INCREASE OF TECHNOLOGICAL INDICATORS USED IN THE ENERGY INDUSTRY

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When evaluating the suitability of using coal in various industries, it is subjected to technical analysis and a number of special technological studies. The obtained results in combination with elemental and group analysis allow choosing the most rational and economically efficient directions of their use, which plays not the least role in determining the economic significance of coal mining deposits. The work is based on theoretical research methods based on the basics of probability theory and mathematical statistics - to improve the existing methods of processing results and assessing the uncertainty of measurements; theories of accuracy - for the development of procedures for assessing the uncertainty of measurements of the quality parameters of solid mineral fuel during its tests; statistical modeling methods - to check the reliability of the developed provisions. A generalized parameter of the quality of solid mineral fuel has been synthesized, which makes it possible to evaluate its quality based on the results of tests conducted in coal chemical laboratories. improvement of methods of testing solid mineral fuel according to quality parameters by developing uncertainty assessment procedures.

KEYWORDS

Solid mineral fuel, quality parameters, particle-size analysis, floatand-sink analysis, uncertainty of measurements, generalized quality parameters

1 INTRODUCTION

The energy sector is a complex industry that is constantly changing [Wang 2023]. Coal is one of the most important types of fuel and energy raw materials [Ryabov 2022]. The main purpose of coal is the basis of modern transformation. The share of coal in the global energy balance is about 25%. Coal is used for many purposes, in particular, for the production of metallurgical coke, chemical products, electricity, electrode products, carbide, during the agglomeration of iron ores, and for other technical and technological needs [Rimar 2021, Somova 2023]. The main consumers of coal are thermal power plants (42%) [Saxena, 2024], ferrous metallurgy (20%), boiler houses and communal households (16%) and others (semi-coking plants, installations for the production of electrode fillers, adsorbents, thermographite, sulfonated coal, etc.). When evaluating the suitability of using coal in various industries, it is subjected to technical analysis and a number of special technological studies. The obtained results combined with elemental and group analysis allow choosing the most rational and economically efficient directions of their use, which plays not the least role in determining the economic significance of coal deposits. Coal reserves, which are economically expedient to develop, are quite large (they are many times greater than oil and gas reserves), and in the future coal can play a major role in solving the problem of meeting the growing need for energy [Kumaresh 2023]. Uncertainties regarding resource and reserve estimates also relate to the grade or quality of coal that will be produced in the future. There is no clear border between different types of coal, all its division is conditional. Normative documents provide for the classification of coal of individual basins and deposits by quality (marking), and it is also divided into technological groups by sintering capacity [ISO 1170:2020, ISO/CD 1928:2020]. When assessing the suitability of using coal in various fields, it is subjected to technical analysis and a number of special technological studies [ISO/CD 1928:2020]. The results obtained in combination with elemental and group analysis allow choosing the most rational and economically efficient directions of their use, which plays not the least role in determining the economic significance of coal deposits. With the growth of production, the absolute mass of coal sent for beneficiation, sorting and briquetting is constantly increasing. The increase in the volume of beneficiated coal is conditioned by the requirements for improving their quality, which determines the economic efficiency of coal use. In addition, as a result of the deterioration of mining and geological conditions of coal mining, widespread mechanization of production and other reasons, its quality characteristics in terms of ash content, particle size distribution, moisture content and sulfur content are deteriorating.

Coal mining is a significant source of greenhouse gas emissions and has been the focus of increasing attention from environmental groups and regulators [Lu 2023]. Therefore, the main direction of technical progress in coal beneficiation, which provides an increase in technological, technical-economic and environmental indicators, is the reconstruction and technical conversion of existing enterprises based on advanced technology and new equipment PLM [Jurko 2011, Monkova 2013, Michalik 2014, Panda 2014 & 2021, Baron 2016, Mrkvica 2016, Balara 2018, Chaus 2018, Duplakova 2018, Sukhodub 2018, Flegner 2019, Harnicarova 2019 & 2020]. The correctness and accuracy of quality indicator calculations are extremely important in the coal sector. The main goal pursued by the analysis of the quality of coal and other types of fuel is to determine their thermal characteristics, which in turn indicate quality and make it possible to carry out calculations for fuel combustion plants.

The results of these calculations are used to determine various key characteristics, including ash content and calorific value, which in turn determines the grade of coal. A wide range of analytical calculations and indicators are used in the process of analyzing a coal sample. This method makes it possible to determine the presence of impurities, which directly affect fuel economy. If there are more of them than there should be, then they will negatively affect the heat of combustion, since more energy will be required for heating, decay and separation of waste. It should be noted that, despite the presence of a large number of methods of testing solid mineral fuel, there are practically no procedures for evaluating the quality and technological indicators of coal used in the energy industry, which have their own specific features. The analysis of regulatory documentation shows that there is no single unified indicator that would clearly determine the quality of solid mineral fuel, therefore it is necessary to determine the requirements for the quality control methods of solid mineral fuel, to develop a generalized indicator of the quality of solid mineral fuel that would allow comparison of solid mineral fuel by quality and would also serve as a key pricing parameter.

At present, a direction of research related to the study of control problems for an ensemble of trajectories is actively developing [Zaborowski 2007, Adamcik 2014, Svetlik 2014, Olejarova 2017 & 2021, Sedlackova 2017, Catlos 2018, Labun 2018, Gamec 2019, Kuznetsov, 2019, Murcinkova 2019, Pollak 2019 & 2020, Straka 2021 & 2022, Vagaska 2021, Thelasingha 2022, Pleshivtseva 2023, Zhai 2023]. These include the problem of normalizing impacts on dynamic systems [Karane 2022, Zhang 2022, Abouelela 2023, Sanchez 2023]. In the works [Cheimonidis 2024, Hui 2023], a unified approach to solving it is developed, based on the application of the expansion principle developed for optimal control problems [Zheng 2024]. In this paper, this approach is extended to multi-stage processes [Tang 2023].

The goal and objectives of the research are to increase the quality and technological indicators of coal used in the energy sector by improving the methods and procedures for evaluating solid mineral fuel according to its condition.

2 MATERIALS AND METHODS

Theoretical research methods are the basis of the work. The existing current regulatory documentation on solid mineral fuel testing has been reviewed and analyzed. Depending on the content of moisture and ash in the fuel, the following states are distinguished: working (index r) - the state of the fuel with total moisture and ash, with which it is extracted; analytical-air-dry state of the analytical sample (index a) – the state of the analytical sample, which is characterized by the establishment of equilibrium between the moisture content of the fuel and the humidity of the surrounding atmosphere; dry (index d) – the state of fuel without general moisture, except for hydrated; dry ashless (d_{af} index) is the conditional state of coal without general moisture and ash. The parameters of the fuel for its various states are interrelated by special coefficients. The main characteristics that determine the characteristics of coal depend on the conditions in which the coal was formed, they are necessary for choosing the type and brand of coal appropriate to the conditions of use. Determining coal composition and moisture, mineral impurities, and yield of volatile substances gives an idea of its composition and technological values.

The above-mentioned parameters are determined in specialized coal chemical laboratories, which are accredited to meet the requirements of the ISO/IEC 17025 standard.

The analysis of the listed parameters and states of the fuel, as well as their coefficients, made it possible to draw up a hierarchy of their definition (Fig. 1).

It can be seen from the given figure that all the parameters of the air-dry state of the analytical sample (W^a, A^a, S^a, V^a and Q^a) are independently determined, as well as the total moisture for the working state of the fuel W^r. All the parameters of the dry state of the fuel are recalculated through the corresponding parameters of the air-dry state of the analytical sample i [Rimar 2022]. All parameters of the working condition of the fuel are calculated through the corresponding parameters of the air-dry state of the analytical sample, W^a and W^r. The yield of volatile substances and the heat of combustion of the dry, ash-free state are calculated through the corresponding parameters of the air-dry state of the analytical sample W^a and A^a. The heat of combustion is used as a classification parameter in the international classification of coal.

On the basis of this hierarchy, a systematization of the evaluation of solid mineral fuel parameters was carried out. Having analyzed the above, the order of evaluation of quality parameters was determined: first, the parameters of granulometric and fractional compositions are evaluated, then, respectively, moisture content, ash content, yield of volatile substances, sulfur content, and lastly the heat of combustion, since for its evaluation it is necessary to use the parameters listed above. When studying various operations of estimating the parameters of luminosity from the point of view of choosing the optimal solution, one has to deal with situations where the situation of the operation is characterized by random uncontrolled factors. In this case, we can say that the operation develops according to the pattern of random processes, the course of which and the outcome depend on the random factors accompanying the operation. In this case, we can say that the operation develops according to the pattern of random processes, the course of which and the outcome depend on the random factors accompanying the operation. To describe random processes, mathematical tools developed in the theory of random processes are used, as well as probability distribution functions of random variables characterizing a given random process. Let's focus on the so-called Markov random processes or “processes without consequences” (Markov chains).

Let us consider an ergodic Markov process [Detkov 2023] with a finite set of states $E_1, E_2, \dots, E_N$, to which there corresponds a transition probability matrix P of size $N \times N$.

Each transition from state E_i to state E_j will be associated with a certain estimate $r_{ij}, i, j = \overline{1, N}$, which we will further call income for one transition from state E_i to state E_j. Obviously, the total income received from the functioning of such a system over a certain period of time will be a random value, depending on the probability distribution of the corresponding Markov process [Zhang 2023].

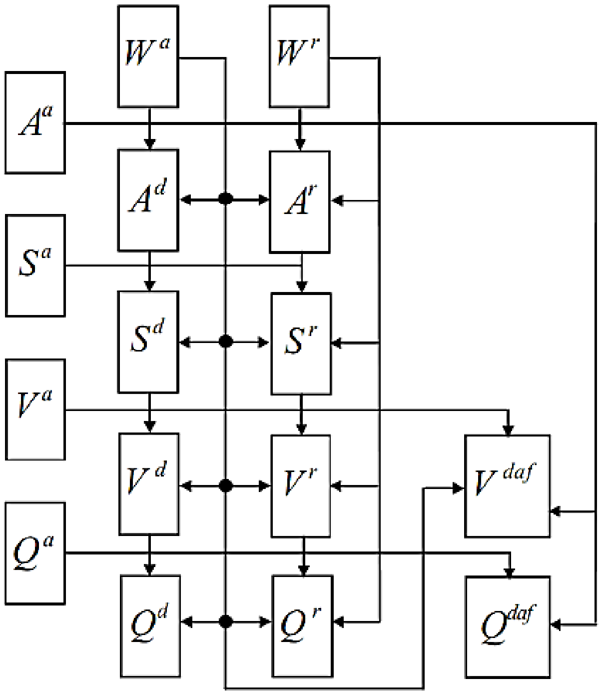

Figure 1. Hierarchy of determination of fuel parameters: key parameters of coal quality – calorific value Q, moisture content W, total sulfur content S, ash content A, yield of volatile substances V, as well as the parameters of granulometric γ^g and fractional γf composition

Let us denote by $\upsilon(m)$ the average expected income received after the system makes m transitions if the process started from state E_i [Jurko 2012, Jurko 2013]. Revenue for m transitions can be obtained as revenue for one (first) transition plus income for the remaining $m-1$ transitions. The income for one transition of the system from state E_i will be denoted by q_i

$$q_i = \sum_{j=1}^{N} p_{ij} \cdot r_{ij}, \ i = \overline{1,N} \tag{1}$$

Where p_{ij} is the probability of a transition from state E_i to state E_j. The expected income for the remaining $m-1$ transitions depends on what state the system was in after the first step. Let this be the state E_j, then the average income for the remaining $m-1$ transitions will be equal to $\upsilon_i \cdot (m-1)$.

Since the system could get from state E_i to any state E_j, $j = \overline{1,N}$, with the corresponding probability p_{ij}, the average income for the remaining $m-1$ transitions is determined using the expression

$$\sum_{i=1}^{N} p_{ij} \cdot \upsilon_i \cdot (m-1), \ m = 1,2,\dots \tag{2}$$

Thus, taking into account expressions (1) and (2), the total expected revenue for m transitions

$$\upsilon_i(m) = \sum_{j=1}^{N} p_{ij} \cdot r_{ij} + \sum_{j=1}^{N} p_{ij} \cdot \upsilon_j \cdot (m-1), \ \ i = \overline{1,N}; m = 1,2,\dots \tag{3}$$

Or

$$\upsilon_i(m) = q_i + \sum_{j=1}^{N} p_{ij} \cdot \upsilon_j \cdot (m-1), \ \ i = \overline{1,N}; m = 1,2,\dots \tag{4}$$

The state of solid mineral fuel, which is characterized by the index r_j, $j = 1,2,\dots,P$, should be such that for the maximum possible profit obtained by the enterprise from the use of solid mineral fuel obtained at the coal mining deposit x_i, if its quantitative values of its parameters u_i, the condition was fulfilled [Panda 2011, Panda 2013]

$$\upsilon(m) \ \rightarrow \max \tag{5}$$

Expression (4) is written in vector form as follows:

$$V(m) = q + P \cdot V \cdot (m-1), \tag{6}$$

where

$$V(m) = \begin{pmatrix} \upsilon_1(m) \\ \upsilon_2(m) \\ \dots\dots \\ \upsilon_N(m) \end{pmatrix}; q = \begin{pmatrix} q_1 \\ q_2 \\ \dots\dots \\ q_N \end{pmatrix}$$

Using recurrence relation (6), the total expected income for any number of transitions can be successively determined. From expressions (4) or (6) it follows that in order to determine the expected total income there is no need to introduce an income matrix into consideration. It is enough to know the matrix of transition probabilities P and the column vector q of expected income for one transition.

Considering the ergodicity of the Markov process, the expected income $\upsilon_i \cdot (m), i = \overline{1,N}$ for large m can be calculated by the formula

$$\upsilon_i(m) = m \cdot g + \upsilon_i \tag{7}$$

Or vector form

$$V(m) = m \cdot g + V \tag{8}$$

Where

$$g = \sum_{i=1}^{N} p_i \cdot q_i \tag{9}$$

p_i are the limiting probabilities of the Markov process. The value of g is nothing more than the average expected income per transition when the system carries out a sufficiently large number of transitions.

The values $\upsilon_i, i = \overline{1,N}$ are relative weights. Having fixed two states E_i and E_j, and taking into account expression (7), we can write: $\upsilon_j(m) - \upsilon_i(m) = \upsilon_j - \upsilon_i$. The difference $\upsilon_j - \upsilon_i$ can be considered the amount of income that will be additionally received if the system starts functioning from the state E_j and not E_i [Zaloga 2019 & 2020].

Different strategies correspond to different probabilities of transitions from one state to another, as well as different incomes. For each strategy, we will mark the corresponding probabilities of transitions and income with the letter k on top, i.e., p_{ij}^k, r_{ij}^k. Note that the number of strategies corresponding to each state of the system must be finite, although different for each of them. A process with multiple strategies corresponding to each state is a controlled Markov process. The task is to indicate for each state E_i the number of the strategy $d_i(m)$, which will be used at the m -th step and provide the maximum average income g per transition. The set of these strategies forms the vector $d(m)$ [Zhou 2022]

$$d(m) = \begin{pmatrix} d_1(m) \\ d_2(m) \\ \dots\dots \\ d_N(m) \end{pmatrix} \tag{10}$$

When sequentially analyzing strategies, it is easy to notice that optimal behavior of the system at the $(m+1)-$th step is possible only if the previous step m was optimal. Using relation (4), we can express this using the formula

$$\upsilon_i(m+1) = \max_k \left(q_i^k + \sum_{j=1}^{N} p_{ij}^k \cdot \upsilon_j(m)\right), \ \ i = \overline{1,N} \tag{11}$$

Or, taking into account formula (1), we can write

$$\upsilon_i(m+1) = \max_k \sum_{j=1}^{N} p_{ij}^k \cdot \left[r_{ij}^k + \upsilon_j(m)\right], \ \ i = \overline{1,N} \tag{12}$$

Here $\upsilon_i(m+1)$, $\upsilon_i(m)$ denote the total expected return for the chosen optimal behavior. The sequential calculation of expected income and optimal strategies using expression (12) ends when the vector of strategies $d(m)$ stops changing.

Using expressions (4) and (7) we obtain the relation

$$m \cdot g + \upsilon_i = q_i + \sum_{j=1}^{N} p_{ij} \cdot \left(\upsilon_j + (m-1) \cdot g\right) \tag{13}$$

Opening the brackets and taking into account that $\sum_{j=1}^{N} p_{ij} = 1$, we have

$$g + \upsilon_i = q_i + \sum_{j=1}^{N} p_{ij} \cdot \upsilon_j \, , i = \overline{1,N} \tag{14}$$

Thus, a system of N equations with $N+1$ unknowns $g, \upsilon_1, \upsilon_2, \dots, \upsilon_N$ is obtained. In the future, when determining the optimal strategy, there is no need to know the absolute values of the weights $\upsilon_j, j = \overline{1,N}$.

It is enough to require that the differences $\upsilon_j - \upsilon_r$ maintain a constant value. And this can be easily achieved by adding one equation to system (14), for example $\upsilon_N = 0$ (you can put any of $\upsilon_i = 0$). Solving system (14) together with the equation $\upsilon_N = 0$, we obtain a set $g^0, \upsilon_1^0, \upsilon_2^0, \dots, \upsilon_N^0$ for determining the asymptotic values $\upsilon_j(m)$.

With fixed strategies, there is no need to solve system (14) to determine g, but expression (9) can be used. But defining g using this expression does not provide any information for searching for optimal strategies.

The resulting solution $g^0, \upsilon_1^0, \upsilon_2^0, \dots, \upsilon_N^0$ can be further used to evaluate various strategies. From relation (12) it follows that if you adhere to optimal behavior until step m, then to find the optimal strategy at the $(m+1)$ step in state E_i it is sufficient to maximize the expression

$$q_i^k + \sum_{j=1}^{N} p_{ij}^k \cdot \upsilon_j(m) \tag{15}$$

Relative to all strategies corresponding to state E_i. Using expression (7), based on relation (15), we can write $q_i^k + \sum_{j=1}^{N} p_{ij}^k \cdot \upsilon_j(m \cdot g + \upsilon_i)$.

Since $\sum_{j=1}^{N} p_{ij} = 1$ and the relative weights $\upsilon_i, i = \overline{1,N}$, differ from the absolute values by the same amount, independent of the chosen strategy k, from the previous expression it follows that when searching for an optimal strategy for state E_i, it is enough to choose a strategy that provides a maximum to the expression

$$q_i^k + \sum_{j=1}^{N} p_{ij}^k \cdot \upsilon_j \qquad (16)$$

The entire process of solving the problem can be presented in the form of the following algorithm (Fig. 2).

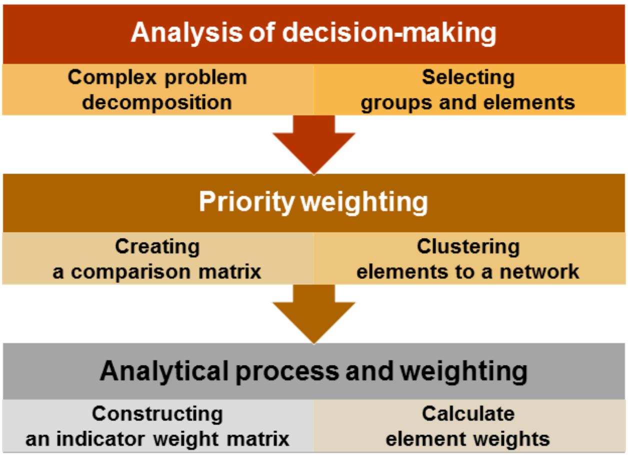

Figure 2. Algorithm for finding the optimal strategy

3 RESULTS

The Lviv-Volyn coal basin occupies an important place in Ukraine's economy and is the main fuel and energy base of the Western region. Lviv Volyn Coal Basin, which is part of the large Lublin Basin. It is known for its brown coal, which is used mainly in thermal power plants. All mines produce coal, which needs to be enriched to acquire suitable qualities for sending to thermal power plants. The solid fuel supplied to the thermal power plant has a certain particle size, which is discussed in the terms of delivery. The coarseness of the fuel depends on the conditions of its extraction and preparation for supply (for example, sorting, enrichment). Preparation of fuel at a thermal power plant for pulverized combustion is carried out in two stages: preliminary crushing in station crushers to the size of pieces of 15...25 mm and further grinding in mills to a pulverized state. An increase in coal ash content by 1% reduces its price by 2.5%. The ash content of coal is distributed roughly in proportion to their density. Energy coal is enriched according to simpler schemes and in those cases when it is economically advantageous. The chemical composition and technological properties of coal (table 1) are the main indicators that determine the technical and economic feasibility of mining and rational use. Let us determine possible strategies depending on the chemical composition and technological properties of coal from the Lviv-Volinsky Kamyanova Coal Basin. If the quality of the coal is in the E_1 state, i.e. If coal of high quality in terms of chemical composition has been mined, then two strategies are possible: $k = 1$ is do not enrich the coal for use; $k = 2$ use coal enrichment technology to improve its quality indicators, depending on the intended use. If the condition of coal E_2 is poor, then two strategies are also possible: $k = 1$ – do not enrich coal for use; $k = 2$ - use coal enrichment technology to improve its quality indicators depending on the intended use. Using the formulated algorithm, we will determine optimal strategies.

The numerical values of transition probabilities and income are presented in Table 2.

Table 1. The value of coal indicators of the Lviv-Volyn coal basins (Ukraine)

The ash content %	The moisture content	Heat of combustion	The price %
23*	**8.9***	5550	100.0
24	8.9	5510	97.5
25	8.9	5470	95.0
26	8.9	5430	92.5
27	8.9	5390	90.0
28	8.9	5350	87.5
29	8.9	5310	85.0
30	8.9	5270	82.5

* Base parameters: ash 23.0%, moisture 8.9%.

Table 2. Probabilities of switching from one strategy to another

Solid mineral fuel condition	Strategies k	Probabilities of transitions		Income		$q_i^k = \sum_{j=1}^{2} p_{ij}^k \cdot r_{ij}^k$
		p_{i1}^k	p_{i2}^k	r_{i1}^k	r_{i2}^k	
Good quality	No enrichment	0.5	0.5	9	3	6
	Enriched	0.8	0.2	4	4	4
Poor quality	No enrichment			3	-7	-3
	No enrichment			1	- 19	-5

Let's set V(0)=0 and determine the optimal strategies using recurrence relation (12)

$$\upsilon_1(1) = \max_2 \left(q_1^1 + \sum_{j=1}^{2} p_{1j}^1 \cdot \upsilon_j(0), q_1^2 + \sum_{j=1}^{2} p_{1j}^2 \cdot \upsilon_j(0), \right) = \max(6,4) = 6$$

$$\boldsymbol{\upsilon_2(1) = \max_2 \left(q_2^1 + \sum_{j=1}^{2} p_{2j}^1 \cdot \upsilon_j(0), q_2^2 + \sum_{j=1}^{2} p_{2j}^2 \cdot \upsilon_j(0), \right) = \max(-3,-5) = -3}$$

Thus, at the first iteration, the optimal strategy is $\boldsymbol{d} = \begin{pmatrix} \mathbf{1} \\ \mathbf{1} \end{pmatrix}$, and it corresponds to the income vector

$$\boldsymbol{V(1)} = \begin{pmatrix} \upsilon_1(\mathbf{1}) \\ \upsilon_2(\mathbf{1}) \end{pmatrix} = \begin{pmatrix} \mathbf{6} \\ \mathbf{-3} \end{pmatrix}$$

For m=2 we get

$$\upsilon_1(2) = \max_2 \left(q_1^1 + \sum_{j=1}^{2} p_{1j}^1 \cdot \upsilon_j(1), q_1^2 + \sum_{j=1}^{2} p_{1j}^2 \cdot \upsilon_j(1), \right) = \max\Big(6 + \big(0.5 \cdot 6 + 0.5 \cdot (-3), 4 + \big(0.8 \cdot 6 + 0.2 \cdot (-3)\big)\big)\Big) = \max(7.5, 8.2) = 8.2$$

$$\upsilon_2(2) = \max_2\left(q_2^1 + \sum_{j=1}^{2} p_{2j}^1 \cdot \upsilon_j(1), q_2^2 + \sum_{j=1}^{2} p_{2j}^2 \cdot \upsilon_j(1),\right) = \max(-2, 4, -1.7) = -1.7$$

In this case, the optimal solution would be $d = \binom{2}{2}$. The results of the subsequent steps are presented in Table 3.

Table 3. Optimal Strategies of Controlled Markov Processes

m / i	0	1	2	3	4
$\upsilon_1(m)$	0	6	8.2	10.22	12.22
$\upsilon_2(m)$	0	–3	–1.2	0.23	2.23
$d_1(m)$	–	1	2	2	2
$d_2(m)$	–	1	2	2	2

After the third step, the process proceeds in such a way that the second strategy is optimal.
To calculate the criterion and determine the optimal strategy, we draw up Table 4.

Table 4. Results of searching for optimal strategies

i	k	$q_i^k + \sum_{j=1}^{N} p_{ij}^k \cdot \upsilon_j$
1	1	6+0.5·10+0.5·0=11
	2	4+0.8·10+0.2·0=12
2	1	–3+0.4·10+0.6·0=1
	2	–5+0.7·10+0.3·0=2

As a result of three successive iterations, it was established that the solution $d = \binom{2}{2}$ is optimal, and it corresponds to income $g = 2$.

4 CONCLUSIONS

In the work, an analysis of regulatory documents and scientific and technical literature was carried out according to the methods of testing parameters of the quality of solid mineral fuel. On the basis of this analysis, the key parameters of the quality of solid mineral fuel were selected - heat of combustion, moisture content, total sulfur content, ash content, yield of volatile substances, as well as parameters of granulometric and fractional composition. The justified relevance of the development of procedures for assessing the uncertainty of measurements of the quality parameters of solid mineral fuel for specialized coal chemical laboratories that are accredited to meet the requirements of the ISO/IEC 17025 standard. Improved methods for assessing the uncertainty of measurements in accordance with previously unresolved specific tasks that arise during tests of solid mineral fuel according to quality parameters. All prospective directions of the economic development of most countries provide for the limitation and (or) reduction of ash content and sulfur content in coal and its processing products. In view of the current situation, the work practices of producers (suppliers) and consumers of coal products, as well as international requirements, it is proposed to consider the following standards for ash content and sulfur content for market economy conditions. The selection of products according to ash content and sulfur content between producers (suppliers) and consumers within the limit values should be carried out according to regulatory documents for products. A method of determining the general indicator of the quality of solid mineral fuel is proposed as a scientific and technical basis for the creation of a regulatory document for its pricing when purchasing at thermal power stations. The presented general indicator of quality should also be used when conducting a technical examination of solid mineral fuel in order to protect the interests of consumers and the participation of Ukrainian business entities in international scientific and technical cooperation and trade.

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