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Optimal Investments in Geological Exploration under Price and Geological-Technical Uncertainty: A Real Options Model

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Abstract

Relevance of the work. Mining companies seek to maximize shareholder value in an environment of increasing uncertainty. Commodity prices are far more volatile than they were just a few years ago, and emerging economic challenges are increasing the uncertainty of exploration investments. In an environment of complex capital investments driven by joint ventures, licenses and partnerships, inadequate or inaccurate accounting for uncertainty can lead to poor decisions and loss of value. Investing companies are therefore seeking more useful and effective methods to assess and analyze the impact of uncertainty on their investments.

The purpose of the work is to develop a methodology for optimizing investments in mineral exploration under conditions of price and geological-technical uncertainty based on the real options model. The concept of the model directs managers to maximize opportunities while minimizing obligations, encouraging them to consider each situation as an initial investment in future prospects. As a result, the field of view of decision makers expands beyond long-term plans that are too rarely revised to cover the entire spectrum of changing opportunities.

Methods. In the process of research, general scientific and special methods of scientific knowledge were used, namely: analysis, synthesis, systematization, generalization, grouping.

Results of the work and scope of application. In the course of the study, a methodology for assessing investments in the exploration of a new field with the joint existence of price and geological and technical uncertainty is proposed, while taking into account the managerial flexibility for the step-by-step implementation of the exploration project strategy. The peculiarity and advantage of the methodology is that two sources of uncertainty – price and geological and technical – were combined into a single-factor model of expected value, which allowed maintaining its simplicity and operational flexibility. The results obtained can be used by public and private mining enterprises to improve methods in the field of mineral resource base management.

***Keywords*:** exploration, investment, real options, deposit, mineral resource base, management.

Relevance of the work

As the average size of newly discovered fields decreases, the uncertainty underlying investment decisions is constantly increasing. Before developing a small field, fewer appraisal wells are usually drilled, which reduce the uncertainty in the subsurface, compared to large fields [1]. In this regard, it is necessary to find new solutions for the commercialization of small fields in the conditions of technical and market uncertainty. In such conditions, managerial flexibility, which allows changing the course of the project, in the event of new information, should be critically taken into account in the investment appraisal process. In addition, it should be noted that the value of maintaining the possibility of choice in geological exploration is also obvious from the point of view of the fact that in such investment-intensive industries, where the processes of licensing, prospecting, evaluation and development are naturally divided into stages, each of them continues or stops depending on the results of the previous stage [2].

International studies and reports show that a number of high-performing mining companies instinctively or intuitively view their investment opportunities as real options, looking forward to exploiting probable cash flows but not making a final investment decision until the potential is proven [3]. However, companies in any industry are forced to allocate resources between competing opportunities, whether existing businesses or new ventures, and must decide whether to invest now, take preliminary steps while reserving the right to invest in the future, or do nothing. For example, it is very common for exploration investments in a given area to be considered in the presence of combined price and geological and technical uncertainty. Price risk relates to the market value of the extracted raw material, and geological and technical risk relates to reserves, investment in development, and cost structure [4]. And because each of the possible options creates a set of potential benefits and losses associated with

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further choices, all management decisions can be viewed in terms of real options.

Real options are a paradigm of investment analysis that links value creation to the bottom-up aspect of uncertainty. In this way of thinking, a conscious effort is made to assess the impact of uncertainty on investments and to create value from favorable outcomes [5]. However, despite their obvious importance for business decision making and the fact that they are gaining increasing support in academic circles, real options have not yet found widespread use in industries characterized by high levels of investment in R&D, manufacturing, and marketing.

Thus, the subject matter under consideration is a relevant area of research, which predetermined the choice of the topic of this article.

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Methods

In the process of research, general scientific and special methods of scientific knowledge were used, namely: analysis, synthesis, systematization, generalization, grouping.

The features of economic evaluation of mineral exploration projects and methods of decision-making in conditions of significant uncertainty in the subsoil are considered in the works of Dushin A. V., Nazarova Z. M., Pashkevich N. V., Komarov A. I., Kholmogorov V. V., Zabotkina E. M., Vakulenko A. I., Alireza Malehmir, Gordon Cooper, Musa Manzi, Andrei Swidinsky, Umair Bin Waheed.

The advantages of real options in strategic and financial analysis compared to traditional evaluation tools such as NPV, which ignore the value of flexibility, are described by Sergeev I. B., Khatkov V. Yu., Zubarev G. V., Demkin I. V., Joon Mahn Lee, Jung Chul Park, Guoli Chen, Roberto Serrano.

At the same time, it should be noted that in the period following the first application of real options valuation to mining investments, several approaches to calculating the value of uncertain investments have been proposed. Unfortunately, the assumptions underlying these various approaches and the conditions appropriate for their application are often not specified. Where they are specified or can be assumed, they vary widely across methodologies and even contradict each other.

Results of the work

Decisions related to exploration and production of minerals are very complex due to the large number of factors that influence this process. During the project development stage, the project team must determine, among other factors, the composition of geological exploration work, the optimal number of exploration wells and their placement. This decision is especially difficult in conditions of technical and market uncertainty. In addition, investments in geological exploration are considered irreversible, since the investor cannot recoup the costs after they have been made [6, 7]. Therefore, establishing a balance between the expected benefit from additional geological exploration work and the associated costs in conditions of prevailing uncertainty, management must make a fundamental decision that cannot be changed during the course of the project.

A standard approach to reducing reservoir uncertainty in order to improve the quality of field development design and subsequent operation is to drill appraisal wells [8]. However, this approach may not be appropriate for some projects where the investment in an extensive appraisal program is considered to be inadequate compared to the information disclosure potential. In such circumstances, a more optimal strategy for dealing with reservoir uncertainty may be to begin developing the field based on available information without conducting an additional appraisal program [9]. Rather than undertake a large-scale preliminary exploration project for the entire field, some of which will likely fail to produce at an acceptable level, management can prioritize them and conduct exploration sequentially, i. e. develop the field in several stages. This is done to begin production early in the field's life, which can last from several months to several years, which will allow positive cash flow from operation to be generated and used for further detailed exploration of the field. Table 1 demonstrates the main advantages of the phased exploration strategy compared to the standard one.

Exploration of natural resources involves several stages, each of which has an investment schedule and corresponding probabilities of success and failure. The representation of n stages of geological exploration is reflected in fig. 1.

In fig. 1, X^j is the cost of the exploration project at the initial moment at stage j; I^j is the current cost of investments at stage j; T^j is the time of exploration stage j; p^j is the probability of success at stage j; H is the cost of the project at the end of the exploration stage, subject to success.

Thus, we will consider exploration project X as an infinite-sum option that can be exercised continuously as exploration investments are made. The model assumes that at any point in time, investments can be stopped or resumed as a result of uncertainty arising, depending on the expected

Table 1. Key advantages of the phased exploration strategy compared to the standard one
Таблица 1. Ключевые преимущества стратегии поэтапной разведки месторождения по сравнению со стандартной

Risk	Benefits of a Phased Exploration Strategy
Low Inventory/Resource Price Scenario	The ability to reduce risks by eliminating unprofitable stages of geological exploration
Deadlines	Reducing the loss of value due to waiting (time value of money) and probable losses in stage 1
Territorial feasibility of geological exploration work	Reasonable selection of the subsoil exploration area at stage 2 based on production experience and obtained data, which increases the expected return
Capital expenditure (CAPEX)	Ability to defer significant capital expenditures until Stage 2

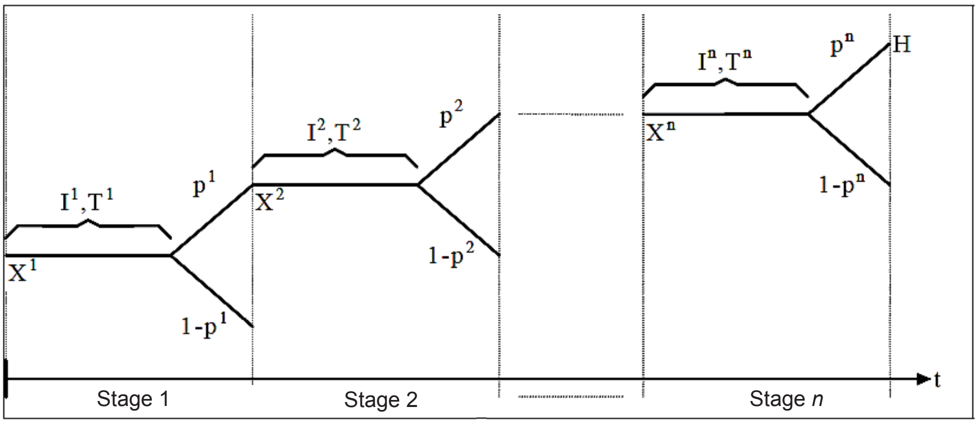

Figure 1. Illustration of the stages of geological exploration of the project
Рисунок 1. Иллюстрация этапов геологоразведки проекта

value of the project, which in turn depends on geological and technical data.

Uncertainty in exploration and production has two sides: one side is the undesirable outcomes, collectively called risk, and the other is the upside that can be achieved by properly using management options [10]. Uncertainty is a platform for creating flexibility, and flexibility is only valuable when uncertainty is resolved. This relationship is at the heart of real options thinking [11].

A short-sighted interpretation of uncertainty in exploration projects is a passive ("lottery") view of decisions under uncertainty. A decision followed by uncertainty may be a common view of most decisions, but this view ignores the opportunity to wait and learn from the evolving uncertainty. The fact is that some investment decisions may be delayed until the uncertainty is resolved.

At the next stage of the research, we will consider the features of modeling price and geological-technical risk.

Commodity price risk has traditionally been modeled using continuous-time arbitrage financing models [12]. Although recent multifactor pricing models have shown considerable promise in explaining commodity price behavior, for simplicity it seems appropriate to use a standard single-factor model with constant returns for risk-neutral prices.

$$\frac{dS}{S} = (r-c)\,dt + \sigma_S d\omega_S,$$

where S is the spot price of the raw material, r is the risk-free real interest rate, assumed to be constant, c is the amount of income from the extraction of minerals, σ_s is the instantaneous volatility of the return on owning one unit of minerals, $d\omega_s$ are the increments of the standard Gauss–Wiener process.

While price risk is constant across all three stages of a project (exploration, development, and exploitation), the geological and technical risk is much higher during the exploration stage. This geological and technical risk can be divided into two parts: the first is the success or failure of finding an economically viable deposit, and the second is related to the characteristics of the deposit found [13]. The first part can be modeled using discrete probabilities of success and failure at each stage of exploration, while the second is determined by the mine's reserve levels, development investment, production schedules, and cost structure.

To formalize the model, we introduce a geological and technical risk factor G (for example, the number of reserves in a mine), which follows Brownian motion with zero drift and constant volatility as follows:

$$\frac{dG}{G} = \sigma_G d\omega_G.$$

It is assumed that this geological and technical risk factor does not depend on the production price S:

$$d\omega_S d\omega_G = 0.$$

The value of a mine, H (S, G), can be modeled as a function of the output price, S, and the geological-technical variable, G. Now a new state variable, Z, a function of S and G, can be defined such that:

$$H(Z) \equiv H(S,G);\, Z \equiv F(S,G).$$

Applying Ito's lemma, we get:

$$dZ = \left(F_S S(r-c) + 0{,}5F_{SS}S^2\sigma_S^2 + 0{,}5F_{GG}G^2\sigma_G^2\right)dt +$$
$$+ F_S S\sigma_S d\omega_S + F_G G\sigma_G d\omega_S.$$

Now let's look at how the cost of a geological exploration project is calculated.

Let us assume that while the project is in the implementation stage and investments in exploration are being made, its value is equal to X, on the other hand, at the moment when the project is optimally stopped, its value is equal to Y. It should be noted that while investments in geological exploration are being made, the corresponding volatility is higher than when they are temporarily stopped, since geological and technical information is accumulated and updated only during investments [14].

The cost calculation can be done for each stage j, where $j = 1, n$. To do this, we start with the solution for stage $j = n$ and

Binomial Lattice for Project Cost Calculation Binomial Lattice for Option Cost Calculation

Рисунок 2. Диаграмма решетки для примера
Figure 2. Lattice diagram for example

move backwards to $j = 1$. The equations for the intermediate stage j are as follows:

$$\left[0{,}5X^j_{ZZ}Z^2\sigma^2_Z+(r-c)ZX^j_z+q^j_iX^j_i-q^j_i-\left(r+\lambda+\gamma^j\right)X^j\right]=0;$$

$$0,5Y^j_{ZZ}Z^2\sigma^2_S+\left(r-c\right)ZX^j_z-\left(r+\lambda\right)Y^j=0.$$

Given that:

$$X^j\left(0,I\right);Y^j\left(0,I\right);X^j_{ZZ}\left(Z,I\right);$$

$$X^j\left(Z,I^j\right)=X^{j+1}\left(Z,0\right),\text{если } Z\geq Z^{*j};$$

$$Y^j\left(Z,I^j\right)=Y^{j+1}\left(Z,0\right),\text{если } Z\geq Z^{*j}.$$

In the final step, these two boundary conditions are replaced by:

$$X^n\left(Z,I^n\right)=H\left(Z\right),\text{если } Z\geq Z^{*n};$$

$$Y^n\left(Z,I^n\right)=H\left(Z\right),\text{если } Z\geq Z^{*n}.$$

Since the probability that no Poisson event (i. e. success of exploration step j) occurs in the interval $(0, T^j)$ is equal to exp $(-\gamma^j T^j)$, we can conclude that γ^j must be $-\ln(p^j)/T^j$.

The notations in the above formulas are interpreted as follows: I – accumulated exploration investment; q^j_i – investment rate at stage j; I^j – current value of investment at stage j; T_j – time of exploration stage j; p_j – probability of success at stage j; Z^{*j} – critical price for investment at stage j; γ^j – Poisson probability of success at stage j.

Example of real options valuation. The example involves an option to invest in a project to explore for a hypothetical mineral resource. A company is considering investing in the exploration of a new deposit. The deposit can be developed now at a cost of $100 million and an NPV of $120 million with an annual volatility of 20% due to fluctuations in the price of the extracted resource and geological uncertainty. The company can also negotiate with the main operator and receive an option to invest $100 million over the next two years. Based on this contract, the company can purchase an option to invest deferred by paying the operator $10 million. The question is, "Is this option worth purchasing?"

In this hypothetical example, the project volatility and net present value are easily calculated. The project is assumed to have a risk-free discount rate of 4%, and the best way to calculate the option value is to use a binomial lattice. The net present value is assumed to be uncertain with an annual volatility of 2%, which means an up move of 1.2214 and a down move of 0.8187 with corresponding probabilities of 55% and 45%. The NPV dynamics of the project are shown on the left side of fig. 2. Solving the binomial lattice using a risk-neutral approach yields the right side of the lattice for the option values. The option is worth $31 million, and compared to the $10 million acquisition cost, it is well worth the purchase.

So, to sum it up, real options is a new paradigm that incorporates a dynamic view of investment analysis. This methodology confirms that value can be achieved primarily through creative design of flexible projects and forward thinking.

Conclusion

The article describes a methodology for evaluating investments in exploration of a new field based on the real options paradigm in the presence of coexistence of price and geological and technical uncertainty, while taking into account managerial flexibility for the step-by-step implementation of the exploration strategy in two stages. By combining both sources of uncertainty, price and geological and technical, into a single-factor model of expected value, its simplicity and operational flexibility were preserved.

By investing consistently, management can gather additional information about the uncertainty of the deposit at the initial stage of the project. Its investment policy can be optimized based on the developed algorithm and threshold boundaries. The proposed methodology is flexible enough to be applied to a wide range of other case studies. The modeling process produces recommendations for managers to facilitate the decision-making process.

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Оптимальные инвестиции в геологоразведку в условиях ценовой и геолого-технической неопределенности: модель реальных опционов

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Аннотация

Актуальность работы. Горнодобывающие компании стремятся максимизировать акционерную стоимость в условиях растущей неопределенности. Цены на ископаемые ресурсы гораздо более волатильны, чем еще несколько лет назад, а возникающие экономические сложности все больше усиливают неопределенность инвестиций в геологоразведку. В условиях сложных капиталовложений, обусловленных совместными предприятиями, лицензиями и партнерствами, недостаточный или неточный учет неопределенности способен привести к принятию неверных решений и потере стоимости. Поэтому компании-инвесторы ищут более полезные и эффективные методы оценки и анализа влияния неопределенности на их инвестиции.

Цель работы – разработка методологии оптимизации инвестиций в геологоразведку полезных ископаемых в условиях ценовой и геолого-технической неопределенности на основе модели реальных опционов. Концепция модели направляет менеджеров на максимизацию возможностей при минимизации обязательств, побуждая рассматривать каждую ситуацию как первоначальную инвестицию в будущие перспективы. В результате круг внимания лиц, принимающих решения, расширяется за пределы долгосрочных планов, которые слишком редко пересматриваются, чтобы охватить весь спектр меняющихся возможностей.

Методы. В процессе исследования использовались общенаучные и специальные методы научного познания, а именно: анализ, синтез, систематизация, обобщение, группировка.

Результаты работы и область применения. В процессе исследования предложена методология оценки инвестиций в разведку нового месторождения при совместном существовании ценовой и геолого-технической неопределенности, при этом учитывается управленческая гибкость для поэтапной реализации стратегии геологоразведочного проекта. Особенностью и достоинством методологии является то, что два источника неопределенности – ценовая и геолого-техническая – были объединены в однофакторную модель ожидаемой стоимости, что позволило сохранить ее простоту и операционную гибкость. Полученные результаты могут использоваться государственными и частными горнодобывающими предприятиями для усовершенствования методов в сфере управления минерально-сырьевой базой.

Ключевые слова: геологоразведка, инвестиции, реальные опционы, месторождение, минерально-сырьевая база, управление.

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