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SYSTEM OF INTERCONNECTED SOLUTIONS "INTELLIGENT QUARRY"

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Abstract. The article discusses the implementation of digital solutions in the management system of the mining and transportation complex using the case of Karelsky Okatysh JSC. An analysis of the initial state of the enterprise's technological chain is presented, highlighting key issues related to the stability of the blend composition, the quality of the mined ore and the efficiency of its transportation management. To address these problems, the software and hardware system called "Intelligent Quarry" was developed, comprising interconnected modules for blend stabilization, automated raw material quality monitoring and predictive equipment condition control. The effectiveness of the proposed solutions was confirmed by simulation of the expected results and subsequent comparison of production indicators before and after the system's implementation. A technical and economic analysis confirmed the increase in concentrate output by 0.84%, a decrease in magnetic iron content in tailings by 0.2% and an additional annual concentrate yield of 171438 tons.

Keywords: mining and transportation complex, intelligent mine, mining and processing plant, automated management systems, hyperspectral sensing, neural networks

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СИСТЕМА ВЗАИМОСВЯЗАННЫХ РЕШЕНИЙ «РАЗУМНЫЙ КАРЬЕР»

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Аннотация. В статье рассмотрены вопросы внедренных цифровых решений в систему управления горнотранспортным комплексом на примере АО «Карельский окатыш». Представлен анализ исходного состояния технологической цепочки предприятия, выявлены основные проблемы, связанные со стабильностью состава шихты, качеством добываемой руды и эффективностью управления ее транспортировкой. Для решения указанных проблем был разработан программно-технический комплекс «Разумный карьер», включающий взаимосвязанные модули стабилизации шихты, автоматизированного мониторинга качества сырья и предиктивного контроля состояния оборудования. Эффективность предложенных решений подтверждена с помощью моделирования ожидаемых эффектов и последующего сравнения производственных показателей до и после внедрения комплекса. Технико-экономический анализ подтвердил увеличение производительности по концентрату на 0,84%, снижение содержания магнитного железа в хвостах на 0,2% и дополнительный годовой выход концентрата в объеме 171438 тонн.

Ключевые слова: горнотранспортный комплекс, интеллектуальный рудник, горно-обогатительный комбинат, автоматизированные системы управления, гиперспектральное зондирование, нейронные сети

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Introduction

The energy costs of open-pit mining enterprises are significant, with mining technological processes accounting for approximately half of these expenses. Quarry excavators, which perform more than 80% of the total volume of operations, consume a considerable amount of electricity. Therefore, the quality of their performance largely determines the overall efficiency of the mining enterprise.

The modernization of the control system for the mining and transportation complex (MTC) is a key stage in the development of the modern mining industry. In recent years, there has been significant progress in the field of automation and digitalization of mining enterprises. The evolution of technologies, from advanced data analytics to artificial intelligence (AI), has enormous potential to transform the mining industry by improving operational efficiency, productivity and production safety.

The totality of methods for automation and optimization of all aspects of mineral extraction is reflected in the concept of the *intelligent quarry*. The main components of intelligent mines include equipment automation, real-time monitoring systems, data analytics, AI, digital twins and advanced safety management systems [1–3].

Review of existing solutions in the field of integrated automation of ore mining and transportation processes

Below are the examples of successful implementations of integrated automation in various regions of the world.

1. *Rio Tinto's "Mine of the Future" program*

The Australian company Rio Tinto implemented the Mine of the Future™ program aimed at creating fully automated mines. As part of this project, autonomous haul trucks, automated drilling rigs, and AutoHaul™ system, the world's first fully autonomous railway network for iron ore transportation, were deployed at mines in the Pilbara region. These solutions led to a 15% increase in productivity and a 13% reduction in operating costs [4].

2. *Intelligent control systems at BHP mines*

BHP has implemented intelligent dispatch systems at the Jimblebar and South Flank mines in Australia. These systems use geoinformation technologies and predictive analytics algorithms to optimize the routing of haul trucks, which has resulted in a 25% reduction in equipment downtime and increased accuracy in mine planning [5].

3. *Digital transformation of Vale mines*

The Brazilian company Vale is actively implementing the Internet of things (IoT) technologies, digital twins and hyperspectral sensors for real-time monitoring of ore quality. This improves the accuracy of forecasting the composition of extracted raw materials and reduces losses during processing. In addition, the use of predictive analytics has contributed to a 30% reduction in equipment maintenance costs[1].

4. *Kankberg smart mine by Boliden*

The Swedish company Boliden implemented a smart mine project at the Kankberg site, where a 5G network was deployed for wireless control of underground equipment. The use of digital twins and automated monitoring systems resulted in a 10% increase in productivity and a 15% reduction in operating costs[2].

5. *Norilsk Nickel's "Smart Mine" project*

The Russian company Norilsk Nickel is developing an autonomous "unmanned" mine project, which employs computer vision and AI technologies for monitoring and controlling mining processes. One of the mines of the Polar Division was selected as a test site for the implementation of autonomous systems[3].

6. *Application of AI in ore beneficiation at KAZ Minerals enterprises*

KAZ Minerals has introduced an AI-based tool to optimize the ore beneficiation process. The system analyzes data from the mine face to the tailings storage facility, using more than 500 million experimental data points, and is capable of self-learning, offering recommendations to improve technological processes[4].

Despite significant achievements in the automation of ore mining and transportation, the implementation of digital technologies is accompanied by a number of technological, economic and organizational limitations. An analysis of existing projects shows that the comprehensive integration of digital solutions in the mining sector remains a complex task requiring a systematic approach.

One of the key limitations is the high capital intensity of digitalization. The implementation of autonomous systems, digital twins and predictive analytics requires substantial investments in equipment

[1] Vale launches innovative program for digital transformation of its supply chain, Available https://vale.com/w/vale-launches-innovative-program-for-digital-transformation-of-its-supply-chain (Accessed 10.03.2025)

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modernization, sensor systems and data collection infrastructure. In the context of commodity market volatility, enterprises are forced to limit the scale of digitalization, focusing on specific nodes of the technological chain.

An additional problem is the difficulty of integrating digital solutions with outdated infrastructure. Most existing mining complexes use equipment installed several decades ago, which complicates the adaptation of modern automated systems. The integration of autonomous haul trucks and drilling rigs into existing dispatch systems requires significant modifications, increasing the overall cost of digitalization.

Furthermore, automation remains fragmented. Most projects are focused on individual aspects, such as transportation operations, intelligent data analytics, or predictive maintenance of equipment [6–8].

To minimize the identified drawbacks of the existing approaches to the automation of mining and transportation processes, the authors propose the concept of an "Intelligent Quarry." This system is an adaptive platform that includes automated monitoring systems, autonomous haul equipment, intelligent control algorithms and predictive analytics.

A key feature of the concept is the modularity of its architecture, which enables the phased implementation of individual components depending on the production conditions of a particular enterprise. This allows digital solutions to be integrated without a complete infrastructure overhaul, adapting the system to the changing requirements of the technological process. The flexibility and scalability of the approach ensure its applicability at enterprises with varying levels of automation, reducing implementation costs and increasing the efficiency of digital transformation in the mining industry [9].

Audit of the MTC of the mining and processing plant

For conducting industrial trials and subsequent implementation, *Karelsky Okatysh* JSC was selected – one of the largest mining enterprises in the north-west of Russia with significant development potential. The company's core activity is the extraction and processing of ferruginous quartzites into high-quality iron ore raw materials, namely pellets [10].

The enterprise's MTC includes several main components: ore extraction, transportation, processing and storage. To identify bottlenecks in the technological chain and to form the most effective system of interconnected solutions, an audit of the MTC was conducted, the results of which are presented in Table 1.

The enterprise's main request was the modernization of the MTC in order to increase the volume of iron ore concentrate depending on the properties of the ore in the flow. This includes identifying methods for increasing concentrate output and reducing production losses by improving the accuracy of information on the incoming ore. Refining ore characteristics, such as iron and sulfur content and beneficiation potential, from the moment of extraction to delivery at the crushing and beneficiation plant (CBP) is also a critical task.

To address the key issues identified during the audit, the proposed system is presented as a set of interconnected solutions encompassing the entire MTC production process. This approach ensures integrity and continuity throughout the production chain, while the modular structure provides flexibility and adaptability to the specific conditions and technologies of each enterprise [11–13].

Integrated set of interconnected solutions

The comprehensive system of interconnected solutions for quality planning and ore blending covers the entire production process of ore extraction, transportation and storage. This approach ensures the integrity and continuity of the production chain. The modular structure of the hardware and software system (HSS) provides flexibility and adaptability to the conditions and technologies specific to each enterprise.

To achieve the main goal of implementing the system, namely, increasing iron extraction regardless of the type of incoming ore, the HSS must aggregate information at all levels and manage processes either in automatic mode or through recommendation-based control.

The solutions developed within the "*Intelligent Quarry*" HSS can be divided into two groups depending on the performed task: stabilization or optimization of the ore blend (Table 2).

Table 1

Bottlenecks in the MTC of Karelsky Okatysh JSC

Main processes	Identified bottlenecks
Ore extraction	– Insufficient accuracy of data in the block model of the rock mass. – Lack of automatic solutions for the analysis of the surface layer of the mining face. – Inaccuracies in excavation and extraction processes.
Ore transportation	– Ore samples at the ore control station (OCS) are not always representative. – Insufficient automation of haul truck movement in the cyclic-flow technology (CFT) area. – Problems with predicting the ore loading time into dump cars.
Ore processing	– Insufficient reliability of information on the qualitative characteristics of ore at transfer stockpiles. – Deficiencies in forming the gradient of ore quality indicators. – Problems with accounting for oversized material.
Storage and logistics	– High time expenditures at the planning stage and when forming the delivery order to the plant. – Poor optimization of in-pit logistics. – Difficulties in forecasting outcomes under emergencies. – Inaccuracies and incompleteness in the database.
Ore blending	– Existing ore blending algorithms are suboptimal and require refinement to account for ore beneficiation potential. – Current blending methods do not adequately consider ore processability.
Information systems and accounting	– The enterprise database contains inaccuracies and incomplete information. – The use of different data calculation algorithms across departments results in contradictions. – Deficiencies in methods for constructing the blasted ore model from the block model.

Figs. 1 and 2 present diagrams illustrating the key components of the "Intelligent Quarry" HSS and their interconnections with technological processes, from geological exploration to railway transportation.

– **Geological Exploration → Drilling and Blasting → Excavation**

At the initial stages of mining, the *Block-to-Blast Model Conversion* module is used to transform the block model into a blast model, which is applied in both long-term and operational planning [14, 15]. This information is then transferred to the drilling and blasting planning stage (Fig. 1, *a*).

– **Excavation**

After blasting, the *In-Pit Transportation Accounting* module tracks the delivery of backfill material for road and excavator pad preparation, and records transportation data and ore conditions at the block in case of emergency. The same *Block-to-Blast Model Conversion* module is used for planning excavator operations, forming a digging map based on its results. During excavation, the *Ore Quality Recognition* module using a Fourier interferometer is applied to distinguish overburden from ore and collect data on ore quality characteristics [16–18]. This data is transferred to the *Stockpile Formation Algorithm* and *Blend Formation* modules to generate dispatch plans for ore delivery to the processing plant (Fig. 1, *b*).

– **Ore Transportation by Haul Trucks**

After ore is loaded, the haul truck moves to the Ore Control Station (OCS), where the *Ore Mass Measurement in Haul Trucks* module estimates the ore mass based on volumetric fill level, increasing accuracy in quantitative ore accounting. In the case of an emergency dump within the pit, the *In-Pit Transportation Accounting* module records ore presence on the block and sends this information to the duty geologist for further decision making. Upon unloading at the transfer stockpile, the *Stockpile Formation Algorithm* calculates the quality gradient based on the unloading location, refining ore characteristics for the *Railcar Movement Scheduling* module, which plans rail dispatch from the transfer stockpile [19–21] (Fig. 1, *c*).

Table 2

Description of the modules of the "Intelligent Quarry" HSS

Module	Tasks	Description
Stabilization of the blend		
Conversion of block model to blast model	– Reduce specific consumption of explosives through adaptive drilling and blasting grid planning based on rock characteristics	This module uses neural networks to analyze geological data and drilling parameters. Inputs include physical and mechanical properties of rocks, explosive parameters and drilling configurations
Fourier spectrometer	– Speed up ore quality assessment by visualizing in-blast ore characteristics. – Improve ore quality data in haul trucks	The module uses interferometer-based Fourier spectrometry for remote sensing and in-pit ore visualization. It allows distinguishing ore from waste and collecting data on valuable components and impurities
In-pit transportation accounting	– Improve planning quality of new block development. – Reduce transport costs through accurate haul truck load tracking	Uses GNSS for real-time vehicle tracking and RFID for automatic vehicle identification. The module accounts for vehicle location and load status in different quarry zones
Ore mass measurement in haul trucks	– Improve mass accounting for ore transported to stockpiles. – Improve ore inventory accuracy at stockpiles	Uses LiDAR to measure distances via laser beam. LiDAR scanners installed at the OCS capture 3D profiles of truck beds to determine transported ore volume and mass
Stockpile formation algorithm	– Improve ore inventory accuracy at stockpiles. – Improve information on ore properties dispatched to the plant	Based on data integration: ore properties, logistics, and production plans. It accounts for stockpile dynamics and ore distribution strategies
Railcar scheduling module	– Improve planning quality by accounting for organizational factors. – Automate the railcar dispatching process	Operates on real-time data about ore availability, stockpile status, and plant operations. It generates production plans and optimized transport schedules
Granulometric composition control	– Improve drilling and blasting planning via analysis of grid structure and actual particle size data	Analyzes drilling and blasting grid and granulometric composition using machine vision. This improves drilling patterns and explosive usage based on rock fragmentation
Stockpile positioning system	– Improve accuracy of ore property information in formed stockpiles	Uses radio frequency sensors to refine ore quality tracking in formed stockpiles
Optimization of the blend		
Blend formation module	– Reduce losses via optimal processing modes for specific ore types. – Reduce risks of losing magnetic properties due to overgrinding	Uses AI-based modeling to simulate ore processing, adjusting production parameters. Targets maximum output under given constraints by combining data on ore quality, stockpile state, and transport logistics
Calculator	– Improve ore mass accounting for material transported to stockpiles	Using a mathematical modeling apparatus, the module allows monitoring production processes in real time, without being tied to three-hour cycles of chemical analysis, but using this information as calibration.

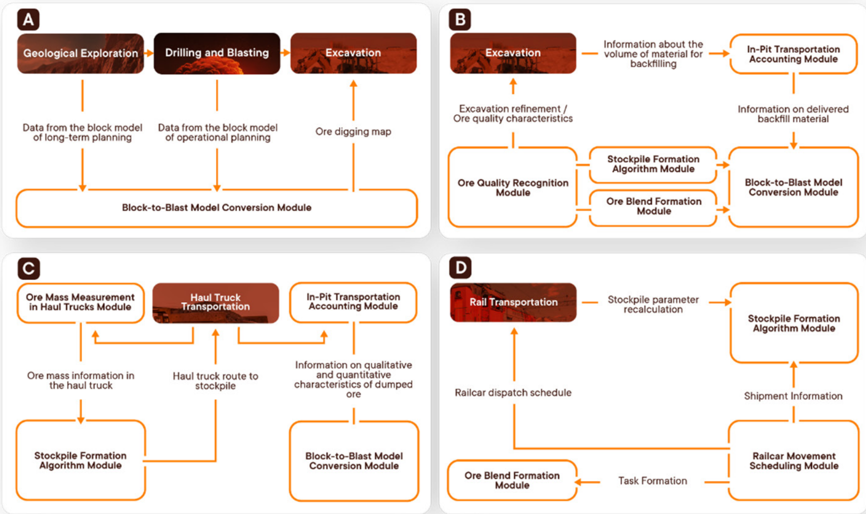

Fig. 1. Interconnection of modules in the “Intelligent Quarry” HSS

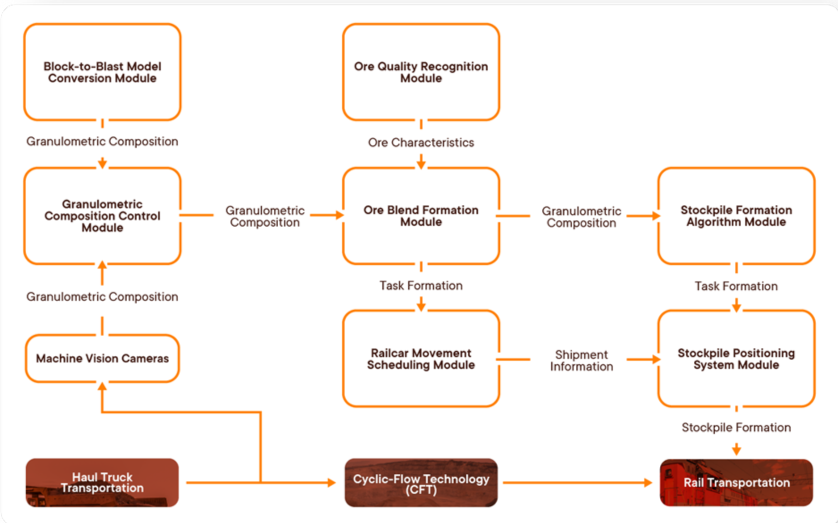

Fig. 2. Interconnection of modules in the CFT framework

– **Ore Transportation by Railcars**

During scheduling of railcar dispatch to transfer stockpiles, the *Railcar Movement Scheduling* module calculates the number of trains, their travel, loading, and unloading times, taking into account organizational constraints and data from the *Blend Formation* module, which forms ore “packages” considering iron and sulfur content for further crushing [22].

Ore shipment from the stockpile is accompanied by recalculation of ore characteristics in the *Stockpile Formation Algorithm* module (Fig. 1, *d*).

– **Cyclic-Flow Technology (CFT)**

When operating at the central quarry, CFT will be used for the transportation of ore and overburden. To monitor ore quality characteristics, the *Granulometric Composition Control* module collects grain size data from the *Block-to-Blast Model Conversion* module and technical vision cameras [23–25].

The *Ore Quality Recognition* module or sensors of the ore stream monitoring system provide real-time control of ore quality parameters.

The *Stockpile Formation Algorithm* module forms ore piles based on data from the *Blend Formation* module. The positioning of the stacking machine is carried out using a radio-frequency-based positioning system [26] (Fig. 2).

Results and discussion

To justify the feasibility of implementing the proposed solutions, a techno-economic assessment (TEA) was conducted. This included evaluating the mutual influence of solutions on one another. A methodology was proposed that combines expert evaluation, statistical methods and combinatorics. Table 3 presents the list of solutions along with their weighting coefficients [27, 28].

Table 3

Weighting coefficients of solutions in the "Intelligent Quarry"

№	Solution	Weighting coefficient
1. *Blend Optimization*		
1.1	Blend Formation Module	0.80
1.2	Calculator Module	0.20
2. *Blend Stabilization*		
2.1	Block-to-Blast Model Conversion Module	0.10
2.2	Imaging Fourier Spectrometer	0.30
2.3	In-Pit Transportation Accounting Module	0.10
2.4	Ore Mass Measurement in Haul Trucks	0.20
2.5	Stockpile Formation Algorithm Module	0.15
2.6	Railcar Scheduling Module	0.05
2.7	Granulometric Composition Control Module	0.05
2.8	Stockpile Positioning System	0.05

The normalized effect for each group of solutions is determined by the following equation:

$$Э_i = \begin{bmatrix} \gamma_1 \\ \vdots \\ \gamma_n \end{bmatrix} \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} Q_i, \tag{1}$$

where $Э_i$ is the normalized effect for the i-th group of solutions; γ_n is the weighting coefficient of the solution; Q_i is the production increase in concentrate for the i-th group.

If a solution is selected from a group, a "1" is assigned in the identity matrix row corresponding to the relevant weighting coefficient.

The total normalized effect, considering the mutual influence of the solutions, is calculated by the equation:

$$Э_\Sigma = \sum_{i=1}^{3} Э_i + \Delta Q \cdot \sum_{i=1}^{3} \alpha_i \frac{n_i}{N_i}, \tag{2}$$

where ΔQ is the production increase from the synergistic effect; α_i is the influence degree of the weighting coefficient (see Table 4); n_i is the number of solutions implemented from the group; N_i is the total number of solutions in the group [29, 30].

Table 4

Influence degree of weighting coefficients

Influence Degree	Value	Condition
α_1	0.1	if $\gamma_n \in [0; 0.1]$
α_2	0.3	if $\gamma_n \in [0.1; 0.2]$
α_3	0.6	if $\gamma_n \in [0.2; 1.0]$

The increase in concentrate production from the synergistic effect is calculated as:

$$\Delta Q = Q_{\Sigma} - \sum_{i=1}^{3} Q_i, \tag{3}$$

where Q_{Σ} is the increase in concentrate production.

Thus, using the formula for the total normalized effect, it is possible to calculate the total technical effect depending on the decisions taken for implementation.

To conduct a quantitative assessment, key production indicators were selected, such as ore and concentrate productivity, magnetic iron content in tailings, product yield and extraction [31, 32].

The implementation of the "Intelligent Quarry" HSS is expected to result in: an increase in productivity from 356 to 359 t/h, an increase in iron extraction by 0.61% and a decrease in the magnetic iron content in tailings from 1.72% to 1.52%, which indicates an improvement in the beneficiation efficiency.

The expected increase in the yield of the final product was 0.2%, and the annual concentrate production was 171438 tons, which confirms an increase in technological efficiency due to the optimization of ore flow management processes and stabilization of the blend parameters [33, 34].

Conclusion

The concept of the "Intelligent Quarry" HSS demonstrates high potential for implementation across various mining and processing plants due to its adaptability to production conditions and modular architecture. This enables enterprises to gradually integrate digital technologies without the need for complete infrastructure modernization, minimizing costs and reducing associated risks.

The system's flexibility allows for customization to match specific parameters of ore extraction, transportation, and processing, making it applicable to large-scale mining and processing plants as well as medium and small enterprises. Further development of the system may include the expansion of predictive analytics, digital orebody modeling and automated equipment control, providing opportunities to optimize production processes, increase recovery rates of valuable components and reduce technological losses.

The prospects for deploying the *Intelligent Quarry* system are associated with the continued expansion of its functionality, including the advanced use of predictive analytics, integration with digital twins of deposits and the implementation of autonomous equipment control systems. The evolution of AI and the IoT technologies creates the groundwork for establishing a unified intelligent environment that unites mining, transportation and processing into a closed-loop automated circuit. This will not only improve operational efficiency, but also reduce environmental impact through the rational use of resources and optimization of energy consumption.

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