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# FOUNDATIONS FOR TECHNICAL SOLUTIONS IN ORGANIZING EXCAVATION OF OPEN ORE PITS

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To study stochastic mining technical systems of opencast mines, where parallel to clearly defined values random and indefinite factors operate, probabilistic and statistical techniques are mostly used nowadays. Formally, the task of producing a design solution may, under the conditions of indeterminacy be transformed into an equivalent deterministic problem formulated for a risky situation.

Uncertainty in the initial mining, geological and technical-economic information available during the design stage may result in changing the principal output characteristics of the opencast mine and undermine its operational efficiency during its exploitation. Lowering the possible economic losses is then possible via designing a stable technological system.

To minimize the degree of indeterminacy one first of all needs to identify the area of potential risk, define the probability of its emergence and assess its potential consequences. In case such consequences may be precluded, a clearer more complete understanding of the problem would promote a better thought through reaction to potential risk in the course of implementing design solutions.

***Key words*:** planning, opencast mine, organization, risk, uncertainty, opencast mine parameters, deposit, probability.

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The issue of accuracy and reliability of the decision adopted is a typical feature of modern stage in the development of every aspect of substance handling processed, mining among them. There is a wide area of unsolved problems related to improving reliability of their operational plans [17, 18, 20].

Uncertainty of the initial information results in indeterminacy during selection of solutions, while the uncertainty itself dictates the approach to problem solving and may result from lack of knowledge. Such a situation is typical for operations in which the role of uncontrolled factors is played by natural conditions. In other cases the uncertainty emerges due to organized counteraction.

The uncertainty of the initial information is the larger, the farther down the timeline is the period one needs to consider to solve the problem. When providing the foundation for a solution in case of stochastic nature of the initial information there always remains an element of uncertainty. Because of that it makes no sense to demand too much in terms of accuracy from such solutions. Instead of pinpointing a single solution it is feasible to highlight a range of acceptable solutions, within which the experts may make their final choice.

The psychological theory of decision making identifies algorithmic an heuristic strategies: the first are mathematical algorithms while the second present a system of rules, principles and heuristics of intuitional nature [1-3, 11, 12]. Three factors play their separate roles in decision making: the environment; the human personality, one's tendency to take risks; the social group within which the person operates. The choice of alternatives mainly follows the comparison of expected values and utility functions. These functions are derivatives of the two variables: the outcomes probabilities and their values.

Professor A.I.Arsentiev has used utility functions to analyze the influence of psychological aspects on the choice of solutions adopted in the course of opencast mine planning [1]. He introduced the concept of the function of misgiving the consequences of higher risks, which is inverse to the utility function in its phenomenologic meaning. Using these functions fits better the needs of analyzing psychological attitude to risk while choosing rational solutions for the tasks of mining.

A number of approaches have been developed in the modern theory of decision making that make it possible to mitigate the level of uncertainty of the initial information. Note that in some cases one may use expert techniques, where subjective probabilities are assessed of expert opinions. Others find it more rational to employ probabilistic guaranteed result or Bayes approach [13, 14, 16, 21].

In certain cases one may deplete the number of employed initial data thus lowering the cumulative error at the output due to rational simplification of the problem solving algorithms. Following the requirements of consistency, absence of bias and efficiency also provides the best conditions for adequate

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specification of properties of the initial data used in such problems. One of the ways to account for the uncertainty of the initial data consists in using models and techniques of stochastic programming.

Research, design and production practices indicate quite vividly that there remains some inconsistency between the initial data and activity indicators and operational results of mining enterprises, which may be quite significant sometimes. Such inconsistency is due to lack of exhaustive initial information on the designed or developed deposit, capabilities of the mining enterprise built on its basis, and the stochastic nature of the initial mining and geological data, etc.

Adopting specific technological solutions is a derivative of such factors as the proportion of accurate and uncertain initial data, reliability of the techniques of decision making and the adequacy of criteria used to assess their agreement with the actual conditions. There is a certain economic limit to increasing the accuracy of each of these components at any given moment, therefore one needs to substantiate the ratio of credibility and uncertainty for each specific case so that the decision taken on a given issue is optimal. In case when it is impossible to lower the level of uncertainty, it appears feasible to specify the level of risk and possible consequences of taking that risk, provided the project decision planned for that case remains unfulfilled.

Decision making is a process of conscious selection of one of a whole series of alternatives. When solving a specific task a model is built of the situation of that choice. The model includes a set of solutions and a description of selection criteria. Same as any such model it simplifies and coarsens the study object. To study stochastic systems, where parallel to those clearly defined factors there exist random and indefinite factors, probabilistic and statistical techniques are mostly used nowadays.

In this case risk is understood as an event or a group of related random events that are detrimental for the object that carries that risk. Damage to property interests is expresses as loss or decrease of the enterprise profit.

Most adverse events feature certain probability of their realization, that is a mathematical attribute meaning a possibility to calculate the frequency of advent of such an event provided a sufficient number of statistical data is available. Risk as a combination of events features a set of their realizations, each of them having its own probability and level of damage it entails [9, 15].

Using the average values of expected parameters and opencast mine indicators in the course of assessing decisions taken leads to significant errors quite often. Moreover, it is assumed that the principal parameters of the system used to develop them shall reach their specified levels.

By way of example consider a case when the drilled block of the opencast mine may include boreholes with conditional and under-non-conditional content of the utilized component in its ore. The data on the composition and structure of rocks forming the drilled blocks are of stochastic nature. The larger is the number of drilled blocks concerned, the higher is success probability, i.e. the probability that the borehole containing the conditional mineral resource has its content approaching the average ore value preset in the project for the opencast mine in general.

The strategy of opencast mine mining of the deposit shall be founded on the analysis of risks associated with various project solutions. The basis of such strategy is the enterprise profitability.

The probability of success for one of the values of opencast mine parameters, e.g. the exceeding the average designed content of the sought component in the ore from one of the blasted blocks is

$$J = (1-g_1)(1-g_2)(1-g_3)...(1-g_n), \quad (1)$$

where $g_i$ is the $i^{th}$ value of success probability for the considered opencast mine parameter, $i = 1, 2, 3,\ldots, n$.

In case all the values of success probability for a given opencast mine parameter equation (1) may be presented in the following form:

$$J = (1-g)^n \quad (2)$$

or

$$J = (1-g)^{[C/x]}, \quad (3)$$

where $C$ is the topmost possible expenses needed to achieve the prescribed value of opencast mine parameter; $x$ is the operational expenses necessary to achieve the prescribed value of opencast mine parameter.

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The ratio [*C/x*] defines the number of parameter values that may be achieved within the limits of acceptable expenses (the initial investments). Expression (3) characterizes the probability of exhausting acceptable expenses without reaching the prescribed value of the opencast mine parameter.

Assuming an average value of success probability for a given opencast mine parameter g, that remains constant over a certain development period, the process may be considered to be binominal [11, 19].

The probability of achieving *m* preset values of the opencast mine parameter, the overall number of parameter values being *n,* is

$$G(m/n) = \frac{n!}{m!(n-m)!} g^m (1-g)^{n-m}, \quad (4)$$

where $0 < m \le n$.

As the result of achieving preset value of the opencast mine parameter the net current value *R* may be achieved, then $n_m$ is the total number of values of opencast mine parameter that meet the inequality,

$$\frac{C+mR}{x} \le n_m \le \frac{[C+(m+1)R]}{x}. \quad (5)$$

The probability of exceeding permissible expenses in reaching the preset value of opencast mine parameter while not exceeding the value *m* means lack of profitability

$$J_{\text{н}} = \sum_{i=0}^{m} P\left(\frac{i}{n}\right). \quad (6)$$

Note that in case $n_m = [C/x]$ for $m = 0$, formula (6) transforms into formula (3).

The probability of exceeding permissible limit expenses to reach the preset value of opencast mine parameter

$$J_{\text{н}} = \sum_{i=0}^{m+[C/R]} G\left(\frac{i}{n}\right). \quad (7)$$

The principal limitation for expressions (6) and (7) consists in assuming that the production program would still go on even in case the limit possible expenses for its implementation would be exceeded.

In case the probability of lack of profitability and success failure is unacceptably high, one may use the factor of production interest $\Phi_n$ to decrease it. In case the designer sets forth the maximum possible values of failure probability for the given conditions, it becomes possible to define the maximum possible value of production interest factor $\Phi_n$ for the given conditions.

Expression (3) may be presented in the form:

$$J = (1-g)^{C/(\Phi_n x_c)}, \quad (8)$$

where $\Phi_n$ is the factor of production interest; $x_c$ are cumulative operational expenses needed to achieve the preset value of opencast mine parameter.

The factor of production interest

$$\Phi_n = \frac{C \log(1-g)}{x_c \log J}. \quad (9)$$

Therefore, using expression (9) the factor of production interest may be defined for a preset value of failure probability $J_{\text{н}}$.

Assume that to prepare a set of drilled blocks in the opencast mine that would provide the designed amount of resources ready for excavation (drilled and blasted), the mining enterprise has working capital to the amount of $C = 10$ mln rub. Preparing a single block requires the operational expenses of $x = 1$ mln rub., on the average, with a probability of exceeding the average project content of utility mineral equal to $g = 0.15$, i.e. 15 % of ore meeting the requirements on its averaging.

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Assuming the value of production interest factor of 100 % ($\Phi_n = 1$), we find the probability of exceeding the limit expenses from formula (8): $J_н = 0.196$. Hence, the probability of failing production program will be about 20%. Such rather high value of failure probability may become unacceptable for a mining enterprise.

For example, the designer takes a decision to lower that probability to 6 % ($J_н = 0{,}06$), then using formula (9) we obtain $\Phi_n = 0.552$ or 55.2 %; the ratio $[C/(\Phi_n x_c)] = 18.65$ shall be rounded to the nearest whole number of blocks, i.e. we get 19.

Therefore, $\Phi_n = 10/19$ or 52.63 %, $J_н = 0.0456$. In other words we find that the maximum possible value of production interest factor is 52.63 %, for failure probability not to exceed 6 %. The values of maximum possible production interest factor for various failure probabilities in meeting production program of ore opencast mine are presented in Table 1 and Fig.1.

*Table 1*

**The maximum possible factor of production interest**

| Failure probability $J_н$, % | The maximum production interest factor $\Phi_n$, % | Number of blocks $C/(\Phi_n x_c)$ |
|---|---|---|
| 1 | 2 | 3 |
| 20 | 100 | 10 |
| 10 | 66.7 | 15 |
| 5 | 55.2 | 19 |
| 2 | 41.7 | 24 |
| 1 | 34.5 | 29 |
| 0.6 | 30.3 | 33 |

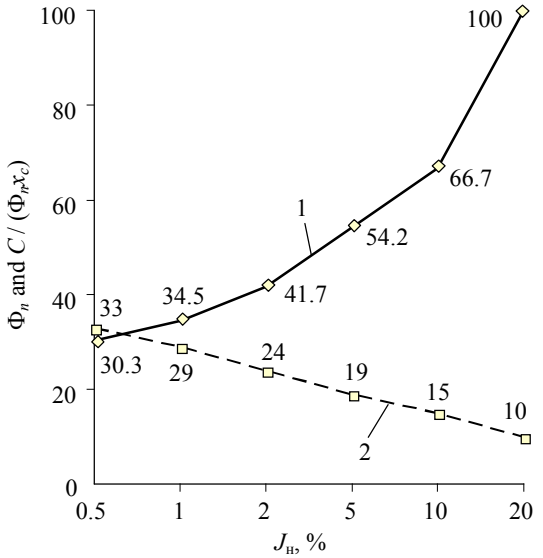



Fig.1. Dependence of production interest factor $\Phi_n$ (1) and the number of blocks on the probability of failing to reach the project opencast mine parameter $C/(\Phi_n x_c)$ (2)

Consider implementation of the program of providing the opencast mine with excavation ready reserves (ERR). Let the probability of exceeding the project average content of the mineral in the ore of drilled block be $S$ (success), and the probability of not exceeding the preset average content be $D$ (failure). For simplification purposes we assume that while implementing production program of ore opencast mine, success is equally probable for each drilling block. Assessing the possible result is done using the binominal expression: for single block

$$D + S = 1$$

or

$$D + S = (D + S)^1, \qquad (10)$$

for two blocks

$$DD + DS + SD + SS = 1. \qquad (11)$$

Sinse $DS + SD = 2DS$, expression (11) may be presented in the form

$$D^2 + 2DS + S^2 = (D + S)^2 = 1. \qquad (12)$$

For three blocks

$$D^3 + 3D^2S + 3DS^2 + S^3 = (D + S)^3 = 1.$$

$\underline{DDS, DSD, SDD}$ $\underline{DSS, SDS, SSD}$ $\underline{SSS}$
The probability of success at least in a single block

$\underline{DSS, SDS, SSD}$ $\underline{SSS}$
The probability of success in at least two blocks

$\underline{SSS}$
The probability of success in at least three blocks

$\underline{DDD}$
The probability of complete failure

The binominal expansion is simple to be used in case the number of blocks is insignificant. For example, if one assumes the probability of success and failure to be equal to 50 % (the success norm), then the possible result for two drilled blocks will be characterized by the expression

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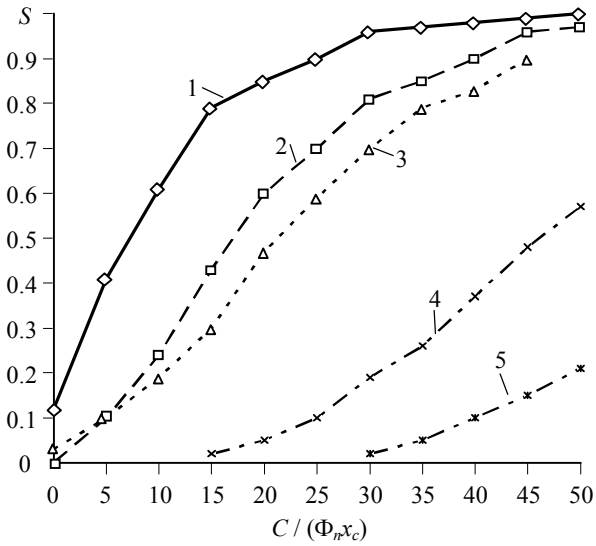



Fig.2. The cumulative dependence of success probability in implementing project solutions $S$ on the number of blocks $C / (\Phi_n x_c)$ for the success norm of 10 %

$$DD + DS + SD + SS .$$

Then we obtain: 25 % – is the probability of failure for 2 blocks ($DD$); 50 % – is the probability of success for single block only ($DS + SD$); 25 % – is the probability of success in two blocks ($SS$); 75 % – is the probability of success in at least a single block ($DS + SD + SS$).

However, if one considers a larger number of blocks and other values of probability for $D$ and $S$, the mathematical expression for assessing the possible result, e.g. for five drilled blocks shall be

$$D^5 + 5D^4S + 10D^3S^2 + 10D^2S^3 + 5DS^4 + S^5 = 1.$$

Many publications on statistics offer tables with probability values in dependence of the number of parameters (blocks in our case). Such tables make it possible to plot a cumulative profile (Fig.2), characterizing the probability of exclusive success for various number of blocks and a preset norm of success (10 %). Curve 1 in Fig.2 characterizes the success in a single block minimum; curve 2 gives the same for two block minimum; curve 3 characterizes the success in three blocks minimum; curve 4 yields success in five blocks minimum, and curve 5 yields success in seven blocks minimum.

The value of success probability provides additional information on the value of risk for a given norm of achieving the project parameter value.

As a means of forecasting the possible range of variations for the values of opencast mine parameters and indicators various types of distributions are used. Normal and lognormal distributions of random variables are of particular importance in mining. It is explained by the fact that the studied random variables present sums of a large number of random components [3-8, 19]. Such random variables may follow different distribution laws, and there are no variables among them that would outstand in their dispersion spread.

The level of profitability and the risk of hitting a loss in the result of implementing project solutions maybe controlled by way of designing a project implementation strategy. An example of action of such a strategy is temporary suspension of developing a deposit in case its actual opencast mine parameters and indicators fail to confirm respective project values; another example consists in using the factor of production interest to increase the possible profitability of opencast mine operations, plus regulating the number of opencast mine parameters that take part in the assessment.

To assess the risk of project solutions one needs to specify the following variables:

• annual capital expenses ы with the account of tax remissions;

• income proceeds with the account of the calendar plan of developing the deposit, minus tax remissions;

• flow of expenses and revenues over the assessed period;

• discount factor;

• net current cost of project implementation or the net discounted revenue.

*Table 2*

**Weighted average risk cost**

| Result | Failure | Discounted current profit, mln rub. | Weighted average risk cost, mln rub. |
|---|---|---|---|
| Failure to reach the project average content of utility component | 0.71 | –1.50 | –1.065 |
| Success in achieving the project average content of utility component | 0.29 | 7.50 | +2.175 |
| Total | 1.00 | – | 1.110 |

With the probability of success and failure of achieving preset value of opencast mine parameter and the current cost of project implementation known, the value of average weighted risk may be retrieved.

Consider the example of retrieving the average weighted risk of achieving a preset value of opencast

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mine parameter, its results presented in Table 2. The average weighted risk cost is retrieved as the product of result probability and the current implementation cost.

To consider that example in more detail (Table 3), lets us present the probability of achieving the project value of opencast mine parameter as three different cases: the minimum, the most probable and the maximum.

*Table 3*

**Average weighted risk cost for three cases of achieving the opencast mine parameter**

| Result | ERR Volume, thousand $m^3$ | Probability | Risk-weighted ERR volumes, thousand $m^3$ | Discounted current profit, mln rub. | Weighted average risk cost, mln rub. |
|---|---|---|---|---|---|
| Failure to reach project average content of utility component | 0 | 0.71 | 0 | –1.50 | –1.065 |
| Minimum | 300 | 0.09 | 27 | –0.10 | –0.009 |
| Most probable | 1000 | 0.18 | 180 | 7.50 | 1.350 |
| Maximum | 4000 | 0.02 | 80 | 30.50 | 0.610 |
| Total | – | 1.00 | 287 | – | 0.886 |

Additional consideration of the max-min cases made it possible to retrieve the information needed for a more accurate implementation of project solution. The weighted average risk cost for three additional cases has only reached 0.8886 mln rub, which is 0.224 mln rub lower than the presented result (Table 2).

The result presented in Table 3 makes it possible to claim higher sensitivity of probability for the maximum possible volume of reserves in the opencast mine ready for excavation. The value of the minimum possible volume of conditional reserves ready for excavation that guarantees profitability of the pit development should be somewhat above 300 thousand $m^3$ at the interest rate of $i = 10$ %. However, if the interest rate is lowered to 8 %, the value of the minimum possible volume of excavation ready reserves (ERR) would only be 250 thousand $m^3$.

The total risk-weighted volume of ERR makes 287 thousand $m^3$, while the most probable volume of reserves ready for excavation is 1000 thousand $m^3$. Note the lack of any guarantee that the blasted block would contain a volume of conditional reserves ready for excavation to the amount of 287 thousand $m^{3;}$ however that is the most probable assessment for the average over $n$ blocks of the opencast mine.

In contrast to uncertainty, the risk originates only when the decision is taken to implement the project, that is when the risk is accepted. Decision making and, respectively, taking certain actions entails accepting adequate risks. Therefore, minimizing the possible losses and being successful with the project on the whole depend on the completeness and quality of their assessment.

Managing project risk on the basis of the newly developed indicator of production interest makes it possible to increase the probability of gaining preset value of opencast mine parameter and the project profitability norm.

Adopting well-founded project solution is impossible if one is limited to accounting for just the probability of achieving a preset value of a parameter or indicator. Assessing the economic risk of project solutions saves one from possible serious consequences of potential mistakes in the profitability of of project implementation. Defining the expected retrieved value, risk and net current cost of project implementation makes it possible to assess the return on investment into developing the deposit.

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