Improving the process of coal extraction based on the parameter optimization of mining equipment

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Abstract. The aim of this paper is to develop and validate methods of choosing the means of the mining face mechanization. This paper analyses existing methods of optimizing processes in mining. It was established that the effectiveness of the performance map of coal field is formed by a group of technological, operational, and economic parameters which can be represented as a vector of solutions. To find the optimal solution, it was suggested to use network models and graphs. The essence of the technique is to represent the input and output (production level, prime cost) resource flows in an organized structure. Regularities of forming technological schemes of coalfield operation with a given level of performance, taking into account the relationship between technological parameters of mining face, operational parameters of the stoping equipment, technical and economic performance are defined. We developed the system for decision-making support, which allows optimizing operational parameters, reducing the production prime cost, and selecting the structure of the mechanized complex of stoping equipment with a specified level of performance. This paper describes approaches that can be used at the design stage of mining face and in the process of operation.

1 Introduction

The coal industry is one of the most resource-intensive in the energy sector. For the effective operation of coalfields, it is necessary to solve a number of issues that are associated with the justification of rational operation of the stoping equipment, increase in the productivity of the mining face, decrease in the production prime cost, etc. Solving each task separately does not allow increasing the overall efficiency. Moreover, a group of technological, operational, and economic parameters forms performance indicators, so it is necessary to develop an integrated approach. Today, there is a number of methods and means of decision-making support in mining, which are aimed at improving the production process. One uses most frequently the multi-criteria decision analysis (MCDA), the essence of which is in priority setting, selecting the most important factors with further optimization. It is worth noting that, because of using MCDA, the solution is not optimal but efficient according to a specified function of "usefulness".

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In mining, one uses the analytic hierarchy process (AHP), designed by T. Saaty and adapted by scientists to operating condition of enterprises in the mining complex: M. Ataei [1], S. Alpay [2]. However, there is a number of difficulties: importance and priority of the criterion establish the decision-maker (DM) – for the accurate decision-making, there should be consistency between DMs (Pareto optimality); a great number of samples and a poll do not always guarantee the right choice; in addition, the selection criteria do not always correspond to the task [3]. Given the specificity of the mining industry, we developed modifications of the method taking into account deviations from the model of rational choice (TODIM) [4], as well as deviations from the "ideal" value with subsequent normalization [5] (Grey-AHP).

Also, the wide-spread is the method of preferences analysis (PROMETHEE), the essence of which is to set the preference function, comparison of options, and subsequent ranking of obtained preference functions. This method is used by Wang Chen [6] to solve tasks of transporting coal in the mining face, Zhang Jianping [7] to balance the supply of materials. The use of this method is difficult because nobody knows weighting coefficients for each parameter group (equipment, technological parameters, technical and economic indicators).

Analysis of the AHP method and its varieties (TODIM, Grey-AHP), as well as the method of preferences analysis PROMETHEE has found out that there is an issue of incommensurability and inconsistency in the selection of criteria. Therefore, the idea of adopting a "compromise solution" appeared [8]. This method was used at the stage of design transportation chains [9], to solve the tasks of production organization in the mining face [10]. However, there is the issue of "indistinct" uncertain objects that have different characteristics, for example: roof stability, soil rock category of opening, etc. To solve this issue, it was proposed to use fuzzy-set methods [11], while for the efficient design there should be the basis for "good" design decisions [12], which can be represented by graphs and network models.

The analysis of papers [1, 2, 4 – 12] allowed us to find out that the increase in the efficiency of technological schemes for the operation of coalfields is impossible without optimization of parameters of the stoping equipment. To achieve this task, one can use methods of the decision-making theory that are based on the comparison of possible solutions and priority setting. There are also factors that do not allow efficiently applying these approaches for the solution of tasks in the optimization of parameters of the stoping equipment:

– iincommensurability of efficiency criteria values; for example, the daily performance at mines of Ukraine is 500 to 3000 t/day, the level of significant preference $H_d = 0.5$ is adopted based on the condition of the break-even $Q \geq 1.000$ t/day, and the maximum preference $H_d = 1.0$ will correspond to the maximum capacity $Q \geq 3000$ t/day; in fact, 66% of performance indicators values will be preferred;

– when choosing means of the mining face mechanization in addition to quantitative criteria (performance, equipment life, prime cost, etc.) one also uses qualitative criteria – relationship with the pan line of armoured face conveyor, consistency of the advance increment of powered support and shearer, interrelation between the armoured face conveyor advance system and the shearer transfer system, etc.;

– as previously stated [11, 12], the search for the optimal solution to the task is to analyse good (rational for specific conditions) solutions, but this is impossible without the presence of the "bank of situational solutions";

– listed methods of decision-making [1 – 12] are based on the use of adjacency matrices with the dimensionality $n \times m$, where n is the number of alternatives, and m is the number of criteria that match the alternative n; for the final decision-making, we use methods of

linear programming, special expensive software [13, 14]; at the same time, methods of discrete mathematics allow us to successfully use relevant approaches without additional resources.

Therefore, the process of improving the technology of mechanized coal mining is in support of rational (good) operating conditions with subsequent optimization of parameters of the stoping equipment. There is an area of "rational design" [15], and for our study, this is a set of conditions for the operation of the stoping equipment (layer thickness, face length, rocks length, roof length), which correspond to technical and economic, operational parameters.

To solve this task, we can use network models and graphs. In the paper [16], there is the methodology of selecting the stoping equipment using graphs and network models, and in the paper [17], there is its practical use. It is worth noting that this approach was used to solve transportation issues [18], tasks for the resource allocation at the mine [19], as well as for ventilation of mine workings [20], as well as surface mining of mineral deposits [21, 22].

Thus, establishing regularities of forming technological schemes of the stoping equipment with the set performance level, depending on technological, operational, economic parameters, is a topical scientific task. The aim of this paper is to develop a tool for optimizing parameters of the mining equipment. To do this, it is necessary to establish the rational area for the design of hardware, substantiate the system of principles for selecting the stopping equipment, develop the mathematical model, and offer the program implementation.

2 System principles for selecting the stoping equipment

In relation to the aim of the study, general system principles [23 – 25] are as follows:

– integrity, i.e. the mining equipment is considered as a single structure "mechanical powered support – shearer – face armoured face conveyor" without separation into individual components;

– hierarchy, i.e. one considers the relationship not only between the types of stoping equipment (for example: shearer-armoured face conveyor) but also between the assembly units of equipment (for example: the armoured face conveyor pan line and the shearer transfer system);

– structuring, i.e. the possibility of optimizing not the entire structure "powered support – shearer – armoured face armoured face conveyor", but only certain levels of "powered support – shearer", "shearer – armoured face conveyor";

– consistency, i.e. operating parameters of each type of equipment (layer thickness, mining face length, seam inclination) correspond to operating parameters of the structure "powered support – shearer – armoured face conveyor";

– multiplicity, i.e. the existence of standard models ("bank of good solutions" [12]) for a set of presented options.

Compliance with all principles allows obtaining the property of the "structural optimization" [26, 27] – the process of obtaining a series of system effects for the optimization of the objective function depending on given limitations.

As for the structure of the stoping equipment, we should consider the area of rational design, i.e. operating conditions in which indicators will be maximum and meet the break-even condition (for mines of Donbas $Q \geq 1000$ t/day).

As noted earlier, the efficiency of the production process P is affected by technological operational parameters P_T, means of mechanization P_E, and the production prime cost P_C. Then, the vector $p(P_T, P_E, P_C)$ will represent the rational option of integration of the stopping equipment. From the optimality condition:

$$p(P_T, P_E, P_C) = \min(P_T, P_E, P_C), \quad (1)$$

where $p = \{P_{1T}, P_{2T,\cdots}, P_{NT}; P_{1E}, P_{2E,\cdots}, P_{ET}; P_{1C}, P_{2C,\cdots}, P_{NC}\}$ – the vector and its components $P_{1T}, P_{2T,\cdots}, P_{NT}$ meet rational technological parameters of the working area, $P_{1E}, P_{2E,\cdots}, P_{NE}$ – types of the stoping equipment, $P_{1C}, P_{2C}, ..., P_{NC}$ – the production prime cost.

The group of technological parameters of the mining face $P_{1T}, P_{2T,\cdots}, P_{NT}$ includes the length of the working area l_n and the layer thickness m_n. The group of the "mining equipment" corresponds to the structure "powered support t_n, shearer c_n, armoured face conveyor k_n", which can provide the daily performance q_{nn} at the level of $Q \geq 1000$ t/day.

The level of costs for the purchase of machinery Z_n and equipment life R_n form the specific cost of production $P_{1C}, P_{2C}, ..., P_{NC}$.

Then, the mathematical meaning of the proposed approach can be formed as follows: the totality of types of the mining equipment $\langle t_n, c_n, k_n \rangle$, which is operated under given operating conditions $\langle t_n, m_n \rangle$, generates the level of performance q_{nn} at the prime cost s_n. It should be noted that any groups of parameters and performance criteria could be specified, as long as they meet the objectives of the study. In accordance with planned parameters, one can set the scope of rational design (Table 1).

Table 1. The scope of rational design for solving the task of optimizing the mining equipment.

Indicator	Criterion value	Limitation form
Layer thickness m_n, m	$M \subseteq H \Leftrightarrow \forall m_n \in M : m_n \in H$	$M \subseteq H$
Length of the mining face l_n, m	$L \subseteq W \Leftrightarrow \forall l_n \in L : l_n \in W$	$L \subseteq W$
Powered support t_n	$T \subseteq R \Leftrightarrow \forall t_n \in T : t_n \in R$	$T \subseteq R$
Shearer c_n	$C \subseteq S \Leftrightarrow \forall c_n \in C : c_n \in S$	$C \subseteq S$
Armoured face conveyor k_n	$K \subseteq A \Leftrightarrow \forall k_n \in K : k_n \in A$	$K \subseteq A$
Funds for the purchase of equipment Z_n, mln UAH	$Z_n \to \min$	$Z_{\max} \leq Z_n \leq Z_{\min}$
equipment life R_n, mln tonnes	$R_n \to \max$	$R_{\min} \leq R_n \leq R_{\max}$

where M, L – the subset of rational operational parameters, and H, W – the great number of possible technological parameters; T, C, K – the subset of rational types of the mining equipment, R, S, A – the great number of existing types of equipment.

From Table 1, it is seen that the given level of performance Q is generated only when technological parameters $\langle l_n, m_n \rangle$ are rational: $l_n \in L$, $m_n \in M$, i.e. they are at the subset of rational operational parameters M, L. In addition, the means of mechanization $\langle t_n, c_n, k_n \rangle$ have a high level of interrelation: $t_n \in T$, $c_n \in C$, $k_n \in K$, where T, C, K – the subset of rational types of equipment. The important condition is that the funds for the purchase of mechanization means should be kept at their minimum $Z_n \to \min$ and the equipment life – at the maximum $R_n \to \max$.

To optimize operational parameters, one should formalize them, i.e. present in the form of a network model. Then, the shortest route of the network model g_1 will correspond to the optimal solution. Conditions (2) and (3) shall be met:

$$(m_1 \cdots m_n) \to (l_1 \cdots l_n) \to (t_1 \cdots t_n) \to (c_1 \cdots c_n) \to \\ \to (k_1 \cdots k_n) \to (v_1 \cdots v_n) \to (s_{11} \cdots s_{1n}) \to g_1 \quad ; \tag{2}$$

$$(i; j) = s_n \text{ – the route exists, } (i; j) = \infty \text{ – the route is missing,} \tag{3}$$

where (2) – the condition for the existence of the alternative, i.e. the optimization requires that the route passes through vertices, which correspond to the layer thickness $(m_1 ... m_n)$, the length of the mining face $(l_1 ... l_n)$, powered support types $(t_1 ... t_n)$, shearer types $(c_1 ... c_n)$, armoured face conveyor types $(k_1 ... k_n)$, the level of performance $(v_1 ... v_n)$, the production prime cost $(s_{11} ... s_{1n})$; (3) – the condition for the existence of the link between vertices, i.e. the production prime cost for each type of equipment s_n can be expressed as the distance between vertices $(i; j)$ of the network model.

Then, the task of optimization by the parameter "prime cost" can be solved as follows:

1) define rational types of the mining equipment T, C, K and present them as vertices of the network model $(t_1 ... t_n)$, $(c_1 ... c_n)$, $(k_1 ... k_n)$;

2) define the production prime cost for each type of equipment $s_n = Z_n / R_n$ and present it as the length of the route (i, j) between vertices; if the interrelation between types of equipment is missing, then $(i, j) = \infty$;

3) find the best solution that corresponds to the shortest route from the vertice m_1 to the vertice g_1 using optimization algorithms or methods of linear programming.

The optimization parameter for the route length can be any characteristic of the process (maintenance costs, energy expenditure level, personnel number), and vertices can be represented by types of equipment, intermediate points, stages, etc.

We shall use mines "Krasnolymanska" and "Kotliarevska" as an example to consider the process of optimization and selection of the mining equipment according to the parameter of the "prime cost".

3 Optimization of operational parameters of the mining equipment

The task is in the optimum choice of the technological chain of the mining equipment for specified operational conditions (Table 2).

Table 2. Features of mining faces in mines "Krasnolymanska" and "Kotliarevska".

Mine	Layer thickness, m	Face length, m	Powered support type	Shearer type	Armoured face conveyor type
	m_n	l_n	t_n	c_n	k_n
Krasnolymanska	1.10 – 1.15	295	DM	RKU10	SP251
Kotliarevska	1.20 – 1.25	250	1KD90	1K101	SP26

To solve this task, we analyzed existing options for the integration of the mining face under given operational conditions. There are 57 such options for mines of Donbas. After the setting the minimum level of performance $Q \geq 1200$ t/day, the number of alternatives was reduced to 9.

However, 4 conditions remained for the mine "Krasnolymanska" and 3 conditions for the mine "Kotliarevska". Depending on the number of conditions (limitations), the result will be different, since this is the property of "structural optimization". Table 3 lists possible options available for the integration of mining faces for conditions of mines "Krasnolymanska" and "Kotliarevska".

Table 3. Possible options of completing for mining faces of mines "Krasnolymanska" and "Kotliarevska".

No.	Equipment types			Designation in Fig. 1
	powered support	shearer	armoured face conveyor	
1	KD80	KA80	SP251	1
2	DM	RKU10	SP26	2
3	KD80	KA80	SP250	3
4	1KD90	1K101	SP26	4
5	DM	UKD200	SP326	5
6	1KD90	1K101	SP326	6
7	KD80	1K101	SP250	7
8	DM	K103	SP250	8
9	1KD90	UKD400	SP326	9

For the mine "Krasnolymanska", requirements were as follows: low ash content of coal (excluding the alternative 2), series production of equipment (excluding the alternative 8), and screw type of the executive body (excluding alternatives 1, 3), interrelation of shearer and armoured face conveyor (excluding the alternative 4). In the end, 4 possible options were left (5, 6, 7, 9). Similarly, the choice was made for the mine "Kotliarevska". It is convenient to present the selection process in the form of a decision-making "tree" (Fig. 1).

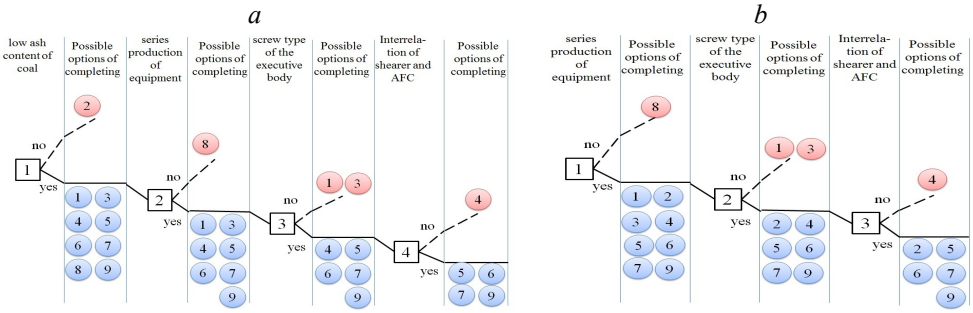

Fig. 1. Decision-making trees at different limitations: a – mine "Krasnolymanska", b – mine "Kotliarevska".

After the preliminary analysis of alternatives, one should choose a single alternative, optimal from the standpoint of minimization of the optimization parameter. In our case, this is the "production prime cost". We shall use the mine "Krasnolymanska" as an example to show the selection of the optimal chain of proposed options. To do this, let us present 4 options in the form of a network model. Vertices represent types of purification equipment, and the lengths between peaks are the values of specific cost (Table 4).

To automate the selection process, the personnel of the Institute of Physics of the Mining Processes of National Academy of Sciences of Ukraine developed the appropriate software [28 – 30]. The program will then automatically find the shortest route that will match the means of mechanization of the mining face, with a given level of performance $Q \geq 1200$ t/day and the minimum prime cost.

Table 4. Data required for optimization.

No.	Equipment type	Costs for the purchase, mln UAH	Equipment life, mln tonnes	Prime cost, UAH/t	Vertice of the network model (Fig. 2)
1	KD80	120.0	2.50	48	2
2	1KD90	193.5	5.00	39	3
3	DM	249.6	7.50	34	4
4	UKD200	35.0	0.60	58	5
5	1K101	15.0	0.29	52	6
6	UKD400	47.4	1.00	48	7
7	SP326	64.7	2.50	26	8
8	SP250	38.7	1.10	35	9

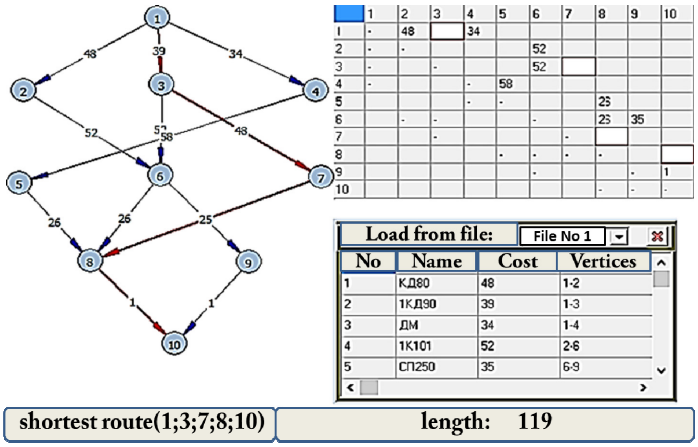

Fig. 2. Optimization of the process chain of the stopping equipment.

As can be seen from Figure 2, the shortest route is the one that passes through the following points: 1, 3, 7, 8, and 10. This corresponds to the equipment chain "powered support 1KD90, shearer UKD400, armoured face conveyor SP326". However, when one uses powered support DM the production prime cost is lower than with powered support 1KD90, so let us rearrange the structure of the production chain. For this purpose, we shall find powered support, shearer, and armoured face conveyor with the lowest production prime cost. In the end, the optimum chain of the mining equipment will consist of powered support DM, shearer UKD400, armoured face conveyor SP326.

Table 5. Technical and economic analysis of proposed solutions.

Equipment			Production volume, t/day	Increment, t/day	Prime cost, UAH/t	Reduction of prime cost, UAH/t
powered support	shearer	armoured face conveyor				
Mine "Krasnolymanska"						
DM	RKU10	SP251	1440	–	118	–
1KD90	UKD400	SP326	1480	40(2.8%)	113	5(4.2%)
DM	UKD400	SP326	1743	303(21.0%)	108	10(8.5%)
Mine "Kotliarevska"						
1KD90	1K101	SP26	848	–	124	–-
DM	RKU10	SP326	1272	424(48.3%)	115	9(7.3%)

The program contains a database, provides various options for entering information and is integrated with office applications. For the purpose of optimization, we shall place points in the working area and set the length between points that correspond to vertices.

Because of the conducted selection, the prime cost will decrease by 10 UAH/t that will decrease the prime cost by 7.1 mln UAH (Table 5). For the mine "Kotliarevska", we also conducted the selection and optimization of operational parameters. Table 5 shows the analysis of proposed solutions.

Thus, the improvement of the mechanized coal mining is in the choice of means of mechanization of the mining face with a given level of performance. Subsequent application of network models and graphs allows optimizing the chain at one of the options. The described approach can be used as an addition to the already known ways of the planning mining works [31 – 32].

4 Conclusions

The study found that the performance of the mining face is an integral indicator, which is formed by a group of technological (layer thickness, length of the mining face), operational (means of mechanization), and economic factors. The effectiveness of the enterprise functioning is directly proportional to the level of interrelation between means of mechanization and inversely proportional to resources involved. This allowed us to draw the following conclusions:

– designing the technology for the mechanized coal mining is in the analysis of the set of rational solutions for specified operational conditions. Possible rational solutions can be formalized in the form of the "bank of decisions". This formalization allows to apply methods of structural optimization, analytic hierarchy process, linear and dynamic programming, and the graph interpretation allows automating the analysis process, increasing the dimension of solvable problems, which are found during the operation of coal fields;

– significant reserve of increasing technical and economic parameters of enterprises at the mining complex is the balanced flow of input and output resources; for this, it is necessary to present them in an organized structure as a network model. The subsequent application of optimization methods allows us to find the shortest route in the network, which corresponds to the balance of resources;

– scope of the described approach is not limited to coal fields and selection process of means of mechanization. Network models can be used to solve transportation problems, formulate emergency response plan, organize and manage resources, reduce the cost of equipment maintenance and repair.

One of the advantages of the proposed tool is its clearness, simplicity, ability to process and store large amounts of data. The characteristic feature of tools described in the paper is the ability to apply them together with MCDA methods at any stage of the study.

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