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MODELING CUMULATIVE AVAILABILITY CURVE OF GOLD RESOURCES

The article presents the authors' approach to evaluation of economic availability of mineral resources. The approach uses the cumulative availability curves plotted for certain minerals, which is a common way of solving such problems abroad. The curves represent the cumulative volumes of mineral resources at the deposits ranked in the sequence from the best to the worst versus the estimated cost of the mineral product. These costs should cover all expenses connected with mining and thus provide a zero net present value of extraction of certain mineral resources. The curves imply that as deposits having the worst mining conditions and containing low-quality minerals are involved in the development, the estimated costs increase. The cost calculation of is a very time-consuming process, and the main difficulty is the cost estimation of mineral mining and processing. The authors propose an approach to modeling the unit costs of mineral mining and processing depending on the deposit development probabilities estimated for a set of mineral bodies of the same genetic type. Using the developed cost estimation models and the information from the US Geological Survey on mineral resources, the cumulative availability curves are plotted for primary gold deposits in the world. On this basis, the forecast rates of the increase in the mineable mineral resources are compared with the rates of the increment in the costs of their development, and the express-appraisal of economically available resources is done.

Keywords: *mineral resources, mineral resource availability, development probability, resource depletion, peak models, cumulative availability curve, gold*
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Introduction

The recent period features fairly extensive usage of nonrenewable mineral resources. Mining practice depletes and exhausts mineral wealth. The future resource-richness raises concerns in this respect. Many researchers tend to ascertain future availability and amounts of mineral resources.

In Russian vocabulary, the term *availability* in the context of mineral resources represents difficulties connected with mineral extraction because of unfavorable geography or geology of mining operations. The United States Bureau of Mines uses the term *mineral availability* in plotting cumulative availability curves [1]. In Russia the term *mineral availability* is understood as the ability of the public–resources system to ensure safe and efficient use of minerals on the basis of the achieved technological development [2].

The problem of scantiness of nonrenewable mineral resources and their effect on economic development was for the first time addressed in The Limit to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind [3]. A key implication of the report says that, given the 1970s' population increase, agricultural production, nonrenewable resource depletion, industrial output, and pollution generation keeps on, the limit to growth will be achieved in the next century, which will cause an uncontrollable drop in production and in population of the Earth. This dismal outlook has now many opponents. Their major argument is that scientific-and-technological advance and mineral exploration can replenish the mineral wealth and move away resource depletion and population decline.

The mineral resource availability for the future generation is most often assessed using either a physical approach to mineral depletion estimated based on a paradigm of fixed resources or an economic approach on the basis of maximum allowable expenses.

Physical approach. Peak curves

Adherents of the first approach [4–8] assess the future mineral resource availability by peak modeling using bell curves and the Hubbert curves [9, 10]. They are based on the fundamental knowledge that mineral resources are limited and finite. According to this theory, mineral production reaches its peak when approximately the half of mineral resources is extracted. The peak modeling was initially used in predicted oil production. The United States anticipated the peak production by the late 1960s or the early 1970s, which was close to the actually happened production peak in 1971. The peak in the global oil production was expected in 2004–2005 [11].

The peak models were also used to predict depletion of solid mineral resources. The peak production times were found for 47 minerals. It is stated that production of two minerals had already reached the theoretical peak (antimony in 2012, gold in 2014), and production of 12 minerals will reach the peak in 50 years to come. The peak in production of copper can be passed over in the present century [7]. The maximum decline in production due to depletion of some deposits now in operation is expected for gold and zinc (>40% as compared to 2015), silver (>30%), diamonds (>25%) and lead (~25%). [12]. The ore production is going to be limited by the ecological and economic constraints, complicated geological conditions of mining and because of growth in mining waste recycling [6].

Many scientists turn down the paradigm of fixed resources in assessment of mineral resource availability in the future as the paradigm neglects the fact the mineral resources can grow as a result of effective exploration and advance in science and technology [13].

The Hubbert model forecasts an unavoidable decline in the global economy, or at least the impossible economic growth for a long time. This conclusion contradicts the public opinion on necessity and advisability of economic growth, and the idea of peak is criticized and rejected by most researchers [14]. Tilton [15] thinks the production peaks are reflective of decreasing availability of mineral resources because of the understatement of undiscovered potential resources. Such forecasts exaggerate the hazard of depletion of mineral resources and often foretell a shortage of mineral resources, which is unlikely in the foreseeable future.

It is difficult to use the peak curves to predict the long-term availability of mineral resources because of the impossible consistent assessment of the finite size of mineable resources. Efficient exploration and scientific-and-technical advance in mineral mining and processing, as well as changes in prices of mineral resources introduce essential corrective amendments in the forecasts of the mineral resource availability.

The models of depletion of mineral resources in the course of production experience improvement to remove the above listed shortages. Russian researchers proposed a model of predicting depletion of nonrenewable resources based on such parameters as a residual volume of proven reserves, initial volume of mineral production, initial rates of growth of mineral production and a decline in the production growth rate. The application of the proposed model is described as a case-study of natural uranium [16, 17].

Economic approach

Alongside with modeling maximum possible (peak) production outputs and their times, the mineral resource availability can be assessed in the framework of an economic approach. The economic approach uses the cumulative availability curves (CAC) [13, 15, 18, 19]. The curves describe the cumulative volume of resources of deposits in the rank order from the best to the worst as function of the mineral product cost per each mineral. It is assumed that the cost should cover all expense connected with mineral mining and, thereby, ensure zero net present value of extraction of certain resources. The curves implicate that the estimated costs increase as more deposits with the worst geotechnical conditions and lowest mineral quality are involved in production. The calculation of the estimated costs is a labor-consuming process with the key difficulty represented by the cost appraisal of mineral mining and processing.

Availability assessment using CAC supposes that the long-term operations will for the first turn involve mineral deposits which have the lowest cost of mining out of the deposits in standby. The cost to define economic efficiency of mining is determined as the cumulative cost of production of final output [19].

The CAC plotting, or the cost calculation of mineral mining, requires extensive information on mineral resources and their quality, and on mining and processing conditions per all deposits within the scope of the analysis. It is impossible to obtain such information in many occasions, moreover, initial data are often unreliable, which limits the actual research using CAC. Regarding data on actual expenses, it is difficult to compare them as operating companies essentially vary the cost estimating methods. Despite many efforts to standardize and unify cost figures, there are no yet common standards and requirements on accounting of unit product costs [20].

The cumulative availability curve plotting and the availability research for many minerals was implemented by the United States Geological Service [1]. The recent researches pursued assessment of the cumulative production curves for certain metals, for instance, Yaksic and Tilton estimated such curve for lithium [21], Jordan et al for thorium [22] and Jasiński et al for platinum group metals and lithium [23].

Regarding gold, such curve has not been plotted so far [15]. It is difficult to predict the moment when depletion is going to begin. Some researchers forecast a steady decline in gold production as soon as the middle of the next decade [24]. The other forecasts say that at the production level of 2015, the decrease in resources of most solid mineral will be not higher than the first per cent by 2030 [25]. On the other hand, these analyses of potential mineral resources neglected some critical impacts on the production level, such as the prices of primary goods and the costs of their production.

This paper presents the prosperity assessment of the global economy with available gold resources based on the cumulative availability curve plotting and the consolidated cost estimate of mineral mining and processing. The costs for the cumulative availability curve were determined using the probabilistic approach based on content/resources relationship (or Grade–Tonnage Diagrams) used in the foreign practice of prediction of undiscovered mineral deposits [26–28].

Cost estimate model

The source information is the data on ore reserves and on average content of useful components at the same-type deposits with similar mining conditions. The data are entered in the grade–tonnage diagram. The deposits which are being mined and in standby today are distinguished and marked.

Logit-regression is used to determine the function of attachment of an object to the classes of deposits being mined or in standby, which means determination of probability P of involvement of a deposit in mining depending on the size of the resources (tonnage) and on the content of the useful components in ore. The probability equation is given by:

$$P = \exp(b_0 + b_1\alpha + b_2S)/(1 + \exp(b_0 + b_1\alpha + b_2S)), \quad (1)$$

where b_0, b_1, b_2 are the coefficients; α is the content of useful component in ore (grade of ore), g/t; S is the resources (tonnage), t. The model of a specific region's mineral resources is constructed, the coefficients b_0, b_1 and b_2 are determined, and the value of the dependent variable P is predicted. The variable P found from formula (1) varies over an interval [0.1]. In model (1), the variable P has a mathematical sense of probability of a deposit with the preset parameters α and S to belong to the class of the deposits being mined. The deposit involvement in mining is a suitable quantitative measure of mineral resource availability.

For getting information on expenses of an individual mine, a threshold (limit) availability curve is plotted to separate the mines with the efficiency lower than the limit. Such curve plotting uses the data in the price dynamics on the raw material market. For example, the London metal exchange shows that prices fluctuate at the highest expenses of a number of mines which make about 10% of the total number of mining companies [29]. The threshold availability curve is plotted in the a–S diagram so that to cut out 10% of mineral deposits which are in operation. **Figure 1** offers an example of the diagram and the threshold availability curve. The current expenses per 1 finished product tone at the mines which lie on or nearby the threshold availability curves are assumable to be closing mines which function at zero efficiency. The threshold availability line characterizes the maximum level of expenditures tolerable by public in satisfaction of the demand for a certain mineral at this time.

The threshold availability line helps estimate mining expenses. The marginal costs of producers are reflective of the mineral raw material prices. Therefore, it is assumable in simplified estimates that the cost per time of metals is equal to the average market prices of this metal for the deposits which are on the threshold availability line. For different volumes of mineral resources, the limit metal content of ore is found from formula (2) derived from equation (1):

$$\alpha_{lim} = (P_{lim}/(1 - P_{lim}))^{1/b_1} e^{b_0/b_1} S^{b_2/b_1}, \quad (2)$$

where α_{lim} is the limit metal content sufficient to ensure minimal efficiency of mining, g/t; P_{lim} is the limit availability of mineral resources.

The cost per 1 t ore extracted is independent of the metal content of ore; for this reason, the grand estimate of expenses assumes that the cost per 1 t at the deposits with equal size resources is equal to the cost per 1 t at a deposit on the threshold availability curve. The costs

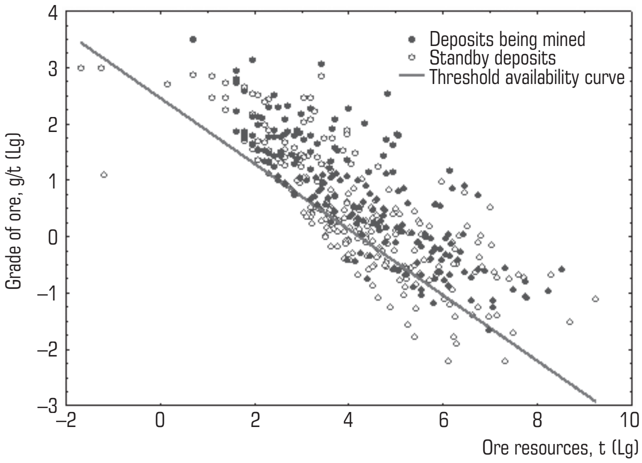

Fig. 1. G–T diagram for gold deposits worldwide

per 1 t of metal differ and depend on a ratio α_{lim}/α For the deposits above the threshold availability curve, the cost per 1 t of metal is less than the limit expenses, the average metal content is higher than the threshold content and, consequently, $\alpha_{lim}/\alpha \le 1$. For the deposits under the threshold availability curve, the cost per 1 t of metal exceeds the limit expenses, $\alpha < \alpha_{lim}$, and, thus, $\alpha_{lim}/\alpha \ge 1$. In this manner, the expenses per 1 tone of metal, E_{me}, lower or higher than the average market price by the ratio α_{lim}/α, is found from the formula:

$$E_{me} = P\alpha_{lim}/\alpha, \quad (3)$$

where P is the end product price, \$/t.

The total metal-related expenses E_p in money terms are:

$$E_p = S\alpha P\alpha_{lim}/\alpha = SP\alpha_{lim}. \quad (4)$$

In natural units: $E_p = S\alpha_{lim}$.

The expenses in terms of metal tonnage (compensation metal) are the metal cost which clears expenses connected with metal production.

The model of formulas (1)–(4) was tested as the case-studies of copper and gold deposits and placers in Russia, Krasnoyarsk Krai, and copper–porphyry deposits in the US, Canada and Chile. The model always describes well the statistically relevant data and real-life processes [30].

In this study, the model is used to plot the cumulative availability curve for gold resources.

We assume that the price and price-unrelated factors are constant. Mineral production proceeds in the best-to-worst line—first goes extraction of the best explored resources [15, 31]. The increment in the output volume is possible by means of introduction of standby deposits into operation. The expenses will be higher at the new-introduced deposits than at the already operating deposits, given the best-to-worst conception is abided to. The limit expenses per each extra unit product can be found as the ratio of the increment in the cost ($PS\alpha_{lim}$) to the increment in the output ($S\alpha$) due to the introduction of new resources in operation. For the best standby object i, the specific marginal cost of metal production is given by:

$$E_{marg} = PS_1\alpha_{limi}/(S_i\alpha_i) = P\alpha_{limi}/\alpha_i, \quad (5)$$

where E_{marg} is the specific marginal cost, \$/t; S_i is the resources of the best standby object i, t; α is the average metal content of ore at the object i, g/t; α_{lim} is the limit metal content calculated for the object i, g/t.

When the marginal cost found from (5) is less or equal to the market prices, mining of these resources is expedient and can increase the output. In case that the marginal cost of mining for the resources of the best explored object exceeds the market price, mining of this object is economically inefficient. Regarding the cumulative availability curve dependent on specific marginal cost (5), this mining object–deposit lies at the boundary of currently economic available resources (**Fig. 2**).

Gold resource availability. Results and discussion

The above-described model was used to determine future availability of gold resources. The source data was the actual information currently available at the United States Geological Survey on the types of gold deposits, their resources, mining methods and quality of resources being mined and yet standby. The source data assisted in plotting the G–T diagram and the threshold availability curve for the gold deposits in the world. The deposits which occur on or nearby the threshold availability curve are mineable at the limit efficiency.

The model parameters (b_0=–3.134 , b_1=0.939, b_2=0.548) from formula (1), the limit gold content from formula (2), the specific cost from formula (3), the mining cost from formula (4) and the marginal cost from formula (5) are determined for all test deposits. The deposits are best-to-worst ranked by the availability value. The cumulative availability curves plotted for gold resources include:

1. The cumulative resources (axis X) versus the anticipated mining cost (axis Y)—Fig. 2, curve *1*. Each point stands for an individual deposit and specifies the project mining cost per compensation metal tons;

2. The cumulative resources (axis X) versus the marginal cost (axis Y)—Fig. 2, curve *2*. When a deposit is minable at the marginal cost higher than the market prices, the deposit is assumed to be closing, and this deposit resources bound the currently economic available resources;

3. The cumulative resources (axis X) versus the price (axis Y)—**Fig. 3.** This curve shows how much gold is producible from the available resources at different prices and with regard to the current technologies and some other conditions.

The currently operating primary deposits 194 in number contain 48 Kt of total gold resources. This point is assumed as the datum in plotting the cumulative availability curve for gold. The introduction of new and yet unmined deposits into operation will increase the cumulative gold resources and the specific cost of the end product will chronically increase given the best of the remaining deposits is included in operation in the first place.

Evaluation of potential increments in production output and in expenses finds out that the increment in production will overruns the increment in expenses till the cumulative resources reach the level of 89890 t. Beyond this point, the increment in the expenses will exceed the increment in the output every time a new deposit is introduced into operation. This means that economic availability of gold resources is currently limited to the total volume of 90000 t. The total cost of the end product is 32000 t of gold in terms of the compensation metal tonnage.

It is possible to introduce the deposits which are on the cumulative curve beyond the economic availability boundary into operation in case of an appreciable advance in mineral mining and processing to enable essential cut-down of expenditures connected with gold production.

Conclusions

Appraisal of the mineral resource availability in the world economy and prediction of the start and rate of depletion of the available mineral resources can use two approaches. The first approach postulates the finiteness of mineral resources by nature and means the production dynamics prediction using the information on the physical parameters of a deposit: mineral resources, annual output and the retrospective dynamics of the output. The modeling assumes the mineral production has peaks beyond which depletion begins and output reduces. This approach enabled calculation of the peak production time and depletion rates for many minerals. The scope of the analysis also involved scenarios of decrease in consumption of minerals, degree of recycling of minerals and reduction of population of the Earth.

Prediction of the depletion start and rate in terms of available mineral resources can also use economic methods. The goal in this case is to determine conditions (specific costs of mineral mining and processing) when mineral production becomes economically inefficient. With this end in view, the cumulative availability curves are plotted for individual minerals. These curves are the cumulative mineral resources ranked by the degree of economic attractiveness versus the specific cost of mineral mining and processing. Transition to mineral deposits worst by the mineral quality and mining conditions leads one day to the stage when the mineral mining and processing cost grows faster than

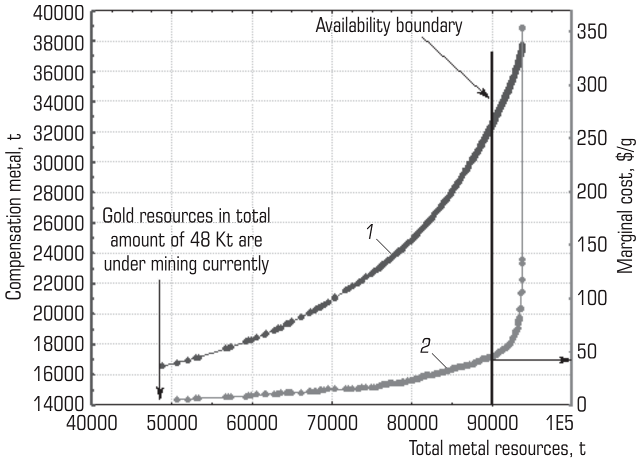

Fig. 2. Cumulative availability curves: resources–mining cost in terms of compensation metal tonnage (*1*); resources–marginal cost (*2*). Each point is an individual deposit

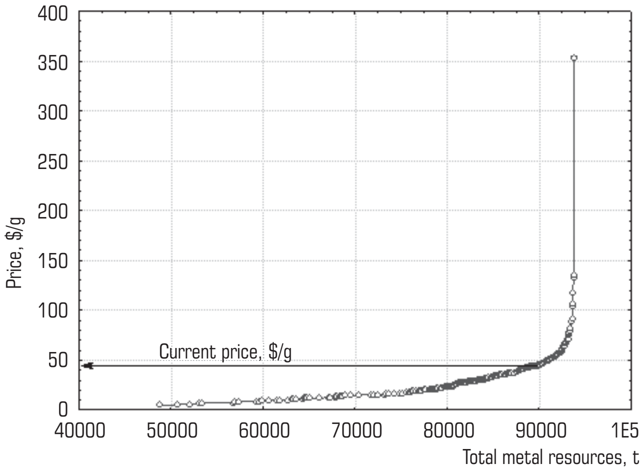

Fig. 3. Cumulative availability curve: resources–price

the mineral output. The cumulative availability curve plotting emphasizes not the estimate of time of reaching the production growth limit but the assessment of resources such that their mining means depletion of economic available reserves. This approach visibly demonstrates that in case of physical depletion of minerals, we will face the ecological, technological and economic obstructions. This approach is rather laborious but the present-day computational capacities enable handling this problem. The major difficulty consists in getting all information required to calculate the cost of production of a specific mineral.

The authors have proposed the method to model the specific cost of mineral mining and processing using the limited information on the parameters and mining conditions at a mineral deposit. First, the deposit mining probabilities are calculated for a set of mineral deposits of the same genetic type. Second, the threshold availability curve (limit probability) is plotted to obtain the estimated specific operating costs of mineral mining of the deposits which are at the boundary of profitability. This is a sort of analogy to the maximum permissible cost for the given mineral resources. The feature of the proposal is that this approach takes into account the values of individual deposits and their cross-effects as the probability of mining of a certain deposit is estimated against the background of the other deposits being mined or standby in the region. Using the cost modeling and the US Geological Service data on mineral resources, the cumulative availability curves are plotted for primary gold deposits in the world. The comparison of the predicted rates of increment in the resources being mined and the rates of increment in their mining cost has enabled the express-appraisal of economic available gold resources which total round 90000 t. The increment in this volume is possible if new and well accessible gold resources are discovered in the nearest time. Mining of the currently known deposits which are beyond the limit of economic available resources may become economically efficient only in case of a substantial technological advancement in mineral mining and processing.

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