Intelligent Management in the Mining 4.0

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The achievements of the Fourth Industrial Revolution, embodied in “end-to-end” digital and convergent technologies, are able to ensure the stable development of the mineral resource sector in the face of fluctuations in raw material demand and the profitability of mining enterprises, strengthening environmental safety legislation. Mining 4.0 is also a response to the technological shocks associated with the accelerated digital modernization of the manufacturing and infrastructure industries. Mining 4.0 is a relatively new platform that allows, with the help of digital innovations, to move to more advanced production optimization.

Mining 4.0 production model

1. General Trend of Deep Digitalization of Processes in Mining

The trend towards the digitalization of mining in line with Industry 4.0 is fundamentally different from previous industrial revolutions in that instead of deepening production automation, new forms of connecting people, machines and technologies come to the fore. These connections are in the nature of supplementing human intelligence with ma-chine intelligence, as well as receiving and processing huge amounts of information used in making engineering, organizational and economic decisions. As a result, the global competitiveness of national mineral resource complexes is determined by the level of development of national projects and programs for the digitalization of industry. It was the Industry 4.0 strategy, being implemented for the first time in Germany that provided this country with technological leadership in the basic sectors of the economy. Similar global advantages in the extraction and export of raw materials have been given by such national digitalization strategies as “Made in China 2025” and “Society 5.0” in Japan [1]. At the level of individual enterprises, digital solutions for the development of processes for the extraction and processing of minerals make it possible to bring productivity to the level that can guarantee profitable operation in the face of shocks in world prices for raw materials, rising labor costs and an increase in the volumes required for technological modernization of investments [2].

The reference method of mining digitalization is the transition to Computer Integrated Mining (CIM), which reflects a certain level of digital maturity of companies involved in the extraction and primary processing of minerals. Its quintessence is the integration of digital systems for planning and managing mining operations, monitoring the condition of equipment, safety of work and product quality into a single enterprise IT system. The main principle of the CIMG method is the absence of “gray” zones of digitalization—processes that are not covered by the use of modern IT, remote sensing, machine vision and intellectual prediction [3].

The digital core of Mining 4.0 is not formed all at once, but is the result of the evolution of human competencies in the use of hardware and software platforms, as well as an increase in the digital maturity of mineral extraction and processing. As the transition from the use of programmable controllers in individual mechanisms to digital control systems and further to artificial intelligence, digitalization expanded from individual mining processes to complete intellectualization of the technological chain up to their processing, taking into account market prices and regional demand specifics. As a result, the concept of Smart Mine involves reducing for a person the growing complexity of organizing production processes, which are managed at the “right time”, i.e., in the required time and volume. At the same time, the digital maturity of existing mining enterprises is significantly lower than that of processing and even metallurgical enterprises, and corresponds to the Digital 2.0 level, compared to the target Digital 4.0 (characteristic of Mining 4.0) [4].

Mining 4.0 is about harnessing the power of digitalization to transform the value chain. This will be due to the integration of the extraction and processing of mineral resources into digital ecosystems, which can increase productivity, reduce operating costs and increase the security of cyber systems and the safety of miners [5].

The peculiarity of Mining 4.0 digital technologies is that they allow changing the vision, strategy, operating model and business opportunities of companies. Combined with the digitalization of the management system, this creates the basis for value maximization.

The wide impact of IT on mining is forming a digital enterprise ecosystem that includes digital twinning, intellectualization, console visualization and robotization of all elements of the supply chain and processes. The actual configuration of mining digital ecosystem depends on the connection and recombination of interactive information systems of individual processes in it, such as extracting, transportation and processing of minerals, material logistics, ventilation and electricity supply [6].

In such digital ecosystem of enterprises of the mineral resource complex, the role of a worker is radically changing —from the operator of equipment (including automated and partially robotic) to Operator 4.0. Such a “miner of the future” should have the following competencies: using biomechanical support to increase strength and endurance, relying on augmented reality to integrate the digital and physical world (for example, to receive online help from equipment manufacturers through interactive VR glasses), the mandatory use of smart sensors (underground 5G) to connect information about the environment and the health of a miner, the use of intelligent personal assistants to interact with equipment (training of collaborative robots) and databases (self-learning, operational forecasting based on the analytics of Big Data) [7]. Industrial digital ecosystems received a new impetus for development during the COVID-19 pandemic, which in-creased the digital maturity of construction, transport and energy to Digital 3.0 and above. These same processes will contribute to the digital maturity of mining in coming years [8].

In the development of the digital ecosystem of Mining 4.0, there is a problem of insufficient unification of software from different manufacturers and difficulties in their system integration. The architecture of the digital ecosystem in mining has a domain structure that integrates IT systems developed by different vendors (for example, ABB—production solutions, OSIsoft—data integration from various systems, IBM Maximo—asset management solutions, Microsoft Azure—cloud data management, Microsoft Dynamics 365—customer relationship management and Microsoft Power BI—integrated business analysis). These information systems have technology stack and data formats, so one system can interact with another system of the same vendor, but communicates with software products from other vendors using Microsoft Excel only.

On the frontier of Mining 4.0, progress in the digital transformation of the mineral sector is largely due to active research in the field of managing dynamic multi-component multi-loop objects in real time. This allows AI-based control systems to take control of the interconnected processes in mining and transportation of minerals and achieve a high lev-el of optimization. The controllers used in such control systems apply the new Flight Control Language (FCL), which are designed considering the methods of fuzzy logic and use a new type of data—a linguistic variable, which connects numerical variables with the names of indicators [9]. A linguistic variable can take on the meaning of artificial language phrases. Therefore, for safe unmanned control of equipment, the linguistic variable “speed” can have not only a specific indicator (quantitative value), but also a qualitative one—high, low, unsafe, safe, etc. This significantly increases the efficiency of decisions made by artificial intelligence.

2. Internet of Things in Mining 4.0

Modern technologies of the Internet of things (IoT) give the mineral resource sector a unique opportunity to exclude humans from many processes of operating machines and mechanisms in complex, harmful and dangerous mining conditions. As a result, there is a radical reduction in the influence of the human factor on mining operations and their dangerous factor on humans, thanks to Smart Sensors for temperature, humidity, light, speed, passive infrared radiation and distance [10].

The Internet of Things in Mining 4.0 is functionally closely related to the Energy Internet, since a significant part of mining equipment has high-power energy drives. Accordingly, such principles of energy network architecture as plug-and-play, bi-directional flows of energy and power consumption information and combinations of renewable and non-renewable sources are implemented using advanced Internet technologies such as the Internet of Things and Block-chain. Machine-to-machine interactions built on these technologies allow not only increasing productivity, but also to reduce power consumption [11]. An important point of application of machine-to-machine interactions based on the Industrial Internet of Things is real-time monitoring of the technical condition of mining equipment [12].

The scope of the Internet of Things in mining extends far beyond advanced diagnostics and control of equipment load along the overall production chain. “Digital Mine” is based on such interactions on the Internet of Things platform as dynamic planning and scheduling, safety and security monitoring, automated supply chain [13].

To process the massive data streams generated by the Internet of Things in the industry, a distributed frequent itemset mining algorithm is required. In relation to the extraction of minerals, the extraction of key data from the general array of engineering information can be called “Data Mining in Mining 4.0”. Perspective engine here is

Apache Spark, successfully used for industrial data mining, includes the SWEclat algorithm, which has good acceleration, parallel scalability and load balancing [14].

3. Intelligent Management and Business Projects Making as Mining 4.0 Economic Basis

A distinctive feature of Mining 4.0 is the transition from relying on the competence of people in the design and management of mining operations to “smart” cyber-physical systems. The technical component of such “smart” systems was discussed in detail above as the integrated use of smart sensors, machine vision and learning, artificial intelligence, unmanned mining equipment. At the same time, the “smartness” of Mining 4.0 also consists in optimizing technological and management systems of mining enterprises. Therefore, smart management and projects making must satisfy the conditions for optimizing the entire enterprise as a whole, and not its individual processes in terms of a single profit indicator, taking into account both production and financial, as well as information and cognitive limitations.

Further, the system optimization in the management of mining companies should go through all the stages of creating a “smart” enterprise: optimization of technological solutions using unmanned equipment and artificial intelligence, drones, 3D modeling; structural optimization of production and financing; parametric optimization of processes.

System optimization of processes, typical for “smart” mining enterprise, requires a multi-criteria decision-making (MCDM) system. The well-established selection and prioritizing smart mine strategies using is a combination of Z-number theory and fuzzy weighted VIKOR technique with a Fuzzy Cognitive Map (FCM) [15]. Design, planning of mining operations and sustainable operation of mining enterprises in the context of the expansion of Industry 4.0 technologies should be carried out on the basis of those strategies that emphasize the social license to operate green mining [16]. For example, the introduction of machine learning in the mining industry requires the formation of a new business model for optimizing production processes, at the heart of which lies the flexible methodology of the Industry 5.0 paradigm, which takes into account the importance of environmental innovation and ESG investment [17]. Systemic digital transformation of extractive enterprises requires the combined efforts of all stakeholders—extractive companies, the state, civil society and academic circles [18].

A “smart” tool for making optimized decisions is Cloud Mining—the integration of the core business through the use of cloud technologies, resources and services. As a result, a new mining cluster management mode is being formed, based on five pillars: digital data, digital technology, digital talent, cloud business and cooperation. On the cloud platform, you can implement geological modeling, reserve estimation, mine design and sales planning.

Incrasing the availability for data analysis at the most detailed level using the Industrial Internet of Things (IIoT) allows creating Key Performance Indicators (KPI) for managers and engineers of different levels based on aggregated information in the chain of cause-and-effect relationships. Consistent operational optimization of all production, logistics, and financial operations of an enterprise can be achieved through the use of modern solutions for IIoT data logging and real-time analysis [19].

Systematic optimization of mining production is impossible without the complete extraction of minerals, which are considered secondary, as well as without reducing industrial injuries in the mining industry. Accurate forecasting of the production and economic potential of recovering secondary minerals requires the use of a computational tool using a decision analysis model with several criteria, for which Analytical Hierarchical Process (AHP) and Python can be used [20]. For a systematic analysis of occupational injury factors, it is possible to use the machine learning models such as DAFW, ANN and MSE. In particular, DAFW is an indicator of the severity of the injury; it also could help the stuff management to plan for replacements when an injury occurs. Using the method of synthetic data augmentation using words embedding allows solving the problem of data imbalance [21].

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