

OPTIMIZATION OF DIGITAL MODELING METHODS IN MINING BASED ON GEOSTATISTICAL AND GIS APPROACHES

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ABSTRACT. The development of modern mining enterprises requires the implementation of advanced digital technologies to improve the accuracy, efficiency and safety of production processes. One of the key directions is the optimization of digital modelling methods based on geostatistical analysis and geographic information systems (GIS), which allow integrating heterogeneous spatial data and improving decision-making in mining operations. The purpose of this study is to optimize digital modelling methods in mining based on geostatistical and GIS approaches. The research is based on the analysis of modern technologies used in deposit geometrization, including 3D modelling, GIS, machine learning methods and digital twins. The methodology includes the use of geostatistical methods such as kriging and inverse distance weighting (IDW), GIS-based spatial analysis, and integration of data obtained from UAV surveys, GNSS measurements and geological exploration. A comparative analysis of software products used for digital modelling in mining was also carried out. The results show that the integration of GIS technologies and geostatistical methods significantly improves the accuracy of spatial modelling and allows optimization of mining processes. It was determined that the use of machine learning algorithms enhances forecasting capabilities and supports real-time decision-making. In addition, the analysis of digitalization costs demonstrated the importance of a phased implementation strategy to ensure economic efficiency. The proposed integrated approach to digital modelling allows improving the quality of resource estimation, optimizing production planning and reducing environmental risks. The obtained results confirm the effectiveness of applying combined geostatistical and GIS approaches for the development of modern mining systems.

Key words: digital modelling, mining, GIS, geostatistics, optimization.

ОПТИМИЗАЦИЯ НА МЕТОДИТЕ ЗА ЦИФРОВО МОДЕЛИРАНЕ В МИННОТО ДЕЛО, БАЗИРАНИ НА ГЕОСТАТИСТИЧЕСКИ И ГИС ПОДХОДИ

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РЕЗЮМЕ. Развитието на съвременните минни предприятия изисква внедряването на съвременни цифрови технологии за подобряване на точността, ефективността и безопасността на производствените процеси. Едно от ключовите направления е оптимизирането на методите за цифрово моделиране, базирани на геостатистически анализ и географски информационни системи (ГИС), които позволяват интегрирането на хетерогенни пространствени данни и подобряването на вземането на решения в минните операции. Целта на това изследване е да се оптимизират методите за цифрово моделиране в минното дело, базирани на геостатистически и ГИС подходи. Изследването се основава на анализ на съвременните технологии, използвани в геометризирани находища, включително 3D моделиране, ГИС, методи за машинно обучение и цифрови близнаци. Методологията включва използването на геостатистически методи като кригинг и обратно претегляне на разстояние (IDW), пространствен анализ, базиран на ГИС, и интегриране на данни, получени от проучвания с безпилотни летателни апарати, GNSS измервания и геоложки проучвания. Извършен е и сравнителен анализ на софтуерни продукти, използвани за цифрово моделиране в минното дело. Резултатите показват, че интегрирането на ГИС технологии и геостатистически методи значително подобрява точността на пространственото моделиране и позволява оптимизиране на минните процеси. Установено е, че използването на алгоритми за машинно обучение подобрява възможностите за прогнозиране и поддържа вземането на решения в реално време. Освен това, анализът на разходите за цифровизация демонстрира значението на поетапната стратегия за внедряване, за да се гарантира икономическа ефективност.

Предложеният интегриран подход към цифровото моделиране позволява подобряване на качеството на оценката на ресурсите, оптимизиране на планирането на производството и намаляване на екологичните рискове. Получените резултати потвърждават перспективността на прилагането на комбинирани геостатистически и ГИС подходи за разработването на съвременни минни системи.

Ключови думи: цифрово моделиране, минно дело, ГИС, геостатистика, оптимизация.

Introduction

The modern mining industry is undergoing rapid digital transformation driven by the need to improve the efficiency, accuracy, and safety of production processes. The increasing complexity of geological conditions and the growing demand for mineral resources require the use of advanced technologies for data processing, analysis, and modelling (Carvalho, 2017; Choi et al., 2020).

One of the key tasks in mining is the accurate geometrization of mineral deposits, which provides reliable information about the spatial distribution of resources and serves as a basis for effective planning and management of mining operations (Hustrulid et al., 2013). Traditional methods are often limited in their ability to process large volumes of heterogeneous data and ensure high accuracy.

In recent years, digital modelling based on geographic information systems (GIS) and geostatistical approaches has become widely used in mining practice. These technologies

allow the integration of various data sources, including geological exploration, geodetic measurements, and remote sensing, into a unified digital environment.

Despite significant progress, there remains a need to optimize digital modelling methods to improve their accuracy, reliability, and efficiency. Therefore, the application of integrated geostatistical and GIS approaches is a relevant scientific and practical task in modern mining.

Theoretical part and methodology

Digital modelling in mining is based on the integration of various data sources, including geological, geodetic, and remote sensing data (Choi et al., 2020; Vangu et al., 2023). Geographic information systems (GIS) provide tools for spatial data management, visualization, and analysis, enabling the creation of comprehensive three-dimensional models of mineral deposits (Choi et al., 2020).

Geostatistical methods play a crucial role in modelling the spatial distribution of geological parameters. Among the most commonly used methods are kriging and inverse distance weighting (IDW), which allow interpolation of data and improve the accuracy of resource estimation in conditions of spatial variability (Kim et al., 2018; Uyan & Dursun, 2021).

Modern digital technologies also include the use of unmanned aerial vehicles (UAVs), GNSS measurements, and photogrammetric processing, which significantly increase the density and accuracy of spatial data (Kunyska et al., 2023). The integration of these technologies into GIS environments allows for efficient data processing and visualization.

In addition, machine learning methods are increasingly used for analysing large datasets, identifying hidden patterns, and forecasting changes in geological conditions. The concept of digital twins enables real-time monitoring and simulation of mining systems, which improves decision-making and operational efficiency.

Thus, the integration of GIS technologies, geostatistical methods, and modern digital tools forms the theoretical basis for optimizing digital modelling methods in mining.

Results and discussion

The analysis of modern digital modelling methods in mining demonstrates that the integration of GIS technologies with geostatistical approaches (Choi et al., 2020; Uyan & Dursun, 2021) significantly improves the accuracy and reliability of spatial models (Fig. 1).

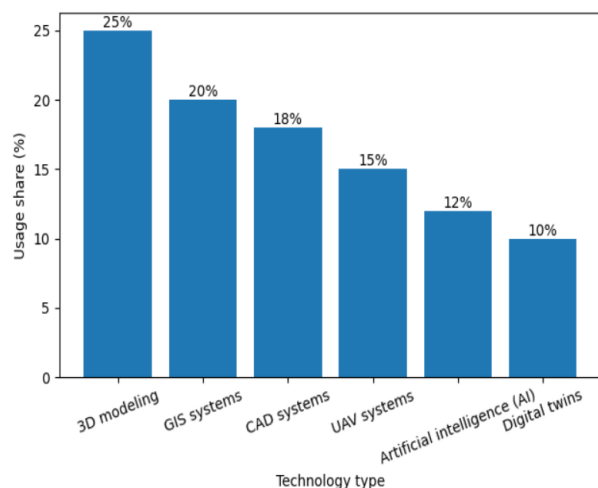


Fig. 1. Distribution of the application of key digital technologies in mining

It was established that geostatistical methods such as kriging and inverse distance weighting (IDW) provide a higher level of accuracy in modelling the spatial variability of mineral deposits, especially under conditions of heterogeneous geological structures. These methods allow more precise interpolation of geological parameters and reduce uncertainty in resource estimation.

The use of GIS technologies ensures efficient integration, processing, and visualization of heterogeneous data obtained from various sources, including geological exploration, UAV surveys, and GNSS measurements (Vangu et al., 2023). This integration significantly enhances the quality of spatial analysis

and supports more informed decision-making in mining operations. (Uyan & Dursun, 2021)

The results also indicate that the application of machine learning algorithms improves predictive capabilities and enables the identification of hidden patterns in geological data. This contributes to the optimization of mining processes and allows real-time monitoring and adjustment of production parameters.

At the same time, the analysis of digitalization processes has shown that the implementation of digital technologies requires significant initial investments and careful planning of financial resources. The distribution of digitalization costs at different stages of implementation is presented in Fig. 2.

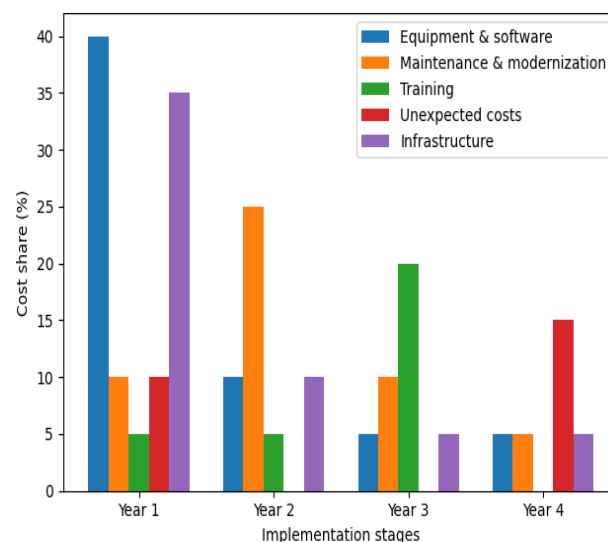


Fig. 2. Distribution of digitalization costs across different implementation stages

An important result of the study is the identification of key challenges in the implementation of digital technologies, including data heterogeneity, lack of standardized approaches, and shortage of qualified specialists (Fig. 3).

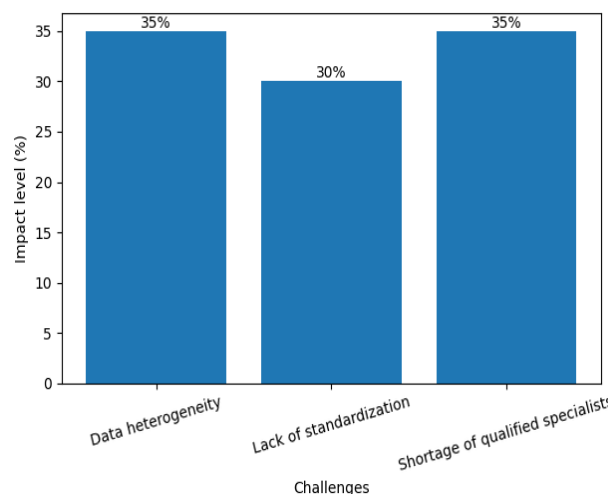


Fig. 3. Key challenges in the implementation of digital technologies in mining

Despite these challenges, the advantages of digital modelling significantly outweigh the limitations, providing improved accuracy, operational efficiency, and environmental sustainability of mining enterprises.

The obtained results confirm that the integrated use of GIS technologies and geostatistical methods is an effective and perspective approach for optimizing digital modelling processes and improving the overall performance of mining systems

Conclusion

The conducted study confirms that the optimization of digital modelling methods based on geostatistical and GIS approaches is an effective way to improve the efficiency and accuracy of mining operations.

It was established that the integration of GIS technologies with geostatistical methods such as kriging and inverse distance weighting (IDW) significantly enhances the reliability of spatial modelling and reduces uncertainty in resource estimation. The application of machine learning algorithms further improves predictive capabilities and supports real-time decision-making.

The analysis of digitalization processes demonstrated that despite the need for significant initial investments, the implementation of digital technologies provides substantial advantages, including improved operational efficiency, better resource management, and reduced environmental risks.

Thus, the integrated use of GIS, geostatistical methods, and modern digital technologies represents a promising direction for the development of mining systems and the sustainable use of mineral resources.

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