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STOPE OPTIMIZER IN UNDERGROUND MINING

Abstract. The article presents a method for optimizing stopes in underground mineral extraction. Based on cluster analysis of the block model, the proposed algorithm forms extraction units by accounting for both quantitative and qualitative characteristics of raw materials. A new approach is introduced to calculate the partial inclusion of geological blocks in clusters, offering greater accuracy than centroid-based methods. To optimize slope angles, the method applies the least squares technique and Mahalanobis distance, which helps reduce ore loss and dilution. The algorithm increased ore recovery by 4.3% while maintaining the target cut-off grade. Its novelty lies in precise geometric modeling of intersections and the use of variable slope angles. The approach enables more accurate planning under diverse geological conditions and improves the efficiency and profitability of mining operations.

Key words: *underground mining, mining units, cluster analysis, optimization, geometric modeling, block model.*

Кен орындарын жер астында өңдеу кезінде қазу блоктарын оңтайландыру

Аңдатпа. Тау-кен өндірісінде пайдалы қазбаларды жер асты әдісімен өндіру барысында алынатын өндіру блоктарын оңтайландыру әдісі ұсынылады. Алгоритм блочный модельдің кластерлік талдауы негізінде шикізаттың сапалық және сандық параметрлерін ескере отырып, өндіру блоктарын қалыптастырады. Блоктардың кластерлерге ішінара кіруін есепке алудың жаңа әдісі енгізіліп, бұл есептеулер дәлдігін центроид әдістерімен салыстырғанда арттырады. Қиғаш бұрыштарды оңтайландыру үшін ең кіші квадраттар әдісі мен Махаланобис қашықтығы қолданылады, бұл шығындар мен кеннің разубоживаниесін азайтуға мүмкіндік береді. Ұсынылған әдіс жобалық құрамды сақтай отырып, алынатын кеннің көлемін 4,3%-ға арттырады. Ғылыми жаңалығы – геометрияны дәл модельдеу және өзгермелі бұрыштарды есепке алу. Алгоритм геологиялық-технологиялық шектеулерді ескере отырып, әртүрлі жағдайларға бейімделеді және тау-кен жұмыстарының тиімділігі мен бәсекеге қабілеттілігін арттырады.

Түйінді сөздер: *жер асты өндіруі, өндіру блоктары, кластерлік талдау, оңтайландыру, геометриялық модельдеу, блочный модель.*

Оптимизация выемочных единиц при подземной разработке месторождений

Аннотация. Представлен метод оптимизации выемочных единиц при подземной добыче полезных ископаемых. Алгоритм на основе кластерного анализа блочной модели формирует добычные блоки с учетом качественных и количественных параметров сырья. Предложен способ учета частичного вхождения блоков в кластеры, что повышает точность расчетов по сравнению с центроидами. Для оптимизации углов наклона применены метод наименьших квадратов и расстояние Махаланобиса, позволяющие минимизировать потери и разубоживание. Метод обеспечивает прирост извлекаемой руды на 4,3% при сохранении проектного содержания. Научная новизна – в точном моделировании геометрии и переменных углов. Алгоритм учитывает геолого-технологические ограничения, адаптируясь к разным условиям, и повышает рентабельность и конкурентоспособность горных работ.

Ключевые слова: *подземная разработка, выемочные единицы, кластерный анализ, оптимизация, геометрическое моделирование, блочная модель.*

Introduction

Optimizing mineral deposits is essential for enhancing the profitability of extraction operations by reducing costs and minimizing losses of valuable ore during extraction.

Contemporary methodologies for the design of mining units incorporate the use of deposit block models and algorithmic procedures for the automated determination of unit dimensions, typically implemented through specialized mining and geological software systems. This approach facilitates a comprehensive assessment of alternative development strategies for distinct deposit zones, accounting for diverse extraction methods and recovery parameters.

Automated planning and optimization in underground operations have been the focus of numerous research studies. For example, the Handbook of Operations Research in Natural Resources [1], in the chapter «Optimisation in Underground Mining», emphasizes the importance of determining cut-off grades and defining the geometry of stopes based on geological conditions to ensure optimal recovery of valuable minerals.

Similarly, in the study «Optimization of Underground Stope with Network Flow Method» [2] conducted at Polytechnique Montréal, the authors present a method for optimizing stopes, primarily tailored to vertical panel mining. However, this methodology can result in higher dilution levels in scenarios involving inclined orebodies, where other mining methods are typically used. It should be noted that the method involves complex algorithms and computations, which may require significant computational resources for its implementation.

In his dissertation «A heuristic algorithm to optimise stope boundaries», M. Ataee-pour, from the University of Wollongong, explores the challenge of optimizing mine geometry – particularly in underground mining – where ore extraction may incur additional costs due to the need to remove waste rock or leave behind unextracted ore [3]. The work also discusses the challenges of developing algorithms to optimize extraction boundaries in underground mining, which are recognized as a key factor in mine planning, affecting ore reserve estimation, mine life, and production schedules.

The book «Introductory Mining Engineering» by Howard L. Hartman and Jan M. Mutmansky [4] places significant emphasis on methods and processes in underground mining. The publication provides a comprehensive overview of underground mining, covering development, various extraction methods, technological advancements, and key operational aspects.

In light of the above, the objective of the present study can be formulated as the development of an algorithm for determining the optimal location, geometric parameters, and quality indicators of stopes in underground mine planning, based on the criterion of maximizing total profit [5].

To achieve this objective, the following tasks have been set and addressed according to the developed methodology:

- *dividing the deposit into elementary clusters based on feasible mining technologies;*
- *calculating the quantitative and qualitative characteristics of the ore that is located within the elementary clusters;*
- *composing a mining unit from a set of sequentially arranged clusters, ensuring compliance with specified technological conditions and quality parameters;*
- *determining the optimal dip angles of stopes with consideration for minimizing ore loss and dilution by waste rock.*

The implementation of these tasks was carried out in the K-MINE software within the Stope Optimizer module, which allowed for an assessment of the effectiveness of the proposed solutions.

Methods / Research

To achieve the stated objective, this study employed a combination of methods, including: mathematical modeling of mineral deposits using block models, cluster analysis of the deposit [6], a method for calculating the precise geometric volume of block model intersections within clusters [7], determination of the optimal cluster set within stopes, and a method for defining the optimal dip angle of stopes. The following sections provide a detailed description of these methods and their implementation using specialized software.

1. Cluster Analysis of a Mineral Deposit. This method involves generating a three-dimensional cluster grid within the boundaries of a geological model of a deposit or its specific section. The grid can be regular or constructed with variable spacing, depending on the operational requirements. The core principle behind constructing the cluster grid is extrusion of a predefined cluster profile along one of the orthogonal axes of the local Cartesian coordinate system. Along the remaining two axes, this profile is duplicated at fixed or variable intervals, as dictated by the mining design parameters. The shape of the cluster profile is determined by the technological requirements of underground mining and may range from a simple rectangle to a more complex contour that reflects the geometry of an actual stope. The thickness of the cluster is set significantly smaller than the profile dimensions, allowing the creation of an elementary spatial cell for subsequent analysis.

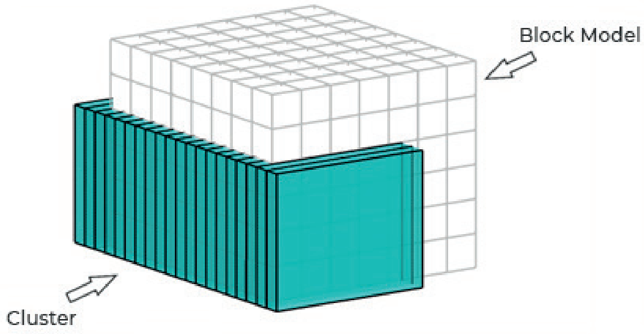

Figure 1. Cluster formation based on the deposit's block model.
Сурет 1. Кен орнының блоктық моделіне негізделген кластерлерді қалыптастыру.
Рис. 1. Формирование кластеров по блочной модели месторождения.

2. Calculation of Cluster Parameters. The next critical step involves the accurate determination of both the quantitative and qualitative parameters of the elementary clusters. Existing methods for calculating volumes within geological block models typically rely on evaluating only those blocks whose centroids lie inside a solid. As a result, techniques such as sub-blocking are often used to improve accuracy. However, when the dimensions of clusters and block model cells are comparable, these methods introduce significant error in volume estimation. Therefore, a more precise method is required for calculating the intersection between block model volumes and cluster boundaries. It's important to note that the intersection between clusters and block model blocks can occur at various angles and is not always aligned with the orthogonal grid, which further complicates the calculation. This issue can be addressed using Boolean operations on solids that represent both clusters and individual blocks of the model. Nevertheless, such an approach demands substantial computational resources and becomes impractical when dealing with large numbers of clusters and high-resolution block models, as it would require intersection checks between each cluster and every block.

To overcome this challenge, the method proposed in this study estimates cluster parameters using projections of the block model edges onto the cluster surface. As a result, the volume calculation is reduced to a straightforward analytical expression without the need for complex solid geometry operations. Figure 2 illustrates this approach.

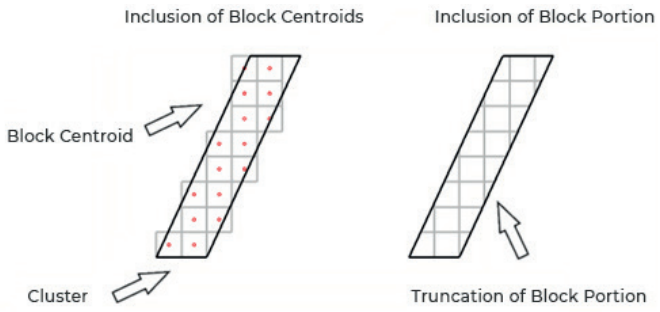

Figure 2. Calculating the partial volume of a block model cell within an elementary cluster.
Сурет 2. Блоктық модельдің бір бөлігі элементар кластерге ену көлемін анықтау.
Рис. 2. Определение объема вхождения части блочной модели в элементарный кластер.

Once the volumetric indicators of the block model within the cluster have been determined, the next step is to calculate the quality parameters of the cluster based on the block model data. These calculations can be performed using various methods:

- *Weighted average by mass:*

$$X_{avg} = \frac{\sum_{i=1}^{n} x_i w_i}{\sum_{i=1}^{n} w_i}, \qquad (1)$$

where:

x_i is the value of the quality parameter of the mineral component;

w_i is the partial weight of the block included in the cluster;

n is the number of block model cells that fall within the cluster.

- *Weighted average by volume:*

$$X_{avg} = \frac{\sum_{i=1}^{n} x_i V_i}{\sum_{i=1}^{n} V_i}, \qquad (2)$$

where:

V_i is the partial volume of the block included in the cluster.

3. Creation of Mining Units. Mining units are created from a set of sequentially arranged clusters. The criteria for determining the optimal set of clusters within a stope are based on two primary conditions: maximizing the volume within a specified range, and ensuring that the average content of the target parameter does not fall below the cut-off grade.

$$\begin{cases} V_n \rightarrow max \\ \gamma_n \geq CutOff' \end{cases} \qquad (3)$$

where:

V_n – volume of the mining unit;

Υ_n – grade of the valuable mineral in the mining unit.

Since this task is solved for each individual set of clusters within a single projection of the mining unit profile, the option that yields the maximum recovery of valuable mineral is selected from all possible variants in that projection. The created stope shapes integrate the recalculated quantitative and qualitative indicators of the clusters they include (see Figure 3*a*). It should be noted that, to achieve more complete recovery of the valuable mineral, in some cases a method of constructing clusters with a specified dip angle of the orebody is applied (see Figure 3*b*).

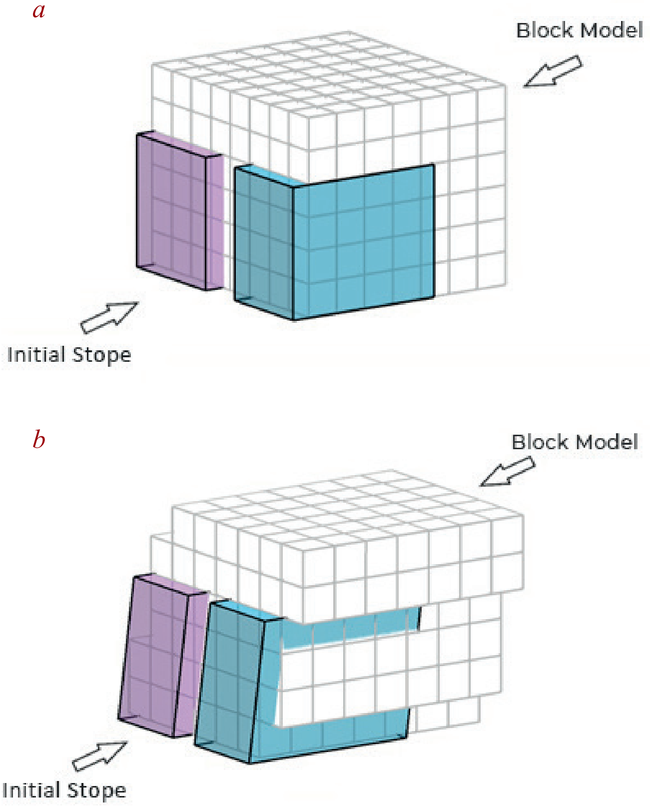

Figure 3. Creation of mining units based on groups of vertical clusters *(a)* and clusters considering dip angle *(b)*.
Сурет 3. Тік кластерлер тобы *(a)* және қабаттың құлау бұрышы ескерілген кластерлер *(b)* негізінде өндіру блоктарын қалыптастыру.
Рис. 3. Формирование выемочных единиц на основе групп вертикальных кластеров *(a)* и кластеров с учетом угла падения *(b)*.

4. Optimization of Mining Unit Shape. The initial aggregation of mining units results in determining the location and dimensions of stopes. According to the applied methodology, the strike angle and dip angle of each mining unit remain fixed, which does not always satisfy the optimal conditions for orebody extraction. Typically, the required strike and dip angles of the hanging wall are dictated by the geological contact with waste rock, as well as technological constraints during cleaning operations. Thus, a local task is to determine the dip angle of the mining unit's end face that maximizes ore recovery and improves the quality of the extracted volume.

To address this task, the following approach is applied: For each end face of the mining unit bordering waste rock, an allowable search zone for the optimal position is constructed (Figure 4*a*).

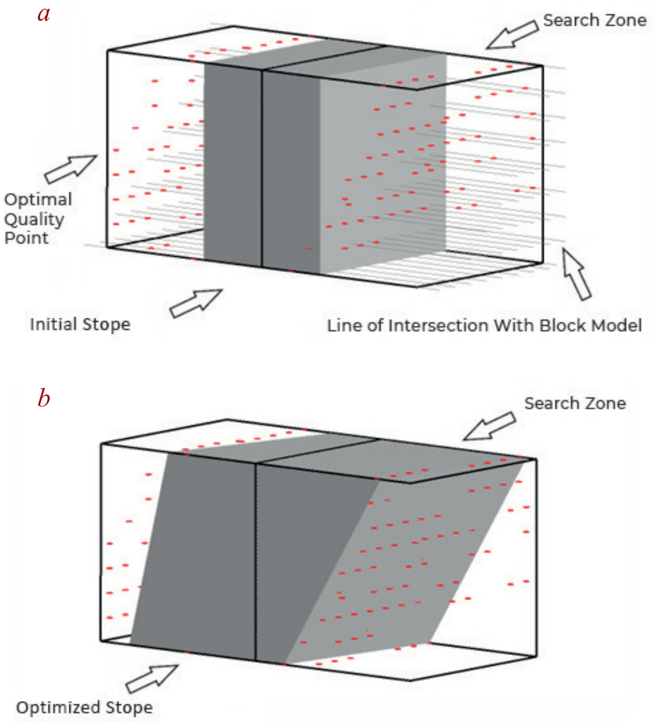

Figure 4. Optimization of the mining unit end wall.
Сурет 4. Өндіру блогының шетіндегі қабырғаны оңтайландыру.
Рис. 4. Оптимизация торцевой стенки выемочной единицы.

Within this zone, boundary points are identified where the target quality parameter meets or exceeds the cut-off grade. To eliminate outlier points from the resulting set, the Mahalanobis distance formula [9] is applied:

$$D_{m(x,\mu)} = \sqrt{(x-\mu)^T S^{-1} (x-\mu)}, \qquad (4)$$

where:

x is the vector of observed values;

μ is the vector of mean values;

S^{-1} is the inverse covariance matrix of the sample;

and $(x-\mu)^T$ is the transposed difference vector.

This approach allows obtaining a set of points within the allowable displacement zone of the mining unit's end wall, which defines its optimized position. The new position of the stope face is determined using least squares approximation of a set of points within a three-dimensional task framework (Figure 4*b*).

Results

To evaluate the accuracy of the developed method for calculating mining unit indicators, computations were performed for benchmark panels. The results of the developed method were compared with calculations based on block centroids (Figure 5). A comparison of the volume calculation methods is presented in Table 1.

It was established that determining the partial inclusion of block model cells significantly improves the accuracy of volume and quality indicator calculations, which is an important factor in optimizing underground mining deposits, especially when developing rare-earth components.

Table 1

Mining Unit Indicator Calculations

Кесте 1

Өндіру блогының көрсеткіштерін есептеу

Таблица 1

Расчет показателей выемочной единицы

Parameter	Calculation by block centroids	Calculation with geometric block truncation
Block Size, m	5 x 5 x 5	5 x 5 x 5
Stope Size, m	25 x 30 x 25	25 x 30 x 25
Cluster thickness, m	5	5
Optimization mineral	***Fe***	***Fe***
Cut-off grade	56	56
Geometric shape volume, m³	18750	18750
Calculated volume, m³	18500	18750
Calculated weight, t	63710	64497
Calculated ***Fe***, %	56.52	56.56

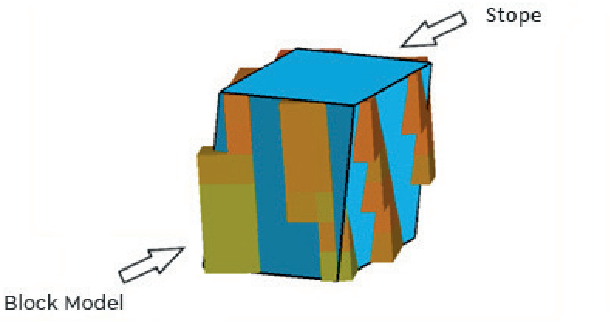

Figure 5. Block model of mineral deposit within the mining unit boundaries.
Сурет 5. Өндіру блогының шегіндегі пайдалы қазбаның блоктық моделі.
Рис. 5. Блочная модель полезного ископаемого в границах выемочной единицы.

Using an example of an underground deposit developed by a sublevel mining method, a set of aggregated stopes was constructed with fixed dip and strike angles, as well as a set of panels with subsequent adjustment of the sidewall angle for each unit by the method described above (Figure 6). The results of the parameter calculations for both creation methods are presented in Table 2.

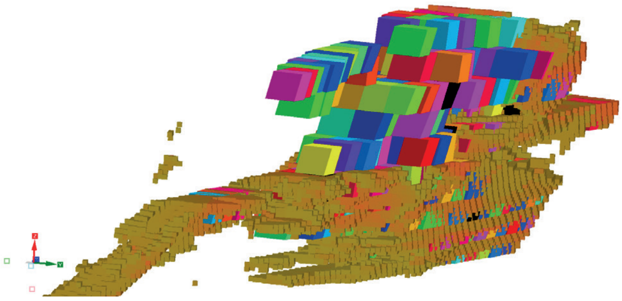

Figure 6. Optimized stopes.
Сурет 6. Оптимизацияланған панельдер.
Рис. 6. Оптимизированные выемочные единицы.

Table 2

Calculation Indicators by stopes with fixed and optimized dip angles

Кесте 2

Бекітілген және оңтайландырылған еңіс бұрыштары бойынша қазу блоктары бойынша есептеу көрсеткіштері

Таблица 2

Показатели расчета по выемочным единицам с фиксированным и оптимизированным углом наклона

Parameters	Fixed angle	Optimized angle
Number of blocks, pcs.	163971	163971
Block size, m	5 x 5 x 5	5x5x5
Cluster size, m	25 x 30	25x30
Dip angle, °	80°	Min 65º – Max 90º
Stope size, m	5	5
Shape optimization	No	Yes
Optimization mineral	***Fe***	***Fe***
Cut-off	56	56
Number of stopes	415	415
Total volume, m³	9,390,004.12	9,791,769.14
Weight, t	32,911,025.52	34,311,118.19
Average grade, %	56.98	56.92

The analysis of the results demonstrated that the application of the proposed method, which incorporates the optimization of dip and strike angles of the mining units, led to an increase in the total extracted ore volume – by 4.3% in this case – compared to the conventional approach with fixed angular parameters. At the same time, the average grade of the valuable component remained stable within the specified cut-off grade, confirming the validity of the developed method.

Discussion of Results

The study results demonstrate that the proposed methodology for optimizing mining units in an underground mining deposit effectively achieves the set goal: maximizing ore extraction volume while maintaining the specified cut-off grade and technological parameters of mining (3).

The developed algorithm for calculating cluster indicators enhances calculation accuracy, which in turn ensures the correct selection of clusters within each mining unit. This is particularly critical for underground mining, where precise delineation of mining units directly impacts the economic efficiency of mining operations.

Compared to similar methods [10], the proposed algorithm offers more accurate accounting of the geometric characteristics of stopes.

However, it should be noted that this methodology has certain limitations, primarily its dependency on the quality of the initial block model and the requirement for substantial computational resources when processing large data sets.

The developed method for optimizing mineral extraction has been implemented in the K-MINE Stope Optimizer module. This module enables the formation of optimal stopes for underground mining of the deposit based on specified quality indicators or economically justified mining parameters. Additionally, a solid orebody wireframe can be used as a constraint to limit the shape of the mining unit.

Mining technological factors are incorporated in the K-MINE software by setting maximum and minimum allowable dip angles of the stope's sidewalls, minimum and maximum stope lengths, permissible ranges for panel width and height, as well as the shape of its profile.

For each stope bordering waste rock, dilution indicators are calculated, which may be defined by regulatory standards or determined via a linear rock caving model.

The stopes formed during optimization are vector objects containing all necessary parameters (volume, weight, quality indicators, dimensions, level elevation, etc.), which can be used for subsequent mine design and planning tasks.

The obtained results are presented in detailed and summary tabular reports, enabling evaluation of the optimization scenario or comparison of multiple optimization variants with different initial data and constraints.

Conclusion

The developed algorithm for stope optimization accounts not only for the quality parameters but also for the spatial and geometric features of how mining units intersect with the block model of a mineral deposit. This approach significantly improves the accuracy of delineating mining units, reduces ore loss, and minimizes dilution during mineral extraction. The results of the conducted studies confirm that the use of variable dip angles for mining units contributes to an increase in the total volume of recoverable rock mass without substantially decreasing the average grade of the valuable component. Therefore, the proposed algorithm is a technologically sound and promising tool for enhancing the efficiency and productivity of mining operations.

The algorithm has been successfully integrated into the functional environment of modern K-MINE software, which confirms its practical relevance for addressing challenges in mining production. Integration with K-MINE's features enabled optimization of calculations based on economic profitability indicators, significantly improved planning accuracy, and increased profitability in deposit exploitation.

The flexibility of accounting for various geological and technological constraints in forming mining units, combined with K-MINE's capabilities for calculating extraction volumes, ensures the method's versatility and adaptability to different orebody configurations and a wide range of mining systems.

The synergy between the proposed method and K-MINE's implemented tools offers an effective framework for improving technological resilience, ensuring responsible subsoil use, and enhancing the overall operational efficiency of mining enterprises.

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