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DIGITAL SIMULATION OF OPEN-PIT MINING ORGANISATION SYSTEM

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ABSTRACT: The process of digitalization in Ukraine is slow, so studying the state of digitalization of the mining industry is a very relevant issue and will help increase the competitiveness and efficiency of enterprises, which is important for the development of the national economy. The research aims to the state of mining industry digitalization in Ukraine, develop an effective methodology for volumetric modelling of open-pit mining enterprises, and implement an effective digital modelling system. Research methods include analysis of literature sources, factor and situational analysis, comparative economic analysis, system analysis of software, and digital modelling of the enterprise system. Mining and geological data processing and mathematical modelling were used to obtain the following results: the data were digitized, a polygon database was built, the area of the ore body was determined, the cut planes were constructed and drilling and blasting operations were modelled. The creation of a frame and block model of the deposit is investigated and a methodology for block modelling of mineral quality is proposed, which will allow for high-reliability zoning of technological types of minerals in the quarry. Implementing an integrated software system for the digital modelling of the deposit will enable efficient visualization of the distribution of useful components, resulting in improved competitiveness and modernized planning and management of mining processes. The proposed block modelling methodology for the open pit space further enhances the practical value of the study.

Keywords: Resource estimation; Block modelling; Digital field model; Digitalization; Automation.

1. INTRODUCTION

One of the major challenges facing Ukraine's mining industry is the need for rational use of natural resources to ensure the sustainable development of enterprises. However, the introduction of the latest technologies at open-pit mining enterprises is slow due to the complexity of production, conservative approach and economic crises. Attracting foreign investment and advanced technologies, exploring and developing new deposits, introducing automation and process optimization, and ensuring harmonization with the environment are the main strategic goals of the Ukrainian mining industry. However, the country has significant potential to increase the production of minerals, including ores, but this requires large investments in the development of efficient mining technologies. The level of an enterprise's efficiency depends on its productivity and operational advantages, and in this context, digitalization and digital system modeling play an important role in enabling mining companies to remain competitive in the future [1]. Currently, Ukraine is a poorly developed market for mining and geological software. The topic of mining and processing enterprise investment was studied by Sundari et al. [2]. They emphasize that the world's leading companies are investing heavily in the development and application of modern digital technologies.

The low degree of scientific research on the issue in Ukraine is explained by the novelty and the poor study of digital modelling systems and their relationship with project management practice. It is worth noting the study of Zub and Kalach, which addresses the theoretical nature of digitalization and the introduction of digital systems and technologies in mining enterprises [3].

Given the above, there are problems in the industry, as noted by Fedulova: the need to use several software solutions, problems with import/export, a decrease in production and mining, increased software costs and increased time for engineering calculations [4]. The economic aspect of the mining industry development in the field of creating computer systems, digital models of deposits and the application of modern technologies in practice is considered in the study of Baryatska [5]. The author notes that digital transformation adjusts traditional business models of companies, making them more competitive and progressing the country.

Lazebnyk and Voytenko describe the problems of growing risks, which are exacerbated by geopolitical threats, trade wars, and fluctuations in global markets and accelerate the use of digital technologies by mining companies to improve business efficiency [6]. The described scientific research related to digital modeling of open-pit mining systems that can be used in Ukraine focused on the study of integrated software systems. However, the technology of rock destruction based on a three-dimensional model of a deposit remains insufficiently studied, which requires further research due to its importance in solving current problems. Therefore, the purpose of this study is to develop an effective methodology for volumetric modeling of mine workings of open-pit mining operations for use in applied geological research and to implement an effective digital modeling system.

2. RESEARCH SIGNIFICANCE

The research constitutes a significant contribution to the modernization of open-pit mining enterprises in Ukraine. The capabilities of advanced integrated software systems, such as GEOVIA Surpac and Geobank MICROMINE, were used. This allows to quickly process huge amounts of data, ensuring accurate modeling of mineral deposits and calculation of key indicators. The research made a significant contribution to the study of rock destruction technology based on a three-dimensional deposit model. By implementing this innovative methodology and technological scheme, open-pit mining enterprises in Ukraine stand to gain a significant competitive advantage and contribute to the overall growth of the national economy.

3. THEORETICAL OVERVIEW

The open-pit mining method provides the best economic performance, so it will dominate the mining industry. Frolov and Kosenko note the main problematic issues in the implementation of open-pit mining plans in the traditional manual way: the duration of the formation of annual, medium-term, long-term plans for the development of work, the lack of alternative scenarios for comparison and the ability to make prompt decisions in case of changes in conditions [7]. Effective development of open-pit mining requires the use of new high-performance mining and transportation equipment and the development and implementation of modern digital management systems for open-pit mining and transportation complexes [8; 9].

The leading companies in the world that own system software are Surpac, Mapter, Gemcom, Data-mine, and Mintec. Most often, these systems are purchased by mining companies with foreign capital that have already switched to international standards [10] (Fig. 1). The functionalities of integrated systems include scheduling, database management, land mass planning and geodetic calculations, three-dimensional modelling of geological objects and mapping, planning of open and closed mining operations, and many other functions [11].

Surpac is focused on the open-pit mining method and is the most popular software package. Estimation of deposit reserves, development of mining scenarios, planning the most efficient way to extract useful components, and environmental studies are just a few of the software's capabilities. The construction of a geomechanical digital model of the deposit in the Surpac software package will allow specialists to carry out effective long-term planning of mining operations, analysing the dynamics and considering the risks.

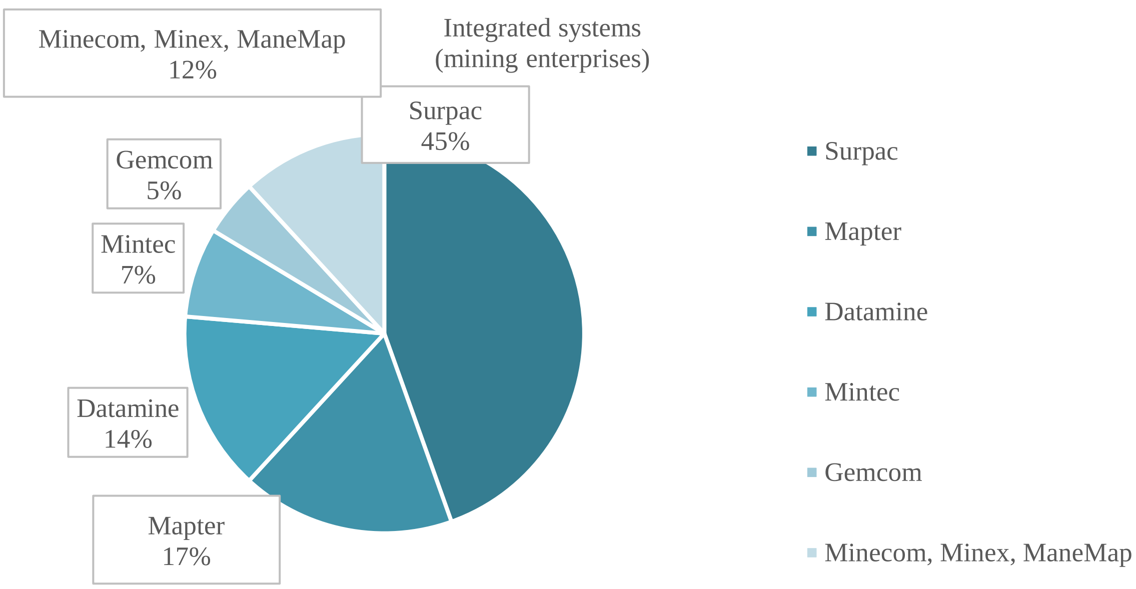

Fig.1 Integrated system employment diagram [10]

The approach to the choice is justified in the work of Slivenko and Sotiropoulos [12], Benardos and Mavrikos [13]. The use of digital deposit models is the basis of modern methods of engineering support for mining enterprises, as a carrier of information on the properties of geometric dimensions, spatial location, physical, mechanical, and technical and economic characteristics of mining facilities. The frame geological model for reservoir deposits and the block model for complex composite bodies are used to assess the prospects of a deposit, and the feasibility of further study and investment [14]. Source analysis of Sigari and Gandomi, Gaiardelli et al. show that advanced international mining companies get the most out of the digitalization of production technology, which allows them to increase the competitiveness of products and long-term continuous production [15; 16]. Well-known foreign leaders include Newmont, I2Mine, Metalkol RTR, Dundee Precious Metals, and Rio Tinto.

Unfortunately, the main problems of Ukrainian mining companies are economic crises, outdated equipment, weak domestic demand for technology, and a deteriorating industry. Ukrainian companies are just starting to improve in this area [12; 17; 18]. Automation and digitalization of production are successfully practiced by a few Ukrainian companies, including DTEK Pavlogradugol, Poltava Mining, and ArcelorMittal Kryvyi Rih.

4. MATERIALS AND METHODS

The main research methods used include literature analysis, methods of factor and situational analysis, digital modelling of the enterprise system, and system analysis of software and open mining enterprises. To assess the economic efficiency of the digital model of the enterprise, the method of comparative economic analysis was used. The theoretical basis of the study is the Ukrainian and global scientific and technical works of specialists and researchers who study strategic issues of economic development and the introduction of digital technologies in mining companies (Fig. 2).

To review and comparatively analyze the issues of enterprise system modelling, the author worked with the following sources of information: official websites of companies, thematic publications, expert opinions of employees of mining companies and design institutes that use specialized software. The authors' personal experience of working with mining and geological information systems was also considered.

The comparative economic analysis method was used to assess the level of the digital readiness of mining enterprises and to identify the economic feasibility of using robotic equipment. The basis for the study was the Industry 4.0 program, the National Economic Strategy 2030, regulatory and methodological documentation and scientific developments in the field of integrated subsoil use and commercial attractiveness, and an analysis of the approach to the selection of technological equipment [19; 20].

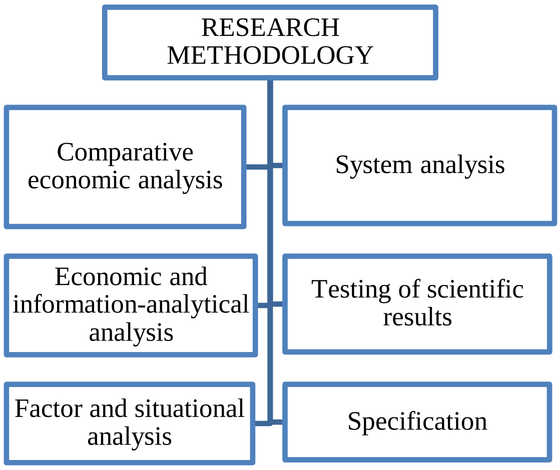

Fig. 2 Flowchart of the research methodology

The study employed a system analysis approach to evaluate the technical and economic data of operational mining enterprises, as well as explore ways to modernize industrial technology. Additionally, the regulatory framework for assessing investment activity was also examined. The study emphasizes the method of economic and information-analytical analysis, modern geological and information technologies, and testing of scientific results. The factors and situational analysis methods were used in the study to analyze the profile problems and factors affecting the development of mining enterprises.

The experience of Ukrainian (DTEK Pavlohradvuhillya, ArcelorMittal Kryvyi Rih) and global (Newmont, I2Mine, Metalkol RTR, Rio Tinto) mining companies that successfully practice digitalization of production was generalized. After conducting a comparative analysis of mining companies, it was found that modern engineering methods rely on utilizing digital deposit models created through an integrated software system. To conduct a comparative analysis of software from leading digital companies, system analysis and analogy methods were used, and a diagram of the use of global systems was drawn.

Currently, it is impossible to obtain reliable information about a software product that requires detailed and expert evaluation. Therefore, the main methods of researching the market of specialized software products (integrated systems Gemcom, Mapter, Mintec, Surpac, Data-mine) are analysis by enlarged blocks and comparison of the functionality of these systems. To study the software, the specification method was used, and research was conducted on options for processing the mining and geological base, developing automated mining complexes, modelling infrastructure facilities and technological processes of mining enterprises.

Deterministic, geostatistical, and neural network methods were used to determine the values of attribute data. The geostatistical method provides an assessment of the qualitative indicators of minerals; the accuracy of the assessment depends on the step of the test network. After conducting the research, it was determined that the most suitable software system for the country's conditions is one that supports an open processing method and enables the utilization of statistical and geostatistical methods.

Utilizing advanced digital and mathematical modelling techniques, a comprehensive model of the deposit database was generated, enabling a precise quantitative assessment of the mineral resources through statistical processing of the research results. Subsequently, employing the mining and geological data processing method based on this model, the relevant data was digitized, the area of the ore body was accurately determined, and the reserves were efficiently estimated and simulated. These innovative methodologies have proved to be instrumental in enhancing the accuracy and reliability of the mineral resource assessment process. Additionally, the sophisticated analytical tools and techniques utilized in this study facilitate a more effective management of mineral resource exploration and exploitation while minimizing the potential impact of environmental and social factors.

5. RESULTS

In design institutes, digital systems can be used to solve various problems related to the planning and design of open-pit mining operations. These digital systems are equipped with various tools and features that allow mining engineers to create and analyze complex geological models, evaluate economic feasibility, and plan the operations of a mining site. One of the main benefits of these digital systems is their ability to create and improve geospatial information support. This support can be used to create detailed maps and plans of a mining site, including horizontal plans that can be constructed automatically in an interactive mode. In addition to geospatial information, these digital systems can also be used to model and form multivariate quarry spaces, taking into account a wide range of technical and economic data.

The action sequence and information support for the preparation and conduct of mining operations at the deposit can be presented in the form of a model of objects that change under the influence of technical processes. The software automation is reliant on frame and block models of ore bodies that contain data on the distribution of rock types within the open-pit space and the mineral content within them. It incorporates frame models of the pits that provide information on the surface structure [21].
Based on the above, the principle of implementing a digital model of an open-pit mining enterprise and its components was illustrated by the example of developing and analyzing a digital model of a deposit using a specialized integrated system. Three-dimensional digital models are the basis of the information and technical database. They may include topographic surfaces, the geological structure of the deposit, the framework of the planned facility, block-component models of minerals and several additional digital characteristics of the open pit (Fig. 3).

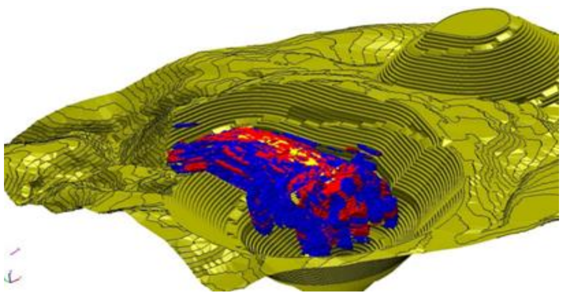

Fig.3 A 3D model of an ore deposit with elements of various useful components

The integrated Surpac system will allow to creation of a digital model of the deposit, considering the current level of geotechnology and determine an effective method of volumetric modelling of mining facilities in the open-pit mining method [13; 22]. Geostatistical three-dimensional modelling consists of the following main stages: database creation, construction of a geometric model of the ore body, compositing and contouring, statistical analysis, block modelling and resource estimation. However, there is one more important feature, thanks to integration with other software tools, Surpac can be integrated into complex mining automation systems, which allows to improve the efficiency and accuracy of the entire production process.

The geological database is a fundamental component of the Surpac software, which serves as the basis for all subsequent calculations and models. Surpac uses a relational database model that links different types of information systems together. The geological database consists of several tables, but two mandatory tables are required for the correct operation of the database: the collar table (Table 1) and the survey table (Table 2). The collar table contains information about the location of drill holes, while the survey table contains data about the orientation and direction of the holes. Together, these tables provide the foundation for the creation of geological models, resource estimates, and mining plans. Surpac's geological database also supports a wide range of additional data types, such as assay data, lithological descriptions, and geophysical data. The software allows users to create and manage their own custom tables, ensuring that the geological database can be tailored to meet the specific needs of each mining project.

Table 1 Bore entry coordinates

Hole_id	x	y	z	Max drilling depth	path
371	52498	71061.21	388.1	40	curved
375	52502.41	71084.07	386.12	30.3	curved
382	52524.07	71045.16	387.11	35.5	curved

Table 2 Drill space coordinates

Hole_id	max	Dip	Azimuth
371	40	-90	0
375	30.3	-90	0
382	35.5	-90	0
387	35.2	-90	0
389	34	-90	0
390	34	-90	0
391	34	-90	0

Using the "Help" function, the projected geological database allows you to generate a report on the location of the object by coordinates, well depth, azimuth of a particular well and drilling angle; issue a report on several specific or all available wells; run a report on the tables and information of the database; obtain information on the minimum and maximum coordinates assigned to the data; generate a lithological column of the selected well in dwf format; run a report on intervals exceeding the specified content [23].

The stage of creating weighted average intervals includes two main operations. The initial stage involves determining the locations of fresh intervals adjacent to the existing intervals within the database using well data. The second operation is related to the calculation of values for the new intervals obtained as a result of compositing and determines the composition of metals. The ore body contour is constructed in sections, combining information on compositing data for individual drill holes. The wireframe model of the ore body is a polygonal object consisting of polygonal shapes, the vertices of which are tied to the points of existing strings. The triangles of the wireframe model form the ore body, which is a completely closed object.

The wireframe model design approach involves constructing a triangulation of the geological sections between segments that are longitudinally furthest apart. By triangulating all segments of the geological sections, we obtain the ore body frame (Fig. 4). From the geological body frame, it is possible to determine its volume by working horizons. The Surpac system supports triangulation and backward distance methods, and grid operations allow us to calculate deposit reserves.

Fig.4 Ore body frame

Block modelling involves creating a model of an object by filling in three-dimensional frames and disassembling the site into elementary blocks. The block model is then imported and analyzed in GEOVIA MineSched, where mining areas are defined and mining equipment is assigned. The block model is a table in which columns indicate the features of an object, and rows are presented in the form of a record (Fig. 5).

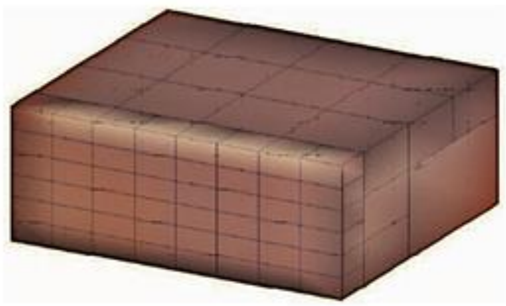

Fig.5 Block-based object modelling

The resulting block model highlights the content of useful components in the ore body in colour (Fig. 6). The geostatistical analysis assesses the degree of heterogeneity of the object, and the construction of a histogram and modelling of the variogram determines the need to divide the deposit into homogeneous areas. The spatial variability of the heterogeneity variable is characterized by the variogram, which takes into account the thickness, dip, and strike characteristics of the ore body.

The dynamic component of the modelling is to track the destroyed material of the block model as it moves under the influence of the explosion to the model of the formation of the exploded rock mass fracture (Fig. 7). Tracking information on the movement of particles predicts the distribution of useful components in the breakdown and increases the reliability of the information in solving production problems.

The modelling results in the form of predictive block models of the dump are transferred to GEOVIA MineSched, which allows increasing the reliability of the information on the distribution of the content of useful components in the dump when solving operational planning tasks. The study describes in more detail the creation of a frame and block model of the deposit and rock breakdown (program I Blast-7) based on GEOVIA Surpac software. By utilizing digital mining technology processes, it is possible to create a digital twin of the enterprise. This allows for the integration of various tasks, such as mining design and planning, safety management through equipment dispatching, and personnel movement, all in a single virtual space [24].

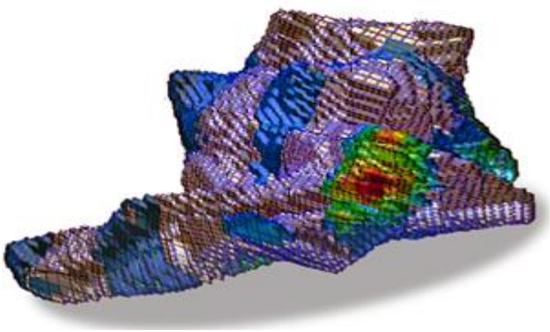

Fig.6 Useful component distribution in the ore body contour

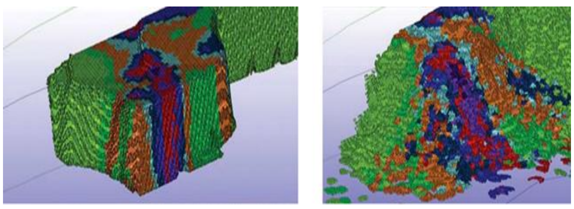

Fig.7 Explosive rock destruction modelling

6. DISCUSSION

To implement the fault modelling, integration with GEOVIA Surpac is successfully carried out, which allows for the timely exchange of geological and survey data in the form of block and digital triangulation models. The GEOVIA Surpac system fully complies with international standards and has all the necessary functions for the successful operation of the digital mining system model. In addition, the combined use of several software systems increases the efficiency of surveying support for deposit development methods [25; 26].

Bariatska and Safronova discuss the MICROMINE system and perform three-dimensional modelling and estimation of ore deposits resources [27]. However, the study found that the main stages of modeling in MICROMINE and Surpac have a similar structure: database creation, wireframe modeling, static analysis, ore body compilation and delineation, geostatistical studies, block modeling and resource estimation. In addition, the MICROMINE system is most used for underground mining, while Surpac is used for open-pit mining.

However, there are several problems that an enterprise may face at different stages of implementing a digital modelling system. Hu et al. examine another aspect of the topic, such as the digital readiness of an enterprise for digitalization [28]. To assess the level of the digital readiness of a mining enterprise, the authors analyzed the most significant factors and identified problem areas: uninterrupted power supply, communication, and Internet access. The digitalization analysis of Ukrainian open-pit mining companies showed that only a few companies have reached a high technological and organizational level of "digital maturity", which can economically justify the costs of using robotic equipment [29]. The lack of highly skilled professionals in the mining industry is discussed by Storey, which is one of the main reasons for the slow adoption of digital technologies in the sector [30]. Based on the above, we can conclude that the main constraint is the lack of qualified personnel to work with specialized software, which results in a serious shortage of specialists in some countries, including Ukraine.

The utilization of modern geotechnologies in planning processes through integrated software systems has enabled the rapid advancement of technological means of mechanization and automation, equipment placement and management, communication tools, and monitoring of product quality and equipment condition in the mining industry [31; 32].

7. CONCLUSION

In conclusion, this study aimed to investigate the state of digitalization in the mining industry in Ukraine and develop a methodology for volumetric modelling of open-pit mining enterprises, which was implemented through an effective digital modelling system. The research methods included analysis of literature sources, factor and situational analysis, comparative economic analysis, and system analysis of software, among others.

The study found that mining and geological integrated systems are the basis of information support for digital modelling of open-pit mining enterprises, and the GEOVIA Surpac software package is a suitable integrated software system for the Ukrainian market. Using this system, a digital three-dimensional model of the field was created, which allowed for the calculation of reserves, modelling of drilling and blasting operations, and determination of the quality characteristics and technological types of minerals in the quarry space.

The technology of rock fracture modelling was investigated, and it was found that the technology of modelling the collapse allows for an increase in the reliability of information on the distribution of useful components in the collapse, which increases the cost of minerals and ensures the prevention of emergencies before blasting. The implementation of the developed methodology and technological scheme for digital modelling of open-pit mining enterprises will increase their competitiveness and accelerate the modernization of planning and management of mining production processes, contributing to the growth of the national economy.

To further develop the mining industry and improve the efficiency of mining operations, it is necessary to pay attention to the potential of rock fracture modeling technology. The use of this program will significantly reduce the risk of negative consequences of mining operations, as well as increase their efficiency and productivity. In addition, it is important to study the relationship between the company's digital maturity and the growth rate of automation. This will allow us to understand what steps need to be taken to increase production efficiency and improve working conditions for miners. Studying this relationship will help identify shortcomings and problems in the company's operations and find ways to solve them using digital technologies.

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