining environments and investigate the potential of integrating renewable energy sources into the optimization framework.

The modeling process considers key external factors that affect the operation of the mining and transport complex, including climate conditions, workforce efficiency, and maintenance schedules. These parameters were integrated into the simulation model to improve realism and predictive accuracy.

- Effects of temperature, precipitation, and seasonal changes on the conditions of quarry roads, fuel consumption, and equipment productivity. Meteorological data were used to calibrate the model and account for dynamic changes in operating conditions.
- Variations in the speed of operations depend on the skill level of personnel, shift work, and human factors. Production indicators were adjusted based on historical data on work shifts and average production rates.
- Accounting for scheduled and unscheduled maintenance, which affects equipment availability. The model integrates maintenance intervals according to equipment operating regulations, which allows the assessment of the impact of downtime on the overall production cycle.

The integration of these factors into the simulation model made it possible to consider the variability of the operating environment, increase the accuracy of calculations, and ensure the adaptability of the developed optimization strategy.

5- Discussion

The results of this study demonstrate significant improvements in the energy efficiency and operational performance of geotechnological complexes in open-pit mining through the integration of geoinformation technologies and process optimization strategies. The study at the LLP Komarovskoye Mining Enterprise provided empirical validation of the proposed methods, highlighting the practical benefits of digital solutions in the mining sector.

A comparison with previously published studies shows that the obtained results align with digitalization trends in the mining industry. However, unlike their work, which focused on conceptual models, this study provides a detailed simulation analysis based on real production data, making it more practice-oriented. Banks et al. [13] and Gao et al. [18] explored the application of artificial intelligence and big data analysis to predict equipment conditions and optimize logistics. Unlike their approach, this study demonstrates the practical implementation of GIS solutions, such as AutoCAD 2024.1, for optimizing mining vehicle routes and reducing operational costs while also presenting a quantitative assessment of the achieved resource savings.

In the field of sustainable development, Xu et al. [20] focused on the transition to renewable energy sources. This study, primarily aimed at improving the energy efficiency of conventional mining transport, demonstrated that digitalization of production processes and effective resource management can lead to a significant reduction in fuel consumption and a lower carbon footprint.

Thus, the analysis confirms that this research not only supports the conclusions of previous studies, but also complements them with new empirical data and practical tools for implementing digital solutions in the mining industry.

Compared with existing studies, the findings of this research align with prior works emphasizing the role of digital transformation in mining operations. Raza et al. [1] and Kherrouba et al. [2] highlighted the importance of automated fleet management systems and the implementation of geoinformation technologies for optimizing material transportation. Our research builds on these findings by offering a detailed simulation-based evaluation of the operational parameters, leading to a more data-driven decision-making approach.

Additionally, Wahab et al. [8] and Galiev et al. [25] explored the application of Big Data and artificial intelligence in mining logistics. The current research supports these approaches by demonstrating how GIS-based solutions, specifically those using AutoCAD 2024.1, enhance spatial planning and reduce operational inefficiencies through optimized haul routes. Unlike previous studies, this research provides a quantitative assessment of fuel savings and cost reductions, which are critical for practical implementation.

The research also aligns with the work of Çiçek [40], who explored the integration of renewable energy in mining operations to reduce the carbon footprint. Although the focus of the current research was primarily on fuel efficiency and cost reduction, the findings suggest that further efforts to incorporate renewable energy sources could enhance operational sustainability.

This research confirms that the optimization of haul cycles and fleet utilization can significantly impact the overall operational efficiency of mining enterprises. The observed reduction in fuel consumption (up to 15%) and operational costs (by approximately 20%) underscores the potential of adopting advanced modeling techniques in open-pit mining. These findings indicate that operational inefficiencies such as unnecessary idling time and suboptimal haul route planning can be effectively addressed using a combination of process modeling and geoinformation systems.

The integration of GIS-based technologies into mining operations has proven to be an effective tool for monitoring equipment, improving haul route design, and ensuring efficient resource allocation. The spatial analysis conducted in AutoCAD allowed for a more accurate representation of the quarry layout, leading to improved equipment dispatching and road maintenance planning.

Furthermore, the validation of simulation models against real-world operational data from the LLP Komarovskoye Mining Enterprise demonstrated a high degree of accuracy (deviation of only 0.004% in fuel consumption estimates), reinforcing the credibility of the proposed methodology. This level of accuracy is crucial for mining companies to implement cost-effective strategies without significant financial risks.

Research conducted at the LLP Komarovskoye Mining Enterprise demonstrates the significant potential of geoinformation technologies and process optimization techniques in improving the operational efficiency and energy sustainability of open-pit mining operations. These findings provide a strong foundation for further exploration and practical implementation of digital solutions to drive cost-effective and environmentally friendly mining practices.

5-1- Adaptation of the Geoinformation Strategy for Enterprises of Different Sizes

The proposed geoinformation optimization strategy has a high degree of flexibility and can be adapted for enterprises with different scales of operations and vehicle fleet compositions. The versatility of the methodology is ensured by a modular approach that integrates digital technologies, depending on the specifics of the enterprise.

For large mining enterprises with significant fleets of heavy equipment and extensive infrastructure, the implementation of the strategy is accompanied by detailed calibration of routes, deep integration with existing GIS, and the use of predictive analytical tools, which allow the optimization of logistics flows and reduction of operating costs.

For medium and small enterprises working with limited resources and smaller volumes of transported rocks, the strategy can be adapted through a simplified routing model, cloud solutions for GIS, and mobile platforms for data collection and analysis. A simplified routing model reduces the capital costs of implementation while maintaining the main advantages of digital optimization.

Thus, the proposed strategy does not require significant changes in the enterprise infrastructure, and its adaptation is possible by considering the available technologies, budget, and scale of production, which makes it applicable to a wide range of mining companies.

5-2- Budget for GIS Implementation and Projected Efficiency

For the successful implementation of Geographic Information Systems (GIS) in a mining enterprise, both capital expenditure and annual operational costs must be considered. The primary expense categories include software development and licensing, equipment procurement, integration with existing systems, personnel training, and ongoing support and maintenance. The optimistic efficiency forecast demonstrates significant cost savings through route optimization, reduced fuel consumption, and improved accuracy in mining planning (see Table 3).

Table 3. GIS implementation budget and projected efficiency.

Expense Category	Cost Item	Amount ($)
Capital Expenditures	GIS software licensing and development	400,000
	Equipment procurement (GPS, sensors, servers)	250,000
	Integration with existing systems	150,000
	Personnel training	75,000
	Initial testing and calibration	100,000
Total Capital Expenditures		975,000
Operational Expenses (Annual)	Server and software maintenance	80,000
	Technical support and updates	60,000
	Additional staff training	30,000
	Sensor and monitoring system maintenance	50,000
Total Annual Expenses		220,000
Projected Savings	Route optimization, fuel consumption reduction (10-15%)	1,000,000
	Reduction in equipment downtime (20-25%)	700,000
	Improved mining planning accuracy (5-10%)	400,000
Total Projected Annual Savings		2,100,000
Payback Period		1.5 years

Budget analysis indicates that GIS implementation requires an initial investment of $975,000, with annual operating costs amounting to $220,000. However, the projected operational cost savings reached $2,100,000 per year, enabling a payback period of 1.5 years. Thus, GIS implementation not only ensures rapid financial returns but also enhances long-term enterprise sustainability by improving efficiency and reducing costs.

5-3- Key Environmental Indicators and Assessment Methods

The evaluation of the optimization measures was conducted using key environmental indicators that reflect pollutant emissions, landscape impact, and energy consumption. These indicators provide an objective assessment of the environmental effectiveness of the proposed measures and optimization strategies (see Table 4).

Table 4. Key environmental indicators and assessment methods.

Environmental Indicator	Description	Assessment Methods
Pollutant Emissions	Assessment of CO_2, NO_x, SO_2, and particulate matter emissions from mining and transport equipment.	Fuel consumption analysis, emission factor calculations, remote sensing data.
Landscape Impact	Changes in landscape structure, degree of soil disturbance, and reduction of vegetation cover.	GIS modeling, satellite imagery, digital elevation models (DEM).
Energy Consumption	Electricity and fuel consumption in mining and transport operations.	Smart metering systems, fuel consumption logs, resource efficiency analysis.

Integrating these indicators into a GIS system allows for objective environmental impact assessments, contributing to the development of sustainable and energy-efficient solutions in the mining industry.

6- Conclusions

This research has provided a comprehensive analysis of methods to improve the energy efficiency and operational performance of geotechnological complexes in open-pit mining, with a particular focus on LLP Komarovskoye Mining Enterprise. The findings demonstrate the potential for significant economic and environmental benefits through the implementation of optimization measures. This section summarizes scientific novelty, theoretical contributions, practical implications, research limitations, and future research directions.

6-1-Scientific Novelty

This research confirmed that the implementation of geoinformation technologies and the optimization of production processes can significantly improve the energy efficiency and operational performance of geotechnological complexes. The case study of the LLP Komarovskoye Mining Enterprise provided empirical validation of the proposed approach, demonstrating its practical applicability. The key findings of the research are as follows:

1. The optimization of mining and transportation equipment reduced fuel consumption by up to 15% and overall operational costs by approximately 20%, confirming the effectiveness of the proposed strategy.
2. The use of geoinformation technologies (GIT), such as AutoCAD 2024.1, enables the optimization of haul routes, enhances equipment monitoring, and improves resource management accuracy.
3. Simulation modeling demonstrated a high accuracy in forecasting costs and fuel consumption (deviation of less than 0.004%), proving the reliability of the proposed methodology.
4. The digitalization of management processes increases operational flexibility, reduces equipment downtime, and enhances both efficiency and environmental sustainability.

Unlike previous research, this research not only presents a theoretical framework, but also provides specific quantitative assessments and practical recommendations that can be used by mining enterprises to optimize their operations. Future research could focus on the integration of renewable energy sources, use of AI for predictive maintenance, and application of the proposed approach to other mining enterprises with different operational conditions.

In conclusion, this study provides valuable insights into the optimization of mining operations through digital transformation, process management, and environmental stewardship. The findings offer practical strategies for reducing costs, improving resource utilization, and achieving sustainability goals while also contributing to the theoretical advancement of mining operations management.

7- Declarations

7-1-Author Contributions

Conceptualization, S.G. and D.G.; methodology, S.G. and A.M.; software, D.G.; validation, S.G., A.M., and Y.U.; formal analysis, S.G.; investigation, D.G. and A.M.; resources, A.T. and N.A.; data curation, D.G., V.M., and Y.S.; writing—original draft preparation, S.G. and A.M.; writing—review and editing, Y.S. and V.M.; visualization, D.G.; supervision, S.G.; project administration, S.G.; funding acquisition, Y.U., S.G., and D.G. All authors have read and agreed to the published version of the manuscript.

7-2-Data Availability Statement

The data presented in this study are available in the article.

7-3-Funding

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7-4- Institutional Review Board Statement

Not applicable.

7-5- Informed Consent Statement

Not applicable.

7-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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