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Block modeling reserves estimation

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ABSTRACT
The article presents a methodology for resource estimation of a phosphate deposit based on block modeling. The advantages of applying regularization and geometric optimization algorithms for mineable units are demonstrated, ensuring more accurate differentiation of ore grades and a reduction in ore losses and dilution. A comparative analysis is conducted on the excavation of pit benches with varying slope angles and equipment configurations. It is established that a block size of 5m ×5m provides an optimal balance between model accuracy and equipment productivity. The most effective slope angle of the benches is determined based on equipment performance and cost-efficiency. The results contribute to improving the accuracy of resource forecasting and the overall economic viability of deposit development by significantly reducing operating costs and enhancing the quality of extracted material. The study outlines practical approaches to selecting appropriate equipment configurations for different mining scenarios. Special attention is paid to the influence of excavation geometry on the performance of hydraulic excavators. The methodology proposed can be applied to similar deposits with complex morphology. The research findings may serve as a basis for developing more adaptive and data-driven mine planning strategies.

Keywords: block modeling, reserves model, regularization, mineable shapes optimization, losses and dilution, economic efficiency, selective mining.

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Introduction

At the current stage of mining industry development, block models have become the primary tool for the geological and economic evaluation of mineral deposits. Building a block model allows for a more accurate representation of the spatial distribution of ore bodies and their quality characteristics, as well as a sound basis for resource estimation and economic assessment of the deposit.

A block model is a digital representation of the subsurface in the form of a set of blocks of defined size, each assigned specific attributes [[1], [2], [3], [4]]. The primary purpose of a block model is to provide a comprehensive assessment of the mineral resource and to design the most rational mining options, taking into account geological, geotechnical, and economic factors [[5], [6]].

In many cases, the estimation of mineable reserves is based on the "Methodological Recommendations for Technological Design of Open-Pit Mining Enterprises" dated September 19, 2013 [7]. At the same time, average benchmark indicators for the entire deposit are typically used for calculating operational losses and dilution [[8],

[9], [10]]. This approach assumes bulk extraction of the deposit without differentiating between high-grade and low-grade ore types, leading to the loss of benefit in the final product and potential enterprise profit.

Rational subsoil use and achieving high economic efficiency in the development of solid mineral deposits are key priorities in today's mining industry. Accurate estimation of recoverable reserves, based on geological modeling and analysis of discrepancies between actual and projected parameters, has become especially important [[11], [12], [13]].

Resource block models reflect the total amount of mineral material in situ, without accounting for mining and technical constraints. Consequently, a resource model does not provide a full picture of the reserves that can feasibly be extracted during deposit exploitation.

Experimental part

To improve the accuracy of recoverable resource forecasting, a reserve model is developed. This model represents an operational geological block model that incorporates cut-off grade, the geometry of mining units, ore losses, and dilution. The reserve model is essential for pit optimization, pit contour design, and mine scheduling with a higher degree of reliability.

In global practice, the Lerchs-Grossmann algorithm is widely recognized and commonly applied for pit limit optimization [14]. This method is actively used by leading mining companies due to its ability to identify the most economically feasible pit outline based on the balance between the value of recoverable minerals and stripping costs.

A critical preliminary stage in reserve model construction for subsequent optimization is regularization—the process of converting block model cells to a uniform size that corresponds to the concept of a minimum mining unit [15]. Regularization enhances the realism of recoverable resource estimation [16].

Regularization of the reserve model was carried out using three different mining unit sizes:

3 m × 3 m – the minimum size based on bucket width;

5 m × 5 m – aligned with the blast hole pattern (Figure 1);

7 m × 7 m – used to evaluate the effect of increasing the mining unit size on ore loss and dilution indicators.

In all variants, the height of the mining unit was 7.5 meters, which corresponds to the adopted bench height parameters. To differentiate ore grades, the cut-off grade (COG) [17] for P_2O_5 was applied: 28% for high-grade ore and 15% for low-grade ore.

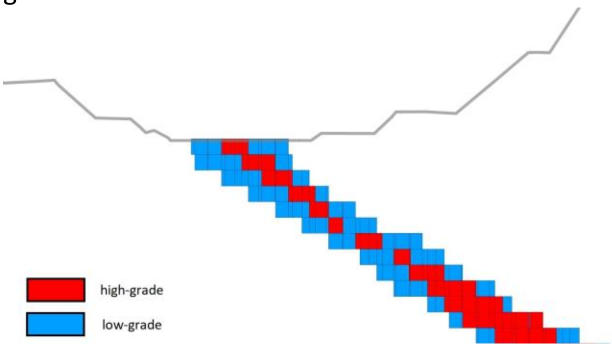


Figure 1 - Reserves model section with 5m x 5m excavation unit size

Table 1 presents the variation in average P_2O_5 content, ore losses, and dilution levels depending on the size of the mining block. As block size increases from 3×3 m to 7×7 m, a consistent decline in ore grade is observed, accompanied by higher dilution and losses. These changes are particularly important for thin-layered phosphate deposits, where selective mining and ore quality preservation are critical.

Table 1 - P_2O_5 content, ore losses and dilution depending on the size of the mining block

Indicator	Resource Model	3m × 3m	5m × 5m	7m × 7m
P_2O_5	27.0%	24.7%	24.6%	24.4%
Losses	0.0%	15.7%	16.3%	17.3%
Dilution	0.0%	9.1%	9.5%	10.3%

Consequently, a block size of 5×5 m was selected as optimal for further analysis, as it provides a balance between modeling accuracy and the technical feasibility of extraction. It corresponds to the typical blast-hole drilling grid used on site and maintains acceptable levels of dilution (9.5%) and losses (16.3%), while still preserving the geometry of the orebody more effectively than larger blocks. This makes the 5×5 m configuration optimal for balancing modeling accuracy and production feasibility in subsequent mine planning stages.

A more advanced and accurate tool for creating block models of mineral reserves is the Mineable Stope Optimiser (MSO). This stope optimization method features extensive configuration options that define the areas within the resource model that can be economically extracted, taking into account the specified geometry [[18], [19]].

MSO employs optimization algorithms to generate mineable shapes based on financial, geotechnical data, and operational constraints. It is used to determine the ideal extraction geometry of an orebody based on a block model. The primary objective of MSO is to maximize financial returns by generating mining units that align with geometric and geotechnical parameters. The shape, geometry, and geotechnical constraints are defined independently for different zones of the same orebody. Examples of geometric constraints include the height, as well as the maximum and minimum width of the mining units. These geometrical constraints were applied to reflect realistic mining conditions and evaluate the impact of varying slope geometries on the shape and continuity of the generated mineable units.

For inclined phosphorite ore bodies with a dip angle ranging from 25° to 35°, MSO optimization was carried out using two slope angle scenarios: 30°, which approximates the average natural dip of the deposit, and 40°, which simulates a steeper extraction geometry aimed at increasing ore recovery in areas with favorable geotechnical conditions (Figure 2).

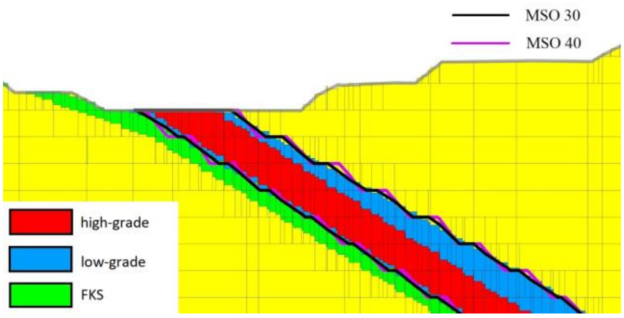


Figure 2 - Section of resource block model with MSO frames with slope angles of 30° and 40°

The purpose of applying different slope angles in the optimization process was to assess the sensitivity of mineable shapes to variations in dip-related constraints, as well as to compare the trade-offs between ore recovery, operational selectivity, and stability. By applying these angular parameters during MSO geometrization, it was possible to generate mineable units that better conform to the geometry of the orebody, reduce over-excavation of barren host rock, and improve the accuracy of production planning.

The results of geometrization facilitate the identification of grade distribution patterns within the deposit, which are used in mine planning processes and in the development of more efficient ore preparation technologies at the mining operation [20].

Table 2 - Comparison of Regularized and MSO Block Model

Indicator	5m×5 m	MSO 40	MSO 30
P2O5	24.6%	25.1%	25.6%
Losses	16.3%	9.4%	7.4%
Dilution	9.5%	4.1%	3.1%

The comparison between the regularized block model (5×5 m) and the MSO-generated geometries at slope angles of 30° and 40° demonstrates a clear improvement in orebody selectivity and overall resource utilization when using MSO-based optimization in Table 2.

The regularized 5×5 m block model yielded an average P_2O_5 grade of 24.6%, with ore losses amounting to 16.3% and dilution reaching 9.5%. In contrast, the MSO-based geometry with a 40° slope produced a higher P_2O_5 content of 25.1%, while significantly reducing ore losses to 9.4% and dilution to 4.1%. The most favorable results were obtained with the 30° MSO scenario, where the P_2O_5 grade increased to 25.6%, ore losses were minimized to 7.4%, and dilution dropped to just 3.1%.

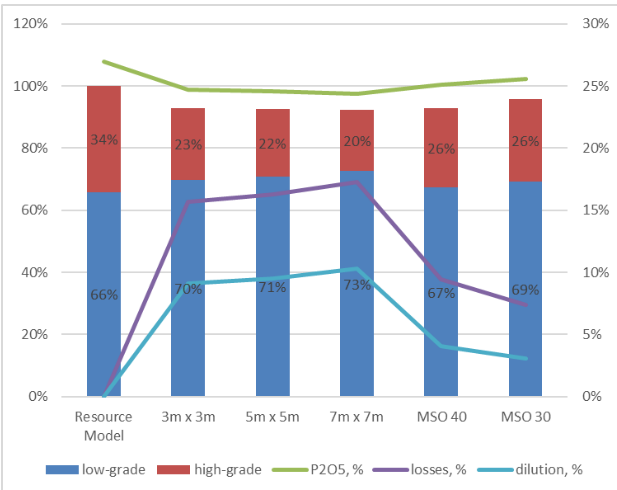


Figure 3 - Relative analysis of block reserves models

As a result of the comparative analysis (Figure 3), it was established that the regularization of the block model is associated with a number of shortcomings. Among the main identified issues is the insufficiently accurate separation of ore grades, which leads to a significant reduction in the volume of high-quality (rich) ore. Furthermore, the application of this approach results in elevated levels of ore losses and dilution, which adversely affect the economic performance of the project.

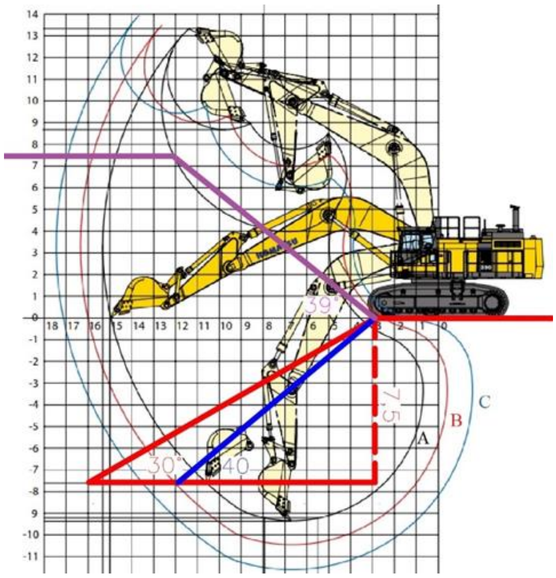
These findings indicate that the application of MSO optimization, especially with a slope angle of 30°, allows for more accurate alignment of the mineable shapes with the dip and geometry of the orebody. This results in better preservation of high-grade zones and minimizes the incorporation of barren material. The significant reduction in both losses and dilution contributes directly to higher operational efficiency and improved product quality during downstream processing.

In contrast, the use of the MSO algorithm allows for a more precise and accurate delineation of boundaries between ore, waste rock, and different ore grades. The implementation of MSO contributes to more effective reserve management and improves the economic indicators of deposit development.

Results and Discussions

In the course of analyzing the extraction parameters for ore blocks, a technical and economic feasibility assessment was carried out for the application of different bench slope angles—30° and 40°—taking into account geometric constraints and the operational capabilities of the selected mining equipment. As a representative example, a Komatsu PC1250 hydraulic backhoe excavator was chosen, equipped with arms of varying lengths: 5.7 m, 4.5 m, and 3.4 m [21]. The diagram (Figure 4) visually presents three operational configurations of this excavator. For comparative analysis, the contours of the designed benches—generated using MSO software frameworks—were superimposed: the red line indicates the 30° slope bench, the blue line represents the 40° slope bench, both designed for bottom-digging operations. The purple line illustrates the minimum feasible angle for top digging, with a corresponding bench height of 7.5 meters.

The results of the conducted analysis indicate that when the bench slope angle is 30°, excavation is feasible only by performing two separate passes. This significantly reduces excavator productivity, extends operational cycle time, and leads to additional costs associated with preparing working platforms. In contrast, with a bench slope angle of 40°, efficient single-pass excavation becomes possible, especially when using an excavator equipped with a short boom (3.4 m). This configuration allows for a considerable increase in operational productivity, minimizes cycle time, and optimizes costs related to the excavation process.



A - arm length 3.4m; B - arm length 4.5m;
C - arm length 5.7m.

Figure 4 - Scheme of ore blocks mining options at angles of 30° and 40°

A comparative analysis of extractable ore volumes based on models generated using the MSO algorithm revealed no significant differences between the 30° and 40° slope angle configurations. Taking into account equipment performance and the technological advantages of the steeper 40° slope, the optimal mining solution involves the use of a Komatsu PC1250 backhoe excavator with a 3.4-meter arm lengh and a bucket capacity of 5.2 m³, or equivalent equipment. In other cases, it becomes necessary to use a smaller 3.4 m³ bucket, resulting in a noticeable decrease in productivity.

Thus, considering the identified technological and economic advantages, the reserve model constructed using the MSO algorithm with a 40° bench slope angle was selected for the further optimization of pit boundaries. This approach ensures an optimal balance between equipment productivity, operational safety, and overall economic efficiency of the project.

Conclusion

Resource estimation using block modeling significantly enhances the accuracy and reliability of forecasts related to recoverable reserves. This approach provides not only a detailed geometric representation of the ore body but also integrates data on qualitative and economic parameters, making the model more adaptable to actual mining conditions.

One of the key advantages is the ability to implement selective mining, achieved through the precise delineation of zones with varying concentrations of the valuable component. This enables minimization of losses and dilution, increases the degree of reserve utilization, and ensures consistent raw material quality.

Based on the block model, it becomes possible to make a justified selection of mining equipment. Block dimensions, dip angles, and geotechnical parameters form the technical requirements for the type and specifications of equipment used, including excavators, drilling rigs, and haulage systems.

Block modeling contributes to transparent decision-making and control at all stages of mine development — from design and planning to operational production management. It creates a unified digital environment in which deviations can be easily tracked and adjustments to mine plans promptly made. As a result, the enterprise gains additional profit and increased project profitability through the maximization of recoverable reserves, while minimizing losses and reducing operational costs.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Блоктық модельдеуді қолдана отырып кен орындарының қорларын бағалау

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ТҮЙІНДЕМЕ
Мақалада фосфор кен орнының қорларын бағалау үшін блоктық модельдеуге негізделген әдістеме ұсынылған. Қазып алынатын блоктар геометриясын реттеу мен оңтайландыру алгоритмдерін қолданудың артықшылықтары көрсетілген. Бұл тәсіл кеннің түрлі сорттарын дәлірек ажыратуға, кен жоғалуларын және құнарсыздандыруды азайтуға мүмкіндік береді. Әртүрлі еңіс бұрыштары мен жабдық конфигурацияларымен жұмыс істейтін карьерлік сатыларды қазу бойынша салыстырмалы талдау жүргізілді. 5 м × 5 м болатын блок өлшемінде модельдің дәлдігі мен тау-кен техникасының өнімділігі арасында оңтайлы тепе-теңдік болатыны анықталды. Техника өнімділігі мен шығын тиімділігіне негізделе отырып, сатылардың ең тиімді еңіс бұрышы анықталды. Бұл нәтижелер ресурстарды болжаудың дәлдігін және кен орнын игерудің экономикалық тиімділігін арттыруға ықпал етеді, сонымен қатар операциялық шығындарды едәуір азайтып, алынатын материал сапасын жақсартады. Зерттеу әртүрлі тау-кен жағдайларына сәйкес келетін жабдық конфигурациясын таңдаудың практикалық тәсілдерін ұсынады. Қазу геометриясының гидравликалық экскаваторлардың жұмыс тиімділігіне әсеріне ерекше назар аударылған. Ұсынылған әдістеме морфологиясы күрделі кен орындары үшін де қолданылуы мүмкін. Бұл зерттеу нәтижелері тау-кен жұмыстарын жоспарлау стратегияларын бейімдеуге және деректерге негізделген шешім қабылдауға негіз бола алады.

Түйін сөздер: блоктық модельдеу, қорлар моделі, тұрақтандыру, алынатын бірліктерді оңтайландыру, шығындар және құнарсыздану, экономикалық тиімділік, селективті өндіру.

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Оценка запасов с применением блочного моделирования

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АННОТАЦИЯ

В статье представлена методика оценки запасов фосфоритового месторождения с использованием блочного моделирования. Продемонстрированы преимущества применения регуляризации и алгоритмов геометрической настройки выемочных единиц, обеспечивающих более точное разделение сортов руды и снижение потерь и разубоживания. Проведён сравнительный анализ отработки уступов с различными углами откоса и конфигурациями оборудования. Установлено, что размер блока 5 м × 5 м обеспечивает оптимальный баланс между точностью модели и производительностью оборудования. Определён наиболее эффективный угол откоса уступов с точки зрения производительности техники и экономической целесообразности. Полученные результаты способствуют повышению точности прогнозирования запасов и общей экономической эффективности освоения месторождений за счёт существенного сокращения эксплуатационных затрат и повышения качества добываемого сырья. В исследовании изложены практические подходы к выбору подходящих конфигураций оборудования для различных горных условий. Особое внимание уделено влиянию геометрии выемки на эффективность работы гидравлических экскаваторов. Предлагаемая методика может быть применена к аналогичным месторождениям со сложной морфологией. Полученные результаты могут служить основой для разработки более адаптивных и обоснованных стратегий планирования горных работ.

Ключевые слова: блочное моделирование, модель запасов, регуляризация, оптимизация выемочных единиц, потери и разубоживание, экономическая эффективность, селективная отработка.

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