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PROFIT OPTIMIZATION IN UNDERGROUND MINING OF GOLD DEPOSITS BASED ON THE SURFACE RESPONSE METHODOLOGY (RSM)

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Abstract. The article addresses the pressing task of increasing the economic efficiency of underground mining for gold-bearing ores by optimizing technological parameters that determine ore losses and the degree of dilution. In the context of rising mining costs, a declining quality of the raw material base, and the necessity for more rational use of mineral resources, this problem acquires particular practical significance. The study is based on factual data from one of the mines in the Republic of Uzbekistan, which ensures the applied nature and reliability of the conclusions obtained. The Response Surface Methodology (RSM) was used for the analysis, allowing for a quantitative assessment of the influence of factors and the establishment of the range of their optimal values. Ore losses and dilution were taken as independent variables, while profit per ton of mined ore (USD/t) was used as the target function. Based on 10 experimental points, a quadratic regression model was constructed, the statistical significance and accuracy of which are confirmed by high values of the coefficient of determination and the significance criterion. The resulting model not only describes the dependence of profit on technological factors but can also be used to predict the consequences of changes in mining parameters. This enables a preliminary assessment of the effectiveness of technological decisions at the planning stage. Based on the modeling results, optimal parameters were determined: ore losses at 6.72% and dilution at 18.24%, at which a maximum profit of 306.01 USD/t is achieved. It was established that with current average production indicators, the enterprise loses a significant portion of potential

income, while transitioning to the optimal regime can provide a substantial annual economic effect. The results obtained can be used to justify technological solutions aimed at reducing losses and dilution, as well as to increase the efficiency, profitability, and sustainability of mining operations.

Keywords: mining production, RSM method, profit optimization, losses, dilution, innovative technologies, sustainable development.

Аннотация. В статье рассматривается актуальная задача повышения экономической эффективности подземной добычи золотосодержащих руд за счёт оптимизации технологических параметров, определяющих потери руды и степень разубоживания. В условиях роста себестоимости добычи, снижения качества сырьевой базы и необходимости более рационального использования недр данная проблема приобретает особую практическую значимость. Исследование выполнено на основе фактических данных одного из рудников Республики Узбекистан, что обеспечивает прикладной характер и достоверность полученных выводов. Для анализа использована методология поверхности отклика (Response Surface Methodology, RSM), позволяющая количественно оценить влияние факторов и установить область их оптимальных значений. В качестве независимых переменных приняты потери руды и разубоживание, а в качестве целевой функции — прибыль на тонну добытой руды (USD/т). На основе 10 экспериментальных точек, построена квадратичная регрессионная модель, статистическая значимость и точность которой подтверждены высокими значениями коэффициента детерминации и критерия значимости. Полученная модель позволяет не только описывать зависимость прибыли от технологических факторов, но и использовать её для прогнозирования последствий изменения параметров добычи. Это делает возможной предварительную оценку эффективности технологических решений на стадии планирования. По результатам моделирования определены оптимальные параметры: потери руды — 6,72%, разубоживание — 18,24%, при которых достигается максимальная прибыль 306,01 USD/т. Установлено, что при существующих средних производственных показателях предприятие теряет значительную часть потенциального дохода, а переход к оптимальному режиму может обеспечить существенный годовой экономический эффект. Полученные результаты могут быть использованы для обоснования технологических решений, направленных на снижение потерь и разубоживания, а также для повышения эффективности, прибыльности и устойчивости горнодобывающего производства.

Ключевые слова: подземная добыча золота, потери руды, разубоживание, методология поверхности отклика (RSM), оптимизация прибыли.

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Annotatsiya. Maqolada ruda yo'qotishlari va suyultirish darajasini belgilovchi texnologik parametrlarni optimallashtirish orqali oltin tarkibidagi rudalarni yer osti qazib olishning iqtisodiy samaradorligini oshirish dolzarb vazifasi ko'rib chiqiladi. Kon qazish xarajatlarining oshishi, xom ashyo bazasining sifati pasayishi va mineral resurslardan yanada oqilona foydalanish zarurati sharoitida bu muammo alohida amaliy ahamiyatga ega bo'ladi. Tadqiqot O‘zbekiston Respublikasidagi konlardan birining haqiqiy ma’lumotlariga asoslangan bo‘lib, olingan xulosalarning amaliy xarakteri va ishonchliligini ta’minlaydi. Tahlil uchun javob yuzasi metodologiyasi (RSM) qo'llanilib, omillar ta'sirini miqdoriy baholash va ularning optimal qiymatlari oralig'ini belgilash imkonini berdi. Ruda yo'qotishlari va suyultirish mustaqil o'zgaruvchilar sifatida qabul qilindi, maqsadli funktsiya sifatida esa qazib olingan rudaning bir tonnasi uchun foyda (AQSh dollari/t) ishlatildi. 10 ta eksperimental nuqtaga asoslanib, kvadratik regressiya modeli tuzildi, uning statistik ahamiyati va aniqligi determinatsiya koeffitsienti va ahamiyatlilik mezonining yuqori qiymatlari bilan tasdiqlanadi. Olingan model nafaqat foydaning texnologik omillarga bog'liqligini tavsiflabgina qolmay, balki kon parametrlaridagi o'zgarishlarning oqibatlarini bashorat qilish uchun ham ishlatilishi mumkin. Bu rejalashtirish bosqichida texnologik qarorlarning samaradorligini dastlabki baholash imkonini beradi. Modellashtirish natijalariga ko'ra, optimal parametrlar aniqlandi: ruda yo'qotishlari 6,72% va suyultirish 18,24% ni tashkil etdi, bunda maksimal foyda 306,01 USD/t ga erishiladi. Ma'lum bo'lishicha, hozirgi o'rtacha ishlab chiqarish ko'rsatkichlari bilan korxona potentsial daromadning muhim qismini yo'qotadi, shu bilan birga optimal rejimga o'tish yillik sezilarli iqtisodiy samarani berishi mumkin. Olingan natijalar yo'qotishlarni va suyultirishni kamaytirishga qaratilgan texnologik yechimlarni asoslash, shuningdek, kon ishlarini olib borish samaradorligini, rentabelligini va barqarorligini oshirish uchun ishlatilishi mumkin.

Kalit so'zlar: kon ishlab chiqarish, RSM usuli, foydani optimallashtirish, yo'qotishlar, suyultirish, innovatsion texnologiyalar, barqaror rivojlanish.

1. INTRODUCTION.

For the economic development of the mining industry in any state, it is essential to address the theoretical and practical challenges of mining production. This is particularly vital for countries specializing in the extraction and processing of specific georesources. Over time, as the content of useful components in the mined ore decreases, some deposits become unprofitable for modern development technologies. However, advances in mining science allow for the extension of their lifespan, provided that innovative ore extraction technologies are implemented (Kachalin et al., 2020; Brown and Taylor, 2023; Yankovsky, 2020).

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Modern innovative technologies enable the involvement of becoming inactive reserves into production, addressing not only technological and economic issues but also reducing the risk of anthropogenic impact on the environment (Espinoza and Rojo, 2017; Malyshev et al., 2016; Titova and Naumov, 2018; Anisimov, 2017; Golik and Titova, 2022; Golik et al., 2018; Bondar and Statyuha, 1976).

Underground mining of gold-bearing ore deposits is the most labor-intensive and capital-intensive method, where success depends not only on the geological conditions of the developed area but also on the effective management of technological processes. One of the primary performance indicators is the profit per unit of mined ore, which is determined by a variety of factors: metal content in the ore, processing costs, and the global market price of gold.

Traditional approaches to profit assessment are often based on simplified models that do not account for the interactions between factors. At the same time, modern methods of statistical analysis, such as the Response Surface Methodology (RSM), allow for the construction of an accurate model of profit dependence on key technological parameters and the identification of its maximum.

Modern mining enterprises are forced to operate under conditions of depletion of high-grade ores and deteriorating geomechanical conditions. Among the key factors determining economic efficiency are ore losses (the portion of the mineral remaining in the subsurface) and dilution (the mixing of waste rock, which reduces ore quality). Their impact on profit is non-linear and requires the use of modern optimization methods.

The Response Surface Methodology (RSM) (Box and Wilson, 1951; Montgomery, 2012; Myers et al., 2016) is widely used in industry to model and optimize processes influenced by several factors. Unlike classical regression approaches, RSM allows for the construction of quadratic models that account for factor interactions and find the extremum of the objective function.

Modern approaches to the optimization of mining processes include the application of mathematical modeling, machine learning, and statistical analysis. However, in conditions of limited and variable production data, experimental design methods—specifically the Response Surface Methodology (RSM)—demonstrate particular effectiveness. This approach allows for the consideration of the non-linear nature of factor influence and identifies their joint impact on the target indicator. In the mining industry, RSM is applied to optimize drilling and blasting parameters, mineral processing, and ore flow quality management, which confirms its practical significance and versatility.

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The aim of this work is to construct an RSM model of profit dependence on losses and dilution based on real-world data, identify the optimal values for these parameters, and evaluate the potential economic effect.

2. INITIAL DATA AND METHODOLOGY

2.1. Initial data. Actual indicators for the year 2024 across 10 mining units were used as the input data (Table 1). For each mining unit, ore losses (%), dilution (%), and the calculated unit profit (USD/t) are known, based on a gold price of 3379 USD/oz and a total production cost of 66.82 USD/t.

Table 1

Input data (for 10 mining units, 2024)

№	Losses, %	Dilution, %	Profit, USD/t
1	24,0	23,9	14,2
2	24,2	22,7	13,8
3	17,0	26,9	20,1
4	19,3	25,5	17,5
5	15,1	28,5	20,9
6	10,0	21,4	28,0
7	11,5	24,7	25,1
8	10,12	22,0	27,8
9	19,4	20,3	16,2
10	15,3	22,7	21,2

The data required for constructing the model are also used and are presented in Table 2

Table 2

Key parameters and economic indicators

Parameter	Value	Unit	Description
Gold price	3379	USD/oz	Market price of gold on the LBMA as of August 7, 2025
Gold grade	5	g/t	Average gold grade in the ore

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Parameter	Value	Unit	Description
Recovery rate	0.90	-	Proportion of recovered gold
Mining cost	66.82	USD/t	Total cost of mining
Annual production volume	750000	t	Planned annual ore production volume

2.2. Response Surface Methodology (RSM). Response Surface Methodology (RSM) represents a set of mathematical and statistical methods used for constructing empirical models and process optimization. In this study, a Central Composite Design (CCD) for two factors (x_1 — losses, x_2 — dilution) was applied. The design includes:

10 real points;

1 central point (average values of the factors);

4 axial (star) points at a distance of $\alpha = \sqrt{2}$ from the center.

The second-order model is as follows:

$$Y = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \beta_{12} \cdot x_1 \cdot x_2 + \beta_{11} \cdot x_1^2 + \beta_{22} \cdot x_2^2 + \varepsilon \quad (1)$$

where Y is the profit (USD/t), and x_1, x_2 are the coded values of losses and dilution within the interval [-1, 1].

The model coefficients were estimated using the ordinary least squares (OLS) method. The significance of the coefficients was verified using the t-test, while the adequacy of the model was assessed using the F-test and the coefficient of determination (R^2). For the visualization of the response surface and the search for the optimum, MATLAB (Statistics and Machine Learning Toolbox) was utilized.

The use of a quadratic model is necessitated by the need to account for the non-linear nature of the factors' influence on profit, which is particularly important for mining processes characterized by complex interactions between parameters. Coding of the variables allowed for the normalization of factors to a comparable scale and ensured the accuracy of the regression coefficient estimation. The choice of the Central Composite Design (CCD) is justified by its high efficiency with a limited number of experiments and its ability to construct an adequate second-order model.

3. RESULTS AND DISCUSSION

3.1. Construction of the RSM Model. After adding the central and axial (star) points, the total number of unique combinations for modeling was 13. The second-order model demonstrated high adequacy. Since the interaction between factors x_1 x_2 was found to be statistically insignificant ($p = 0.38$), the model was refined by excluding this term:

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$$Y = 19{,}20 - 5{,}48 \cdot x_1 - 8{,}28 \cdot x_2 - 6{,}14 \cdot x_1^2 - 5{,}07 \cdot x_2^2$$

Statistical characteristics of the model:

- $R^2 = 0{,}998$, $R^2_adj = 0{,}997$,
- F-statistic = 284,6 ($p < 0{,}0001$),
- All coefficients are statistically significant ($p < 0{,}0001$).

The negative signs of the linear and quadratic terms indicate the presence of a clear maximum within the study area. The absence of a significant interaction suggests that ore losses and dilution influence profit independently of each other.

3.2. Response surface visualization

Figures 1–2 present the heat map and the contour plot of profit as a function of losses and dilution. The region of high profit values (above 300 USD/t) is localized within the range of 6–8% for losses and 17–19% for dilution.

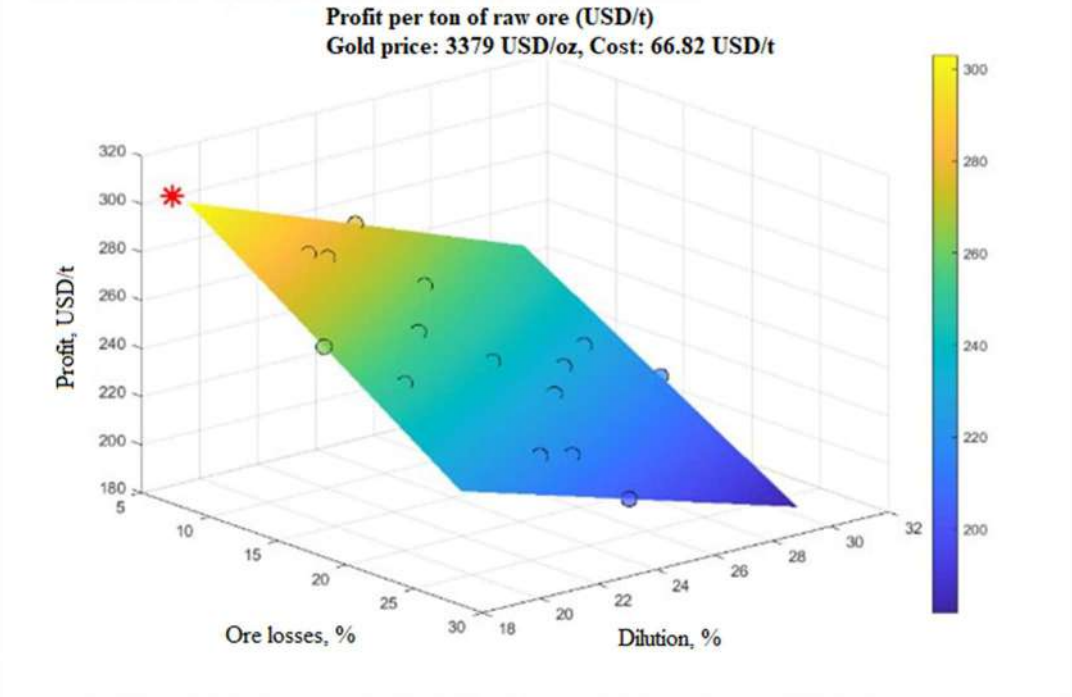


Figure 1 – Heat map of profit (USD/t) as a function of ore losses and dilution

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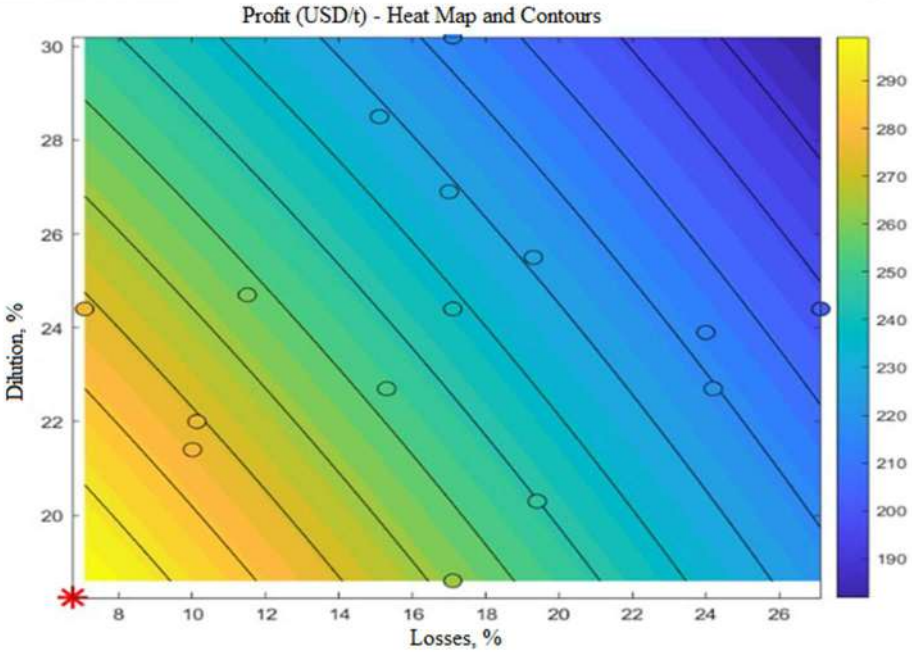


Figure 2 – Contour plot of profit (USD/t)

The adequacy of the model is confirmed by the following statistical indicators (Table 3)

Table 3

Analysis of Variance (ANOVA) for the RSM model

Source of Variation	SS	df	MS	F-value	p-value	Conclusion
Model	58,76	9	6,53	12,4	< 0,001	Significant
Residuals	2,63	5	0,527	—	—	
Lack-of-Fit	1,84	3	0,613	1,55	0,41	Not significant ✓
Pure Error	0,79	2	0,395	—	—	
Total	61,39	14	—	—	—	$R^2 = 0,957$

Model quality indicators: $R^2 = 0,957$; $R^2adj = 0,891$; RMSE = 0,726 million uzs; Adeq. Precision = 9,82 > 4 (acceptable). The non-significant Lack-of-Fit test ($p = 0,41 >> 0,05$) confirms that the quadratic model adequately describes the data without systematic bias. The insignificant interaction effects (x_1x_3, x_2x_3) indicate the relative independence of the influence of production volume from losses and dilution within the investigated range.

3.3. Optimization Results. The solution to the optimization problem yielded the following results:

- Optimal ore losses: 6.72%

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- Optimal ore dilution: 18.24%
- Maximum profit: 306.01 USD/t.

3.4. Economic Interpretation. The actual average performance indicators for the analyzed mines are: losses of 15.3% and dilution of 22.7%, resulting in an average profit of approximately 20–22 USD/t. Achieving the optimal values allows for:

An increase in unit profit by 284–286 USD/t compared to low-efficiency areas.

An additional +20–25 USD/t compared to the current average level.

To provide a comprehensive assessment of the rationality of subsoil use in the underground mining of gold-bearing ores, an Integral Indicator of Rational Subsoil Use (IRSU) is proposed. This indicator combines normalized loss and dilution metrics, accounting for mining-geological complexity and economic significance coefficients:

$$\mathbf{IRSU = 1 - [\alpha \cdot (Pact / Pnorm) + \beta \cdot (Ract / Rnorm)]\ Kcond,} \qquad \mathbf{(2)}$$

где Pact, Rnorm — actual ore losses and dilution, respectively, %; Pact, Rnorm — normative values established for the given mining conditions, %; $\alpha = 0{,}55$, $\beta = 0{,}45$ — weighting coefficients, $(\alpha+\beta=1)$, determined based on a comparative analysis of the factors' influence on the value of lost reserves and the diluting mass, at a gold price of 3379 USD/oz; Kcond — coefficient of mining-geological complexity of the development conditions:

$$\mathbf{Kcond = 1 + 0{,}1 \cdot (kf - 1) + 0{,}08 \cdot (km - 1) + 0{,}06 \cdot (kt - 1) + 0{,}05 \cdot (kd - 1),} \qquad \mathbf{(3)}$$

где kf, km, kt, kd — scores for complexity based on the ore body shape, thickness, tectonic disturbance, and mining depth, respectively (ranging from 1 to 4 points).

Interpretation of IRSU values: 0,85–1,00 — High level of rational subsoil use; 0,70–0,84 — Satisfactory; 0,55–0,69 — Unsatisfactory; < 0,55 — Critically low (requires immediate technological revision).

For the analyzed deposits, with Pact=10% and Pnorm=11%, Ract=21,6%, Rnorm=22% - Kcond =1,15, IRSU = 0,91(high level of rationality). This indicator enables inter-block and inter-mine comparisons on a unified scale.

The results obtained confirm that even a minor reduction in ore losses and dilution leads to a significant increase in economic performance. This is due to the dual impact of these parameters: on the one hand, they increase the volume of the extracted valuable component, and on the other, they reduce the costs of processing waste rock. The practical implementation of the determined optimal values requires improving mine management systems, increasing the precision of drilling and blasting operations, and introducing modern methods of geological and technological control. Furthermore, the research findings can be utilized in

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the development of ore loss and dilution standards tailored to specific mining and geological conditions.

Conclusions. Based on data from 10 extraction units, an adequate RSM model ($R^2 = 0.998$, $p < 0,0001$) was constructed to describe the dependence of profit on ore losses and dilution. The interaction between factors was found to be insignificant, indicating that each parameter exerts an independent influence.

In contrast to traditional models, this study accounts for the complex interrelationships between technological parameters, thereby increasing forecasting accuracy. Statistical checks including Cochran's, Student's t-test, and Fisher's F-test were performed at a significance level of $\alpha = 0,05$, confirming data consistency and model adequacy.

The developed profit optimization RSM model ($R^2 = 0,957$) established a conditionally optimal region with ore losses of 10% and dilution of 21.6%.

The proposed Integral Indicator of Rational Subsoil Use (IRSU) provides a unified metric for assessing the efficiency of subsoil resource utilization across all extraction units of the mine and serves as a criterion for adaptive normalization.

The RSM model accurately characterizes these dependencies and can be utilized for forecasting economic efficiency, as well as for optimizing technological processes during the industrial mining of gold-bearing ores.

The practical significance of the study lies in the potential integration of the developed model into production planning and mine management systems. This enables the rapid adjustment of technological parameters in response to changing mining conditions and market fluctuations.

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