Pre-investment quantitative assessment of the geological risk of the development of coal deposits

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Abstract. The article analyzes the main goals, objectives, and directions of modeling and optimization of technological processes and construction industry. The basic tasks and factors of organizational and technological modeling of the construction industry, as well as their influence on the change in production volumes, labor productivity growth and the efficiency of construction enterprises have been determined. The main directions of optimization of technological processes and construction are formulated on the basis of modernization and development of production and technological capabilities of construction enterprises.

1. Introduction
The consequence of the geological risk manifestation is the increase in production costs, and sometimes the impossibility of fulfilling the contractual conditions both in terms of volume and quality of the supplied raw materials. Therefore, a reliable assessment of the level of geological risk is significant not only for mining companies, but also for banks interacting with them, traders, investment, leasing, and insurance structures.

The practice of the Kuzbass coal extraction enterprises shows that gross errors in assessing the quality of geological information lead to serious economic consequences (up to liquidation of the business), and ordinary ones lead to a decrease in the expected technical and economic indicators of the enterprise by 5–25%.

One of the tools to reduce the consequences of the manifestation of all types of risks inherent in the mining business is the created reserve of the enterprise mine capacity. According to the experience of the coal industry in Russia, the volume of mining by open-cast coal mining enterprises is on average 15% less than their production capacity, and underground mining enterprises (mines) – by 40%. This is due to the fact that the efficiency of underground mining of coal to a much greater degree than open mining depends on the geological conditions and, consequently, is more sensitive to non-confirmation of geological ideas about them which are underlying the design decisions of enterprises. These
differences in the level of capacity utilization are mostly explained by the need to counter the manifestations of geological risk.

The importance of taking into account the confidence of geological information has been widely acknowledged and long recognized by the world business community. Its objectives are reports on solid minerals resources, prepared according to public reporting codes, the main ones being the “CRIRSCO” family codes. The main task of such codes is to uphold the interests of investors and companies consuming resources by preventing the conscious or erroneous underestimation of the level of reliability of geological data at mining enterprises.

The degree of geological risk is determined by the level of confidence of geological data about the field, which is the object of the mining business. The assessment of confidence is carried out primarily by an expert, i.e. in a very subjective way, which does not provide a high level of estimation reliability and does not exclude the possibility of dishonesty and corruption. It is generally accepted that the higher the inherent risk, the greater the amount of evidence is required for the formation and expression of expert opinion. Due to the high significance of geological risk and taking into account the subjective nature of expert assessments, the use of quantitative estimates of the error results of geological exploration of deposits is becoming increasingly important in the world. The use of such methods is encouraged by present-day international evaluation codes [4, 5, etc.], and the Russian state resource classification [6] provides for the mandatory use of them.

2. Quantitative methods for assessing the confidence of the results of geological exploration of deposits

In most mining industries, geostatistical methods are used to estimate the confidence of mineral reserves (estimates of kriging dispersion, relative kriging errors, distances from variogram, etc.). However, for coal deposits, this approach is ineffective. This is due to the nature of the most significant characteristics assessed (hypsometry of the seam, including disjunctive dislocation, continuity of the thickness of the formation), sampling and uneven placement of drill holes. The need to take into account these features is recognized by the world expert community. The Australian manual [7] indicates that the variogram can only help in determining the continuity distances between observation points. Sole use of the variogram is risky. In isolation this is not considered appropriate as it fails to consider all the other necessary factors contributing to the confidence in the estimate, such as sample geometry and local geological features.

In this regard, the assessment methods that have a geometric basis are more acceptable for coal deposits. They are based on the theory of the geochemical field of Prof. P. K. Sobolevsky formulated at the beginning of the XX-th century. The main postulates of this theory are extremely close to the provisions of geostatistics that appeared much later. In accordance with the theory of P.K. Sobolevsky, the field of any geological indicator corresponds to four basic properties, one of which is the property of unambiguity: the value of the indicator at each point of the geological space can have only one single value.

It follows from the above postulate that a model that ideally describes the considered characteristic of a field should also respond to it. And, therefore, the emergence of ambiguity of constructions in the process of modeling is the evidence of the inadequacy of the model being created and the real object. Moreover, the greater the degree of this inadequacy is, the larger the ambiguity of the model is. Thus, the assessment of the geological materials confidence should be based on an assessment of the degree of ambiguity of the model.

Actually, the ambiguity of constructions can be quantitatively evaluated only in the presence of redundant measurements, i.e. in conditions where there are at least two independent measurements of the feature at the same point in the underground space. However, in exploration practice such measurements are extremely rare and undesirable. Therefore, the approach to creating a method for measuring the degree of ambiguity of a model can only be based on the idea of artificial creation of indirect redundant definitions. The implementation of such an idea within a quadrilateral cell of the exploration grid is as follows [8].
We consider a convex quadrilateral with vertices – drill holes (figure 1). In such a quadrilateral one can draw two diagonals (1–3 and 2–4) intersecting at point A. Using an interpolation method, one can determine the value of the feature at point A from each diagonal \((P_{1.3} \text{ and } P_{2.4})\). It is clear that theoretically \(P_{1.3} = P_{2.4}\). However, due to measurement errors and interpolation, the values \(P_{1.3} \text{ and } P_{2.4}\) will not coincide with each other. Therefore, their difference, being the difference of two independent indirect definitions, can be considered as a numerical measure of the ambiguity of constructions.

![Figure 1. Creating indirect redundant definitions in the contour of the cell of the exploration grid.](image)

Thus, the criterion of the reliability of the study of the indicator in the contour of the quadrilateral of the exploration grid can be defined as \(K = |P_{1.3} - P_{2.4}|\).

Cubic spline interpolation is chosen as an interpolation method used in assessing the reliability of the study of seam hypsometry. In this case, the criterion for the exploration of hypsometry, called the lambda criterion, is calculated by the formula (according to the scheme for designating conventional numbers of holes in figure 1)

\[
\lambda = \sec \delta_i \left| \frac{F_1(x_1)T(\delta_1) - F_2(x_1)T(\delta_2)}{R_1} + (Z_3 - Z_2)F_1(x_1) + Z_i - \right| \\
\left| \frac{F_1(x_2)T(\delta_3) - F_2(x_2)T(\delta_4)}{R_2} - (Z_4 - Z_2)F_3(x_2) - Z_2 \right|,
\]

where \(R_1, R_2\) – projections lengths of diagonals 1–3 and 2–4 of a quadrilateral; \(x_1, x_2\) – relations, respectively, of the length of the projection of the distance from hole 1 to point \(A\) to length \(R\) and from hole 2 to point \(A\) to length \(R\); \(Z\) – the elevation of the seam at the point of the \(i\)-th seam subsection; \(\delta\) – dip angle of a seam in the \(i\)-th hole in the direction of the diagonal; \(\delta_i\) – dip angle of a seam at point \(A\); \(T(\delta)\) – tangent of a dip angle \(\delta\), which is marked «»), if the directions of the diagonal (from hole 1 to hole 3 and from hole 2 to hole 4 – figure 1) are directed to one side, or otherwise it is marked «++.»

The functions \(F_i\) are determined by the values of the parameters \(x_1\) or \(x_2\) by the formulas:

\[
F_1(x) = (1 - x)^2x; \quad F_2(x) = (1 - x)x^2; \quad F_3(x) = (3 - 2x)x^2
\]

The criterion calculated by the formula (1) characterizes the ambiguity of the hypsometric constructions in the normal direction to the seam.

For evaluation of capacity models and coal quality indicators, linear interpolation turned out to be quite satisfactory, the use of which allows calculating a criterion, called the delta criterion:

\[
\Delta = \left| (P_3 - P_1)x_1 + P_1 - (P_4 - P_2)x_2 - P_2 \right|
\]

where \(P_i\) – the value of the estimated indicator in the hole with the \(i\)-th vertex of the quadrilateral (evaluation unit).

For practical purposes, the relative delta criterion \(\delta\) is usually used expressing the value of \(\Delta\) in percentage with respect to the average value of the indicator at point \(A\):

\[
\delta = \frac{\Delta}{200 \left(\frac{P_3 - P_1}{x_1} + P_1 + \frac{P_4 - P_2}{x_2} - P_2\right)} \%
\]
As a result of the research conducted, it has been established that the criteria for exploration are representative if the geometric shape of the quadrangular grid cell meets the following conditions:

– parameters $x_1$ and $x_2$ are in the range from 0.3 to 0.7;
– the ratio of the length of the longer diagonal to the length of the less extended one does not exceed 2.6;
– the inside corners of the quad are within the range from 25 to 155°;
– the average length of the two longest sides of the quadrilateral is less than four times the average length of the two short sides.

The calculation of the criteria for exploration is permissible to carry out only if the achieved density of the exploration holes grid ensures the correctness of interpolating the values of the indicator in the interhole space.

To assess the validity of the use of lambda exploration criteria, the validity of interpolation of seam elevations between holes is estimated. The assessment is carried out on the basis of building a relationship between the average values of the lambda-criteria for exploration and the average areas of quadrilaterals (the exploration curve). Its construction is carried out at least by three “points”, obtained according to the initial and rarefied approximately two and four times grid of holes. A uniform rarefaction of observations network and the subsequent averaging of the obtained values ensures the equal complexity of the object for each of the points of the exploration curve, i.e., neutralizes the effect of the complexity factor.

Since, as the areas of quadrilaterals grow (i.e. as the density of the exploration grid decreases), the reliability of the simulation results should objectively decrease (the criteria should increase). Under the conditions of the interpolation validity, this dependence should have the character of a monotonically increasing function. Otherwise, interpolation is not valid. Thus, the criterion for the validity of the interpolation of seam elevations is the shape of the exploration curve. When analyzing its form, if the adjacent points of the exploration curve have slightly (less than 20%) different values of the lambda criteria, the hypothesis about the statistical equality of their values is checked.

The resulting view of the exploration curve is analyzed using a decision table (figure 2), on the basis of which conclusions are drawn about the validity of building a hypsometric plan.

![Decision Table](image)

**Figure 2.** Decision table for assessing the validity of interpolation of seam elevations (statistically equal criteria values are highlighted by framing them with dotted lines).
The decision table singles out three main types of exploration curves. The first type (Types 1A, 1B, and 1C in Figure 2) includes the exploration curves that have the theoretically expected form. The second type of exploration curves (types 3A, 3B and 3C in Figure 2) has a contradictory to theoretical form. With this form of the exploration curve, the lambda criteria are non-informative and cannot be interpreted. The third, intermediate, curve type (types 2A, 2B, and 2C in Figure 2) combines both of the preceding types. At the beginning, as the areas of evaluation blocks grow, the ambiguity of constructions grows (the theoretically expected trend is the first type exploration curve), and then its decrease occurs (the second type exploration curve). For curves of this type, a conclusion is made about the limited legitimacy of interpolation of evaluations in the interhole space: for evaluation units with an area of less critical ($S_k$) it exists, and for the larger one it does not. The value of $S_k$ is taken as the average area of the blocks of the first rarefaction grid (the second point of the curve), calculated without taking into account the blocks whose area is equal to or greater than the average area of all the blocks of the first rarefaction grid. Subtype 2C can also appear in the case of substantial object over-exploration, i.e. under the conditions of ubiquitous interpolation of marks. Therefore, if the criteria for exploration are less than 4 m, two additional dilutions of the holes grid are additionally performed and the obtained curve is analyzed.

The validity of the use of the delta criteria of the seam capacity exploration and coal quality indicators is checked on the basis of the ratio of the total and “non-geometrized” variability measured by the formula

$$\gamma = \frac{\Delta_s}{\sigma},$$

(4)

where $\Delta$ – the average value of the delta-test of exploration, characterizing the “non-geometrized” variability; $\sigma$ – standard deviation characterizing total variability.

Interpolation of indicators in the interhole space is considered valid if $\gamma \leq 0.8$.

3. The use of geometric criteria of exploration to address the risk assessment issues of an investment project

The assessment of the geological risk of an investment project of subsurface development is made on the basis of determining the expected errors of the mining and geometric models of the field. As a result of studies [8], it was found out that the errors of mining and geometric models are directly proportional to their ambiguity (exploration criteria). Therefore, the calculation of the expected error in the geometrization of the hypsometry, the thickness of the seam and the coal quality indicators (hypsometric plans, plans of thickness and ash content, etc.) is performed by multiplying the obtained values of the exploration criteria by the proportionality coefficients $K$, the value of which is determined by the given probability that the actual errors will not exceed the expected

$$R_g = \lambda K_g,$$

$$R_p = \Lambda K_p,$$

(5)

where $R_g$ and $R_p$ – expected errors in geometrization of seam hypsometry and linearly interpolated parameters (thickness, ash distribution, etc.); $K$ – coefficient of proportionality, taken equal to 0.6 for the required probability estimates of 0.68 and 1.2 – with probability of 0.8; $K_p$ – coefficient of proportionality, taken equal to 1.3 when the required probability esti mates 0.68 and 2.0 – with probability 0.8.

For already operated fields, the proportionality ratios can be adjusted considering the accumulated experience of mining operations based on the use of a special technology – monitoring the confidence of resources. The information basis for monitoring is the data obtained on the already developed part of the field. To do this, a quantitative assessment is made of the confidence of the exploration data only, and then the assessment of the confidence of the same data by comparison with the results of mining operations. As a result, a method of quantitative assessment of the confidence of geological information adapted to the subsurface area is formed.
According to the results of calculation of exploration criteria for numerous quadrangular cells of drill holes grid that overlap each other and recalculation into expected errors for each stratum according to the considered indicators, exploration cartograms are built on which areas with different degrees of confidence are indicated by conventional signs. In addition, a generalized cartogram of exploration is being constructed, providing for the cumulative accounting of the confidence of all indicators. The obtained estimates can be interpreted in the categories of mineral resources (figure 3).

![Figure 3. Seam exploration cartogram.](image)

The recommended boundary separating measured and indicated resources by the hypsometry factor is an error of 8 m, and by factors of the seam thickness and ash content – a relative error of up to 20–30%.

Extensive practice of applying the criteria of exploration has shown that their use improves the quality of the assessment of the confidence of exploration information by three to four times compared with traditional expert approaches. At the same time, it does not matter at all exactly how the field models were built and the resources were calculated: polygonal or geostatistical way.

Exploration cartograms are an informational basis for assessing the geological risk of relatively short periods and are used to determine the discount rate that includes the risk premium.

When assessing the risk of developing a field as a whole or a considerable part of it, a simulation method is actively used. When it is applied, a change in the project’s performance indicators is investigated, depending on the degree of “swaying” of the values of the initial parameters, which typically include prices, production costs, production, resources, investments, etc. At the same time, taking into account the geological risk is mainly associated with an estimate of the expected non-confirmation of resources. In coal practice, when determining the expected amount of resources, it is necessary to take into account not only the error of their calculation, but also the error caused by the non-confirmation of the mining and geological conditions of their occurrence in the measure excluding technical possibility of extraction.

Statistical studies conducted on materials of existing enterprises established the dependence of the share $D$ of such unconfirmed resources in the total calculated resources of the enterprise from the values of the criteria for exploration.

The type of this dependence depends on the method of mining:

– with long-pillar method
\[ D = 3.0 + 2.8 \lambda_U + 0.10 \bar{\delta}, \%; \]  
\[ D = 2.1 + 2.0 \lambda_U + 0.07 \bar{\delta}, \%; \]  
\[ D = 1.5 + 1.0 \lambda_U + 0.04 \bar{\delta}, \% , \]  

where \( \bar{\delta} \) – the average value of the relative delta criteria of thickness exploration in the estimated contour, \%; \( \lambda_U \) – the average value of the specific values of the lambda-criteria of the exploration of seam hypsometry, determined by the formula:

\[ \lambda_U = \frac{\lambda}{S} \]  
\[ \lambda_U = \lambda \]  

with \( S \geq 100 \) thousand m\(^2\),

\[ \lambda_U = \lambda \]  
\[ \lambda_U = \lambda \]  

with \( S < 100 \) thousand m\(^2\),

where \( S \) – the average area of projections of quadrangular evaluation units that are within the evaluation contour in hundreds of thousands m\(^2\).

Practice has shown that the use of formulas (7) – (9) is correct in cases where the estimated contour includes at least 20 quadrangular evaluation blocks.

4. Conclusion

Quantitative geometric methods for assessing the confidence of resources have a high degree of reproducibility, which allows for their use by specialists of a non-geological and non-mining profile. These methods provide the possibility of their application to the materials of coal deposits, characterized by high irregularity of exploration networks. Their use allows increasing the confidence of determining the degree of investment geological risk of field development, as well as to determine the boundaries of the contours within which the risk will have the greatest values, that determines the possibility of reducing the risk by conducting additional geological exploration.

References

[1] Dowd P 2018 Quantifying the impacts of uncertainty Handbook of Mathematical Geosciences Springer Cham 349–373

[2] Kulak V, Voloshin V and Friianov V 2015 Evaluation of influence exerted by coal exploration quality on mine planning efficiency Mining informational and analytical bulletin 5 13–22

[3] Kopytov A, Rogova T and Shaklein S 2018 Investment Risks Reduction of Developing Coal Deposits on the Basis of Quantitative Assessment Method of the Geological Information Confidence The 9th Russian-Chinese Symposium. Coal in the 21st Century: Mining, Intelligent Equipment and Environmental Protection. Advances in Engineering Research Vol 176 322–326

[4] Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. The JORC Code 2012 (Melbourne: The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia) p 44

[5] Russian Code for the Public Reporting of Exploration Results, Mineral Resources and Mineral Reserves (NAEN Code) 2013 (Moscow: National Association for Subsoil Examination (NAEN)) p 64
[6] Classification of Reserves and Prognostic Resources of Solid Minerals 2006 (Order of the Ministry of Natural Resources of the Russian Federation No 278 of December 11, 2006) p 9

[7] Australian Guidelines for the Estimation and Classification of Coal Resources 2014 (Melbourne: Guidelines Review Committee on behalf of the Coalfields Geology Council of New South Wales and the Queensland Resources Council) p 47

[8] Rogova T and Shaklein S 2011 The confidence of coal reserves. Quantitative assessment and monitoring (Saarbrücken: LAP LAMBERT Academic Publishing GmbH & Co) p 508