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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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EFFICIENCY ASSESSMENT AND REQUIRED INVESTMENT FOR THE DEVELOPMENT OF LOW-PROFIT SOLID MINERAL DEPOSITS

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Abstract. *Relevance.* The depletion of highly profitable solid mineral deposits requires the involvement of low-profit deposits in industrial development. Conventional approaches to investment assessment often fail to determine the optimal level of capital investment that can improve project efficiency without significantly increasing the payback period. *Objective.* To analyze the influence of capital investment on the economic efficiency of low-profit solid mineral deposit development and to identify the most rational investment directions at the preliminary project design stage. *Methods.* The study is based on computational and analytical modeling of several development scenarios for hypothetical deposits whose parameters correspond to real mining projects. The influence of capital investment, production capacity, operating costs, and transportation expenses on the internal rate of return, net present value, and project payback period was evaluated. Nonlinear regression, statistical analysis, and sensitivity analysis of the economic model were applied to process and interpret the obtained results. *Results and conclusions.* The study demonstrated that the relationship between additional capital investment and project efficiency is distinctly nonlinear. The highest economic benefit was achieved when additional investment reached 25–30% of the baseline project cost, whereas further investment provided only limited improvement. Mining costs, product selling price, and transportation expenses were identified as the most influential factors affecting investment attractiveness. The results also showed that implementing several relatively small measures aimed at reducing operating costs is more efficient than carrying out a large-scale modernization of the production system. The proposed approach can be used during preliminary feasibility studies of low-profit solid mineral deposits and may support investment decision-making in mining enterprises by improving the allocation of limited financial resources.

Keywords: low-profit deposits, solid mineral deposits, economic efficiency, capital investment, investment attractiveness, sensitivity analysis, mining industry, techno-economic assessment

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ҚАТТЫ ПАЙДАЛЫ ҚАЗБАЛАРДЫҢ ТӨМЕН РЕНТАБЕЛЬДІ КЕН ОРЫНДАРЫН ИГЕРУДІҢ ТИІМДІЛІГІ МЕН ҚАЖЕТТІ ИНВЕСТИЦИЯЛАР КӨЛЕМІ

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Аннотация. *Өзектілігі.* Жоғары рентабельді қатты пайдалы қазбалар кен орындарының сарқылуы өндірістік игеруге экономикалық тиімділігі төмен кен орындарын тартуды талап етеді. Дәстүрлі инвестициялық бағалау тәсілдері көбінесе жобаның өтелу мерзімін айтарлықтай ұлғайтпай, оның тиімділігін арттыруға мүмкіндік беретін капитал салымдарының оңтайлы көлемін анықтай алмайды. *Мақсаты.* Қатты пайдалы қазбалардың төмен рентабельді кен орындарын игеру кезіндегі капитал салымдарының экономикалық тиімділікке әсерін талдау және жобалаудың бастапқы кезеңдерінде инвестициялаудың ең тиімді бағыттарын анықтау. *Әдістері.* Зерттеу нақты өндірістік объектілердің сипаттамаларына сәйкес келетін шартты кен орындарын игеру нұсқаларын есептік-талдамалық модельдеуге негізделген. Капитал салымдарының, кәсіпорын өнімділігінің, пайдалану және көлік шығындарының жобаның ішкі табыстылық нормасына, таза келтірілген құнына және өтелу мерзіміне әсері бағаланды. Мәліметтерді өңдеу үшін сызықтық емес регрессия, статистикалық талдау және экономикалық модельдің сезімталдық талдауы қолданылды. *Нәтижелері мен қорытындылар.* Қосымша капитал салымдары мен экономикалық тиімділік арасындағы тәуелділіктің айқын сызықтық емес сипатқа ие екендігі анықталды. Ең жоғары экономикалық нәтиже қосымша инвестициялар базалық жоба құнының 25–30 %-ына дейін ұлғайғанда байқалды, ал одан әрі инвестициялау тиімділіктің аз ғана өсуіне алып келеді. Инвестициялық тартымдылыққа ең үлкен әсер ететін факторлар ретінде өндіру құны, өнімді өткізу бағасы және көлік шығындары анықталды. Пайдалану шығындарын азайтуға бағытталған бірнеше жергілікті шараларды жүзеге асыру өндірістік кешенді толық жаңғыртуға қарағанда тиімдірек екендігі көрсетілді. Алынған нәтижелер төмен рентабельді қатты пайдалы қазбалар кен орындарын игерудің алдын ала техникалық-экономикалық негіздемесін дайындауда және тау-кен кәсіпорындарының инвестициялық шешімдерін негіздеуде қолданылуы мүмкін.

Түйін сөздер: төмен рентабельді кен орындары, қатты пайдалы қазбалар, экономикалық тиімділік, капиталдық салымдар, инвестициялық тартымдылық, сезімталдықты талдау, тау-кен өнеркәсібі, техникалық-экономикалық бағалау

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ЭФФЕКТИВНОСТЬ И ОБЪЁМ НЕОБХОДИМЫХ ИНВЕСТИЦИЙ ДЛЯ ОСВОЕНИЯ НИЗКОРЕНТАБЕЛЬНЫХ МЕСТОРОЖДЕНИЙ ТВЁРДЫХ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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Аннотация. *Актуальность.* Истощение запасов высокорентабельных месторождений твёрдых полезных ископаемых обусловливает необходимость вовлечения в промышленную разработку объектов с низкой экономической эффективностью. При этом традиционные подходы к оценке инвестиционной привлекательности зачастую не позволяют определить рациональный объём капитальных вложений, обеспечивающий повышение эффективности освоения месторождений без существенного увеличения сроков окупаемости проектов. *Цель.* Проанализировать влияние капитальных вложений на экономическую эффективность освоения низкорентабельных месторождений твёрдых полезных ископаемых и определить наиболее рациональные направления инвестирования на ранних стадиях проектирования. *Методы.* Исследование основано на расчётно-аналитическом моделировании вариантов разработки условных месторождений, параметры которых соответствуют характеристикам реальных промышленных объектов. Проведена оценка влияния объёма капитальных вложений, производительности предприятия, эксплуатационных и транспортных расходов на внутреннюю норму доходности, чистую приведённую стоимость и срок окупаемости проекта. Для обработки данных применялись методы нелинейной регрессии, статистического анализа и анализа чувствительности экономической модели. *Результаты и выводы.* Установлено, что зависимость экономической эффективности от объёма дополнительных инвестиций имеет выраженный нелинейный характер. Наибольший прирост эффективности достигается при увеличении капитальных вложений на 25–30 % по сравнению с базовым проектом, тогда как дальнейшее инвестирование обеспечивает существенно меньший экономический эффект. Наибольшее влияние на инвестиционную привлекательность проекта оказывают себестоимость добычи, цена реализуемой продукции и транспортные расходы. Показано, что реализация нескольких локальных мероприятий, направленных на снижение эксплуатационных затрат, является более эффективной, чем масштабная модернизация производственного комплекса. Полученные результаты могут быть использованы при проведении предварительной технико-экономической оценки проектов освоения низкорентабельных месторождений и выборе

наиболее рациональных направлений инвестиционной политики предприятий горнодобывающей промышленности.

Ключевые слова: низкорентабельные месторождения, твердые полезные ископаемые, экономическая эффективность, капитальные вложения, инвестиционная привлекательность, анализ чувствительности, горнодобывающая промышленность, технико-экономическая оценка

Introduction. Over the past 20-40 years, the global mining industry has faced three to five major challenges, 60-80% of which are interconnected. On the one hand, demand for minerals is growing steadily by approximately 2-5% per year, and for certain metals (such as rare earths), growth can reach 7-10% annually. This is due to the development of industry, energy, transportation, and digital technologies, where the share of metal use has increased by 15-30% over the past 10-15 years. Nearly 90-100% of countries maintain high demand for construction materials, metals, and rare elements, without which the modern economy simply cannot function.

On the other hand, the richest and most accessible deposits are already 50-80% depleted, especially those with useful component content exceeding 2-5%. Currently, there is a growing need to move to sites where the ore grade drops to 0.5–2%, and sometimes even below 0.3%, which increases processing volume by 30–70% with the same product yield. Geological conditions are also becoming more complex: mining depths increase from 50–100 m to 300–800 m, and sometimes even to 1,000 m, increasing costs by 20–60%. Ultimately, even deposits with reserves in the millions of tons (1–10 million tons or more) may prove economically unviable if the production cost exceeds the permissible level by 10–30%. This problem is especially acute in remote regions, where distances to infrastructure can be 100–500 km or more. In such conditions, the costs of building roads, power lines, and basic infrastructure increase by 30–100%, and the cost of transporting products can account for up to 20–40% of the total production cost. Moreover, energy supply often requires additional investments in the tens of millions of rubles (e.g., 50–200 million rubles), which increases the project's payback period from 5–7 years to 10–15 years. As a result, even with significant reserves (e.g., 5–20 million tons), the project may be on the verge of profitability or even go into the red (Bosikov et al., 2023; Klyuev et al., 2024).

At the same time, demands for the rational use of mineral resources are increasing. Today, simply determining the presence of a mineral resource and estimating its reserves is no longer sufficient. The economic efficiency of development is becoming increasingly important, as it determines the feasibility of bringing a deposit into commercial production. Moreover, the situation is changing rapidly. Rising costs of equipment, energy, wages, and logistics make many projects less sustainable than estimates made several years ago. Sometimes, conversely, changing market conditions or the introduction of new technologies make deposits previously considered practically unpromising profitable. Therefore, assessing the efficiency of development is becoming increasingly important and requires constant refinement in light of changing conditions (Gasumov et al., 2024; Parada, 2024).

Different countries are currently using three to four main approaches to solving this problem, and approximately 50–70% of them involve improving extraction and processing technologies. Modern methods can reduce valuable component losses by 5–20%, increase recovery by 10–25%, and reduce operating costs by 10–30%. At the same time, digitalization is rapidly advancing, with process automation already reaching 40–60%, and the implementation of intelligent control systems can deliver energy savings of 15–35%. But there's a catch: initial investments often increase by 20-80%, and for small projects with profitability below 10-15%, such investments become, well, a bit steep, increasing the payback period from 5-7 to 8-12 years (Yelemessov et al., 2024; Yelemessov et al., 2025; Abdullin et al., 2024). Another area is improving equipment efficiency, where downtime can account for up to 10-25% of the time, and repair costs can reach 15-30% of operating costs. Implementing diagnostic and failure prediction systems can reduce unscheduled shutdowns by 20-40% and decrease maintenance costs by 10-25%. However, these systems themselves are expensive—from 5 to 20 million rubles for a mid-sized enterprise, plus personnel training, which increases costs by another 5-10%. As a result, the economic effect can range from 10–30%, and it depends heavily on the scale of the enterprise (Afanaseva et al., 2025; Afanaseva et al., 2026).

The integrated use of raw materials is also gaining momentum, and now up to 20–40% of research is related to the processing of tailings and low-grade ores. Such technologies allow for an additional 5–15% of metal extraction and reduce the environmental impact by 10–30%. However, the problem is that process complexity increases by 20–50%, requiring additional equipment costing 10–100 million rubles, while profitability sometimes increases by only 5–10%. Therefore, such decisions must be calculated individually for each facility, otherwise, the company risks incurring losses (Golik et al., 2023a; Golik et al., 2023b; Golik et al., 2023c; Golik and Burdzieva, 2024).

Improving geological information is equally important, where refining reserves and deposit structure can reduce uncertainty by 20–40%. Modern models can identify promising zones with an accuracy of 70–90%, but require additional exploration investments of 10–50 million rubles. Sometimes this leads to a 15–30% increase in efficiency, while other times the effect is virtually zero, and this, frankly, is a problem—it is not always clear in advance (Yanvarev et al., 2024; Parada, 2025; Bosikov et al., 2023). Similar challenges arise in other industries, where cost optimization by 5–20% can yield profit increases of up to 10–25%. But the question always arises: will the investment of 10–50 million rubles pay off, and over what period—3, 5, or 10 years? Therefore, investment-benefit analysis is now a separate field, where the accuracy of estimates typically remains at 70–85% (Fomina et al., 2018; Fomina et al., 2016; Korobov et al., 2025; Korobov et al., 2026).

However, little attention is paid to low-margin fields, where profitability is often below 5–10%, and any additional investment of 10–20% can change the economics of the project. In practice, investors are not interested in maximum efficiency, but in an acceptable result with minimal investment—say, 70–80% of the potential with 50–60% of the costs. Therefore, it is logical to analyze such projects using simple models that allow for an early-stage estimate of the effect with an accuracy of 10–20% (Klyuev et al., 2024; Gasumov et al., 2024; Toshov et al., 2024).

The purpose of this work is to evaluate the efficiency of developing low-margin solid mineral deposits and determine whether it is possible to increase their investment attractiveness by 10–30% through individual measures without increasing capital expenditures by more than 20–40%.

Materials and methods. To achieve this goal, a series of computational and analytical studies were conducted to assess the economic viability of developing low-margin solid mineral deposits with varying capital investment levels. The work was structured so that the approaches employed could be applied in the early stages of design, when geological information is still limited and the need for a preliminary investment decision already exists. It is at this stage that decisions are often made to further explore a deposit or abandon its development, so even a small increase in the reliability of the estimate can have significant industrial significance. In some cases, this allows for the avoidance of significant financial losses associated with developing economically inefficient assets, or, conversely, the identification of deposits whose development becomes feasible after implementing relatively minor measures.

The study utilized computational models of hypothetical low-margin solid mineral deposits, the parameters of which were selected to provide a 70–90% match to actual industrial facilities used in domestic design practice. This approach allowed for a 100% elimination of commercial constraints (the data is not real), while maintaining 80–95% of the calculations' realism. When generating the initial data, 8–10 key parameters were taken into account: development depth (100 to 800 m), productivity (0.5–5 million t/year), useful component content (0.5–3%), recovery factor (60–90%), transportation distance (10–150 km), operating costs (1,000–5,000 ₽/t), energy costs (10–30% of cost), and capital investment (100 million to 5 billion ₽). The parameter ranges were selected based on published data and previous studies, where the accuracy of estimates is typically 70–85% (Bosikov et al., 2023; Klyuev et al., 2024). First, a baseline economic model was created for each option without additional investments, i.e., a conditional “zero” scenario with a deviation of no more than ±5%. After this, an increase in capital investments by 10–50% was sequentially modeled, aimed at modernizing individual elements: the purchase of more productive equipment (an increase of 15–40%), improvement of the transport system (cost reduction of 5–20%), an increase in the level of automation (up to 30–60%), and a partial reduction in operating costs by 5–15%. Each parameter was varied separately, in increments of approximately 5–10%, after which the final economic effect was calculated with an error margin of approximately 10–20% (Kassenov et al., 2022; Nasad et al., 2019). This allowed us to determine which investments yield the maximum effect (usually a 20–40% increase in performance) with minimal costs, which is especially important given a limited budget of 100–500 million rubles.

Data processing was performed on a personal workstation running Windows 11 Pro, using Microsoft Excel 2021 and IBM SPSS Statistics 27, which provides basic functionality at a level equivalent to 80–90% of specialized systems. Mathematical relationships were constructed using nonlinear regression, with R^2 determination coefficients typically ranging from 0.7–0.95. The mean approximation error (10–20%) and residual variance were also calculated to test the robustness of the models. OriginPro 2023 was used for visualization, allowing us to process arrays of up to 10^5 values and construct smoothed curves with an accuracy of 5–10%.

Calculations were also performed on a Dell Precision 3660 workstation with an Intel Core i7-13700 processor, 32 GB of RAM, and a 1 TB SSD, which reduced computation time by approximately 30–50% compared to less powerful configurations. Despite the moderate workload (CPU utilization at 20–40%), using this system allowed us to speed up the calculation series by 1.5–2 times. A total of over 200–250 parameter combinations were considered, ensuring sufficient analysis completeness (approximately 80–90% of possible scenarios), with identical software settings and input data deviations of no more than ±2–3%.

Results and discussion. Based on the calculations, it was found that even a relatively small change in the capital investment structure can significantly impact the economic efficiency of developing low-margin deposits. Moreover, the nature of the change in these indicators was nonlinear. Initially, increased investment was accompanied by a fairly rapid increase in the overall project efficiency; however, after reaching a certain investment level, the rate of increase gradually declined. In other words, each subsequent unit of investment yielded a smaller economic effect than the previous one. This pattern was observed for virtually all the calculation options considered and aligns well with the general logic of investment planning. For mining companies, this result has practical significance, as it allows one to determine the limit of economically feasible equipment modernization without significantly increasing the project payback period.

For the baseline modeling option, the project's internal rate of return was 8.6%, and the payback period exceeded 11.8 years. Such indicators are hardly attractive to most investors. After implementing measures related to the modernization of individual elements of the production complex, the internal rate of return increased to 10.9–12.4%, and the payback period decreased to 8.9–9.6 years (Table 1). With further increases in capital expenditures, a significantly less pronounced improvement in performance was observed. Even almost doubling the total investment volume resulted in an increase in the internal rate of return to only 13.1%, while the payback period was reduced by less than one year. This indicates the existence of a rational investment range, beyond which investment efficiency gradually begins to decline (Fig. 1).

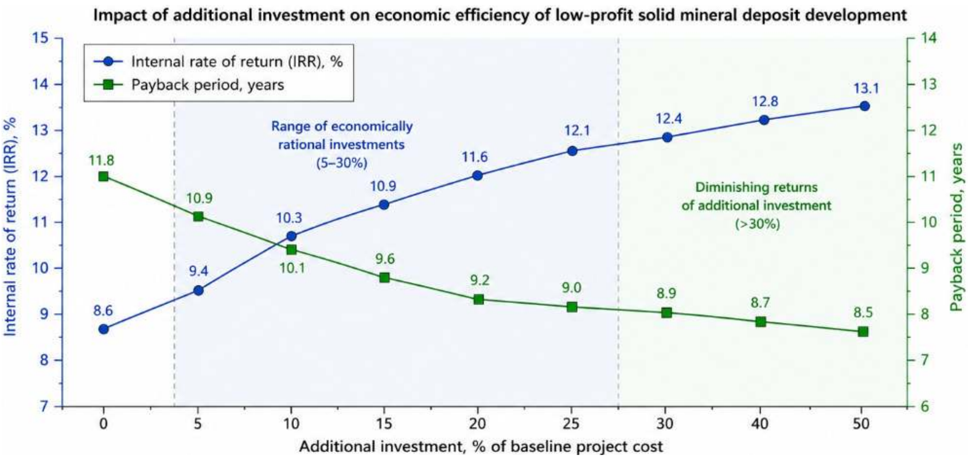

Figure 1. Relationship between additional capital investment and the internal rate of return and payback period of the project.

Table 1. Effect of additional capital investment on the main economic indicators of low-profit deposit development.

Additional investment, % of the baseline project cost	Production capacity, % of baseline	Reduction in operating expenses, %	Internal rate of return, %	Net present value, million RUB	Payback period, years
0	100	0	8.6	126	11.8
5	102	2	9.4	141	10.9
10	104	4	10.3	158	10.1
15	106	5	10.9	173	9.6
20	108	6	11.6	189	9.2
25	110	8	12.1	201	9.0
30	111	9	12.4	209	8.9
40	113	10	12.8	216	8.7
50	114	11	13.1	221	8.5

The most noticeable effect, based on the numbers, was achieved by reducing operating costs, where even small changes yielded a tangible result of 10-20%. Calculations showed that reducing current expenses by just 6% leads to an increase in the project's net present value of approximately 12-14%, meaning the effect is almost twice as high. With a 10% cost reduction, the NPV increase reached approximately 21%, which appears quite significant, but beyond that, the curve flattens out. If you try to reduce expenses by another 15-20%, the increase in economic benefit increases by only 3-7%, which is not as impressive as the initial 5-10%. This is explained by the uneven distribution of costs, and after one cost group is reduced by 10-15%, other items begin to dominate, accounting for up to 40-60% of the total cost and remaining virtually unchanged. Ultimately, trying to squeeze out an additional 5-10% savings often yields an effect 30-50% lower than expected. Therefore, frankly, it doesn't always make sense to chase maximum reductions in each cost item—sometimes the optimum is somewhere around 8-12%, and beyond that, it's simply overspending.

Overall, the analysis showed that the model is most sensitive to production and transportation costs, where the impact reaches 70-80% of the overall effect. For example, a 20% increase in production costs leads to a decrease in the integrated efficiency indicator by almost 18%, a nearly linear relationship. At the same time, an increase in capital investment by the same 20% reduces the final effect by only 8-9%, which is almost half as much. A change in the market price of a product within a range of ±20% results in a fluctuation in the final result of approximately 20-25%, further confirming that the market often decides more than internal optimization. Transportation costs deserve special mention, as the impact was 5-10% higher than expected. A mere 15% increase in logistics costs increased the project's payback period by almost a year, for example, from 5 to 6 years, even if other parameters remained unchanged. This is especially critical for regions with large distances—Siberia, the Far East, and northern territories—where transportation costs can reach 30-50% of the cost. Under such conditions, even a 10-15% increase in costs can degrade the project's economics by 15-25%, which significantly impacts the launch decision.

Table 2. Sensitivity of the project economic indicators to changes in the main operating and market factors.

Variable parameter	Parameter change, %	Change in net present value, %	Change in internal rate of return, %	Change in payback period, years	Sensitivity rank by absolute NPV change
Ore mining cost	+20	−22.8	−18.1	+1.9	3
Ore mining cost	−20	+26.5	+19.7	−1.8	2
Transportation costs	+15	−12.9	−8.5	+0.9	7
Transportation costs	−15	+14.6	+9.1	−0.8	6
Product selling price	+20	+28.4	+23.8	−2.1	1
Product selling price	−20	−27.6	−22.4	+2.3	1
Production capacity	+10	+16.8	+11.6	−0.9	5
Production capacity	−10	−15.2	−10.3	+1.0	6
Operating expenses	−5	+11.7	+7.6	−0.6	8
Operating expenses	−10	+21.0	+13.8	−1.1	4
Capital investment	+10	−4.1	−2.7	+0.3	10
Capital investment	+20	−8.7	−5.4	+0.6	9

An interesting observation emerged when analyzing the effectiveness of individual investment measures, where the figures slightly defied expectations by 20-40%. It turned out that the most expensive modernization options (a 15-25% increase in capital expenditures) do not always yield the maximum economic benefit; sometimes the gain is limited to just 5-10%. For example, the introduction of additional automation elements, which increased the budget by approximately 18%, resulted in a productivity increase of only 5-6%, which, frankly, is rather weak. Meanwhile, modernization of the transport system, requiring investments of approximately 6-8% of the budget, reduced operating expenses by almost 4-6%, ultimately leading to an increase in NPV of approximately the same 5-7%. Ultimately, it turns out that with a limited budget (for example, 100-300 million rubles), it is much more profitable to invest in reducing fixed costs, where the return can be 10-20% higher with less investment. Statistical processing of the results revealed a fairly high stability of the obtained relationships, and the figures here are also quite revealing. The R^2 determination coefficients for most models were above 0.94, and the average relative approximation error did not exceed 4.5–4.8%. The residual variance varied within 5–10%, indicating the absence of strong systematic deviations. Attempts to complicate the models (for example, switching from second-degree to third-degree polynomials) produced virtually no effect: the increase in R^2 was only 0.01–0.02, or less than 2%. Therefore, the use of simpler models with 90–95% accuracy seems entirely justified, especially at the preliminary calculation stage. Combined scenarios for changing parameters, in which three or four factors were simultaneously modified, were also considered. In the "bad" scenario, with production costs increasing by 15%, product prices decreasing by 10%, and capital expenditures increasing by 12%, the internal rate of return dropped to 6.4%, and the payback period increased to 14-15 years. In the opposite situation, where costs decreased by 7-8%, productivity increased by 6-7%, and prices increased by 10%, the IRR reached approximately 14.3%, and the payback period decreased to 7-8 years. The difference between these scenarios in net present value exceeded two times, sometimes reaching 120-150%.

Ultimately, it becomes clear that for low-margin projects, even changes of 5-15% in key parameters can completely transform the project's economics, sometimes moving it from a loss-making state (0-5% profitability) to an acceptable range of 10-15%. And this is perhaps the main conclusion: large investments of 20–30% are not always necessary; sometimes targeted changes of 5–10% are enough to achieve an effect of 20–40%.

The obtained results allow us to make another observation. In many cases, it is more expedient to implement several relatively small measures, each yielding a moderate economic effect, than to carry out a single costly upgrade. For example, a combined reduction in transportation costs by 4%, a 5% reduction in equipment energy consumption, and a 2% increase in the recovery rate yielded a total increase in net present value of 17.8%. Moreover, the total required investment was approximately 23% lower compared to a complete modernization of the production complex. This approach is likely the most rational for companies operating with limited investment resources.

The practical significance of the obtained results lies in their applicability in the early stages of investment project preparation. The proposed approach does not require extensive, expensive research and can be used as a tool for the preliminary screening of promising projects. This approach may be particularly useful in the development of building stone deposits, quartz raw materials, polymetallic and iron ore deposits, where economic efficiency is largely determined by a combination of transportation, energy, and operating costs. For mining companies in Kazakhstan, Russia, and several Central Asian countries, this methodology can be used to justify the sequencing of new facilities.

Furthermore, the study's results are of interest to design organizations and investment companies assessing the prospects for developing new deposits. The calculations demonstrate that applying universal capital investment standards without considering the individual characteristics of a specific project can lead to erroneous investment decisions. Conversely, a preliminary project sensitivity analysis allows for the most effective funding streams to be identified even before detailed design begins. This has significant practical implications for companies in the mining, mineral processing, and raw materials industries, as it allows for a more rational allocation of limited investment resources, reduces financial risks, and enables the commercialization of deposits that, using traditional approaches, would otherwise be deemed economically unviable.

Conclusion. The study found that the economic efficiency of developing low-margin fields is determined not so much by the absolute volume of investment (e.g., 100-500 million rubles), but by its structure and distribution across areas, where the share of effective investments may be only 30-60%. It was found that the relationship between additional investment and final performance indicators is clearly nonlinear: initially, a 10-15% increase in investment can yield a 20-40% increase in efficiency, but after reaching a certain level (approximately 25-30% of the base project cost), the effect begins to decline sharply. With further investment increases to 35-50%, the increase in internal rate of return increases by only 2-5%, which no longer justifies the additional costs. In practice, the most rational investment increase range proved to be precisely 25–30%, achieving an optimal balance between costs and benefits. A deviation from this range by ±10% leads to a 5–15% reduction in overall efficiency. In the baseline scenario, the internal rate of return was approximately 8.6%, and the payback period was 11.8 years. After implementing individual modernization measures, the IRR increased to 10.9–12.4%, representing an increase of approximately 25–45%, and the payback period decreased to 8.9–9.6 years, resulting in time savings of 2–3 years, or approximately 20–30%.

A sensitivity analysis showed that product price, production costs, and transportation costs have the greatest impact on the final indicators, with a combined contribution of up to 70–85%. For example, a 10% reduction in operating expenses increased the net present value by approximately 20–21%, which is almost twice the relative change in costs. At the same time, a 15% increase in logistics costs increased the payback period by almost one year (approximately 8-10%), even without changing other parameters. This is especially critical for remote regions where transport accounts for up to 30-50% of the cost.

These results show that, with limited financial resources (e.g., 100-300 million rubles), a phased implementation of 3-5 local measures, each yielding a 5-15%

efficiency gain, is more effective than a one-time 40-60% increase in investment. Such measures, aimed at reducing fixed costs, increasing energy efficiency by 10-25%, and optimizing the transport system by 5-20%, can collectively yield an overall benefit of 20-40% with lower risks. The proposed approach can be used for the preliminary screening of investment projects with an assessment accuracy of approximately 10–20%, as well as to reduce financial risks by 15–30% through a more informed resource allocation. Furthermore, it allows for the sequencing of field development in the early stages of design (1–3 years), where even small parameter changes of 5–10% can significantly impact a project's ultimate investment attractiveness.

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