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MODELS AND METHODS OF OPERATIONAL MANAGEMENT IN MINING PRODUCTION

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Abstract

The goal of the work is to develop and verify a new methodological approach for the comprehensive assessment of the technological potential of coal mining enterprises.

To address this task, a comprehensive approach has been applied, based on the implementation of the neoclassical production function in the form of the Solow model to analyze the state of the coal mining industry. It also involves evaluating the economic reliability coefficient to develop recommendations for improving techno-economic indicators.

The efficiency of enterprise functioning can be assessed by the ratio of input (capital) to output (production level) flows of resources, with a significant role played by the innovative component. Analyzing the relationships between resource flows allows selecting optimal production development scenarios and forming principles for designing production at a certain stage of development.

For the first time in the paper, a model for evaluating parameters of mining production is proposed, demonstrating the relationship between production functions and resources. Using the developed model, it is possible to track the efficiency of the use of production resources over time, determine production volumes, calculate the main parameters of coal mines' functioning, and investigate the resources contributing to increased productivity.

Regularities in the formation of the efficiency level of coal mining enterprises are established for the first time, and approaches to production design considering the area of rational exploitation are developed.

Methods of combined management of processes of simple and extended reproduction of technological schemes of mines are proposed by regulating the resource potential of mines. The procedure of gradient reduction of the limit on technological resources and adjusting the functional value to approach results in mine operation to a possible breakeven threshold is a widely recognized form of sensitivity analysis of modeling results. The comprehensive assessment of the technological scheme of the mine in four directions significantly increases the objectivity level of the final result compared to evaluating it with only one indicator.

Introduction

The features of the management system of coal mining enterprises at the present stage are closely tied to the change in their strategic orientations. The primary economic goal of enterprises in market conditions is to enhance production efficiency through various influencing factors, including the formation of internal economic reserves. The potential utilization of these reserves enables the implementation of a policy to abandon budgetary support for loss-making coal mining enterprises. In this context, the ability to extract a certain volume of coal and increase reserves without significant reliance on state budget funds, achieving breakeven, ensuring a certain level of profitability, reducing subsidy levels, and creating conditions for investment attractiveness becomes particularly crucial.

Hence, there is a need to develop new methodological approaches to stabilize the situation. To achieve this, it is necessary to:

- analyze innovative prospects for underground deposit exploitation and identify key factors shaping the overall production level, as well as possible ways to enhance efficiency;
- identify the main factors for replenishing internal reserves of coal enterprises;
- propose methodological approaches for evaluating the level of coal mining enterprises.

The aforementioned work is dedicated to addressing these tasks.

The key to improving the efficiency of coal mining enterprises lies in creating conditions that allow for the operational management of production activities. This requires the development of tools and approaches.

Existing Approaches to Mining Production Management

Before delving into the main material, it is necessary to analyze existing approaches to design. This will allow for a concise overview of a multitude of approaches. But before doing so, let's characterize the models that can describe production processes. Management and design processes in mining production can be divided into 6 types of models: optimization, informational, deterministic, probabilistic, static, and dynamic.

Optimization models encompass the description of the functioning conditions of the object in the form of equations and inequalities that represent constraints of the task and reflect the balance of resources (material, labor, financial, etc.). The distinctive feature of optimization models is that there is a set of feasible solutions (sometimes an infinite majority), among which the optimal solution needs to be identified.

Informational models contain the necessary output information for decision-making. With these models, it is possible to establish a regression relationship between the influencing and outcome features. In these types of models, the functioning of the object is described by equations that establish a quantitative connection between the input and output parameter systems.

Deterministic models presuppose a cause-and-effect relationship in the model, which is interrelated and can be expressed analytically. In other words, randomness is considered insignificant in deterministic models.

Probabilistic models take into account the influence of random factors on economic and organizational phenomena and processes. Models of reliability theory, mass servicing, forecasting of mining equipment indicators, quarry transport, etc., fall under probabilistic models.

Static models are applied when the parameters of a specific system, within a defined time interval describing the operation and conditions of the object, practically do not change.

In cases where system parameters undergo significant changes over time, dynamic models are applied.

It is worth noting that mathematical programming methods differ only in the requirements for constraints. If the constraints of the objective function are linear, linear programming methods are applied. If the constraints or the objective function are specified by nonlinear constraints, nonlinear programming is employed. If there is a requirement for the components of the solution vector X to be integers, then integer programming is used. If randomness is considered, stochastic programming is applied. To account for time, dynamic programming is utilized.

After this, we can proceed to the analysis of tasks, which have been classified based on different types.

There are several classifications that can be conditionally divided into:

1. Classification based on the application of economic-mathematical methods. This involves a subdivision into models such as probabilistic, stochastic, deterministic, static, dynamic, etc.

2. Classification based on the type of obtained solution: informational and optimization models.

3. Classification based on the forecasting duration (short-term, long-term) and the method of obtaining the solution (using software, simulation modeling).

Let's delve into each classification separately and analyze the main works in each category.

The classification based on economic-mathematical methods [1] is grounded on the tools (mathematical) employed for model construction. The following methods are known: mathematical programming, which is divided into linear [2], quadratic [3], integer [4], stochastic [5], dynamic [6], and geometric [7]; inventory management [8], game theory [9], network models [10], correlation models [11], queuing theory [12], reliability theory [13], forecasting [14], and simulation modeling [15]. When applying linear, quadratic, and integer programming, optimization, deterministic, and static models can be implemented. For stochastic programming: optimization, probabilistic, and static models. For dynamic programming: optimization, deterministic, probabilistic, and dynamic models. For geometric programming: optimization, deterministic, static, and dynamic models. Inventory management implements optimization, deterministic, probabilistic, static, and dynamic models. Game theory realizes optimization, deterministic, probabilistic, static, and dynamic models. For network models as an economic-mathematical method, optimization, informational, deterministic, probabilistic, and static models are possible. Correlation methods, like queuing theory, implement informational, probabilistic, and static models. Reliability theory, forecasting, and simulation modeling realize informational, probabilistic, static, and dynamic models.

One drawback of this classification is the division of methods based on the type of objective function and decision-making tool, without describing the application area or "rationality of the approach." Additionally, it does not consider the interconnection of production processes.

Examining works [1-15] and methods, it becomes apparent that these can be applied to short-term planning. However, decision-making processes are influenced not only by economic, technological, and social factors but also by qualitative ones. If, for instance, the specific cost or transportation costs [16] are taken as the objective function, the decision will be optimal in terms of the defined parameter. Still, there is a high probability that it will not correspond to the "quality" characteristic - a set of features that characterize the object.

Therefore, a classification of methods based on the type of obtained solution [17] was considered. According to this classification, methods are divided into optimization and informational. Optimization models answer the question of which solution is optimal from a quantitative point of view, while informational models address the qualitative aspect. Optimization methods include all the aforementioned mathematical programming methods [2-7], as well as game theory, network, and correlation models. Informational models are based on the Analytic Hierarchy Process (AHP) method [18] and its variations, such as PROMETHEE [19], ELECTRE [20], TODIM [21], VICOR [22], Fuzzy-AHP [23], Grey-AHP [24], fuzzy set methods [25]. These approaches prioritize and build hierarchies, resulting in a qualitative solution but heavily dependent on the level of expertise. However, situations may arise where it's impossible to construct a connectivity matrix [26]. To address the drawbacks of the first two groups of methods, another classification was considered [27], which is based on planning terms and tools. This classification divides methods into long-term and short-term planning, which are all based on the methods described earlier [2-15, 18-25]. It highlights a group of approaches based on simulation modeling [28] of production parameters. These parameters can consider qualitative or economic indicators, allowing for production activity planning. The difference lies in the simulation modeling method.

The last set of works [29–32] suggests trends in the creation of approaches to designing processes for the development of mineral deposits:

- the optimality criterion is "quality" but distinguished by various quantitative indicators;
- general tasks are divided into local ones; only after optimizing the tasks at the first stage do they move on to optimization at the second and beyond.

With this analysis, we can proceed directly to the development of the operational management model for mining production.

Development of Operational Management Model

Innovative aspects of production can be described using the Solow model [33]. Concerning mining production, this model offers several advantages:

1. Firstly, it is based on the application of a single type of good Y, as in the conditions of Ukraine, mines are considered enterprises for

coal extraction, not components in the energy or metal production system.

2. Secondly, the model takes into account the relationship between capital, labor, and the level of workers' qualifications, thus aligning with fundamental technical and economic indicators that define enterprise efficiency.

3. Thirdly, the introduction of new innovations A is closely associated with the volume of labor resources L, a decisive factor in the production design process.

In its general form, the Solow model considers a neoclassical production function of the form

$$Y=f(K,L,A)$$

де K - the level of engaged capital;

L - the volume of labor resources;

A - the efficiency of one worker, depending on the level of qualification and knowledge.

In this context, the variable A reflects technological progress and innovations in production, correlating with the volume of labor resources. Considering constant returns from investments, the production function can be expressed in per capita variables, reflecting efficiency per unit of labor

$$\frac{Y}{LA}=f\left(\frac{K}{KA}\right)\Rightarrow y=f(k)$$

where y - productivity, k - denotes capital investment with constant efficiency.

The provided model demonstrates the change in the marginal product, i.e., the additional output of production from the application of an additional unit of resources. In other words, the proposed function illustrates the efficiency of implementing innovations.

To enhance production efficiency, it is necessary to balance the flows of input and output resources depending on the production scenario. Let's consider each scenario separately:

-"Scenario *I*" involves transitioning from a crisis to stability and describes the current state of the coal industry in Ukraine, where the pace of mechanization is low, yet it surpasses the rate of workforce reduction in enterprises. In terms of the Solow model, this can be formulated as follows: there is a scarcity of capital, while labor resources are abundant. This situation only exacerbates the state of affairs. For coal mines, the situation is further complicated by the fact that the production cycle is subordinated to a sectional labor organization system. Therefore, reducing the group of workers involved in coal mining or preparatory blasting will lead not to savings but to the uncontrolled collapse of the entire production cycle. To stabilize the situation, it is necessary to implement mechanization, giving preference to domestic analogs. Thus, any innovations aimed at improving the technological process will contribute to the restoration of enterprise potential, leading to a transition from a crisis state to a stable one (Scenario *II*).

- "Scenario *II*" describes a stable production level where the pace of capital depreciation hinders process efficiency. To improve techno-economic indicators, it is necessary to either introduce radically new technologies, achieve a breakthrough, or significantly increase labor productivity. In this case, the implementation of mechanization without justifying a rational area of operation and optimizing operational parameters will not improve the situation. This scenario corresponds to the attempt to technically re-equip coal mines in Ukraine from 2005 to 2009 when the lack of approaches to selecting equipment based on operating conditions prevented an increase in the daily coal production rate.
- "Scenario *III*" involves a transition from stability to crisis, describing a production level where innovations do not contribute to improving production efficiency. Accumulation of substantial funds in enterprises hinders productivity enhancement. This situation may arise in Ukraine when the indicators of average daily output in ore processing increase to 3200 tons/day (as of 2012, it was 847 tons/day, currently lower), and there is a need for foreign counterparts of equipment if they fail to ensure productivity exceeding 8000 tons/day [34]. The transition from stability to crisis will occur in such a scenario. Therefore, for the mining-geological conditions of the Donbas region, innovations will either involve the implementation of new technologies significantly boosting productivity or further optimization of the technological process [35, 36].

To maintain stability, continuous operational management of production should be carried out, aiming to minimize risks and losses. To achieve this, it is necessary to identify the key factors in forming and reproducing internal reserves. We have proposed a methodology for assessing the utilization of internal technological resources in mines, considering the main factors of the production function. Additionally, results regarding the model verification for the Luhansk region are presented [37].

Methodology for assessing the utilization of internal technological resources

The methodology for assessing the utilization of internal technological resources in mines is designed to identify production resources that are not being utilized (reserved). The establishment of such a regulating mechanism will allow for a comparison of mine capabilities based on key parameters (advancement of workings, concentration level of mining operations, labor productivity of the extraction worker). The results of the calculation are presented in Table 1.

Table 1

Calculation of economic reliability parameters for the Dovzhansko-Rovenetska group of mines

Mines	Reliability Components			Economic Reliability
	Technological	Economic	Geological	
"Komsomolska"	0,4	0,13	0,68	0,72
"Partyzanska"	0,9	1,16	0,49	1,55
No. 81 "Kyivska"	0,7	0,86	0,59	1,20
Named after Frunze	0,5	0,49	0,61	0,83
Named after Cosmonauts	0,7	0,76	0,52	1,07
1-2 "Rovenkivska"	0,3	0,41	0,58	0,71
Named after Dzerzhinsky	0,9	0,86	0,46	1,20
"Centrosoyuz"	0,9	1,0	0,46	1,36
"Luhanska"	0,5	0,41	0,2	0,40

Table 2 presents the overall scheme for constructing a direct and dual economic-mathematical model. The goal of this model is to minimize production costs and determine the efficiency of using each technological resource.

In Table 2, U_i represents the objectively determined assessment of a specific technological resource; C_i is the cost of 1 ton of finished coal production; V, K, and P are the respective parameters for advancing the mining faces, the level of concentration of mining works, and the labor productivity of a worker in coal extraction per 1 ton.

The calculation is performed as follows:

1. Enter the initial data into Microsoft Excel.
2. Define the objective function with the aim of minimizing extraction costs.
3. Introduce and set constraints on the enterprise's resources.
4. Calculate the optimal level of extraction.

Table 2

Modeling Initial Data

Direct problem						
№	Resource Name	Costs per 1 ton				
		1	2	...	*n*	Resource constraints
1	Advancement of longwalls, m/month	v_{11}	v_{12}	...	v_{1n}	V
2	Concentration level of the processing line per 1 km of supported output, m	k_{21}	k_{22}	...	k_{2n}	K
3	Labor productivity, t/month	p_{31}	p_{32}	...	p_{3n}	P
4	Coal cost, UAH	C_1	C_2	...	Cn	*min*

Dual Problem			
Resource Names			Resource constraints
Advancement of longwalls, m/month	Concentration level of the processing line per 1 km of supported output, m	Labor productivity, t/month	
v_{11}	k_{21}	p_{31}	C_1
v_{12}	k_{22}	p_{32}	C_2
...	...	...	
v_{1n}	k_{2n}	p_{3n}	C_n
U_1	U_2	U_3	*max*

5

Having the results of solving the direct and dual problem, it is possible to assess the efficiency of the mine's operation (Table 3).

A comprehensive evaluation across the four specified directions allows minimizing the objective function based on only one indicator, even if it is relatively synthetic, such as the cost of coal extraction. Additionally, an assessment based on technical characteristics, including the production capacity of the enterprise and remaining geological reserves, is deemed insufficient [38, 39].

We found it practical and convenient for practical use to compose three components of the quantitative assessment of the mine's technological scheme (*V*, *K*, and *P*) and adjust their sum with the parameter *E* - the probability of the enterprise's evolutionary development. In other words, the structure of the mine's technological scheme passport can be represented as $M_i=(V_i+K_i+P_i)E_i$.

The results of the calculations are presented in Table 3.

Table 3

Level of "objective-oriented " assessments of resource utilization degree

Mine	Concentration of work, 1/1000 t	Advancement of longwalls, m/1000 t	Labor productivity, t/1000 t	Objective-oriented assessment
«Shakhtarska Hlyboka»	12,1	2,00	1,10	0,91
«Progress»	14,0	1,32	0,9o	1,95
«Zorya»	14,3	1,30	0,65	0,95
«Komsomolska»	9,4	1,33	0,08	3,80
«Partyzanska»	9,8	1,90	0,04	0,82
No. 81 "Kyivska"	6,3	1,30	0,70	1,73
Named after Frunze	10,7	1,15	0,43	5,28
Named after Cosmonauts	11,2	1,33	0,74	1,56
1-2 "Rovenkivska"	7,3	1,66	0,10	0,74
Named after Dzerzhinsky	8,8	1,69	0,16	0,80
"Centrosoyuz"	8,90	1,32	0,69	1,85
"Luhanska"	9,2	2,00	0,08	0,70

Table 4 presents the characteristics of the technological scheme passport for 12 anthracite mines.

Thus, by collectively using these indicators, it is possible to quantitatively assess the capabilities of providing the specified production volumes with this technological scheme. Additionally, the level (passport) of the technological scheme allows assessing the investment level needed to support each ton of installed capacity.

Table 4

Potential of technological schemes for the group of anthracite mines

Mine	Components of the technological passport potential				Level of the techno-logical scheme passport
	Probability		Reliability		
	Evolutionary	Innovative	Econom-ic	Resource	
«Shakhtarska Hlyboka»	0,68	2,53	0,91	1,34	3,25
«Progress»	0,78	2,53	1,95	1,33	4,53
«Zorya»	0,35	1,95	0,95	0,72	1,27
«Komsomolska»	0,80	3,65	3,80	0,72	6,54
«Partyzanska»	0,25	2,34	0,82	1,55	1,18
No. 81 "Ky-ivska"	0,81	3,37	1,73	1,20	5,10
Named after Frunze	0,87	3,70	5,28	0,83	8,53
Named after Cosmonauts	0,82	2,90	1,56	1,07	4,53
1-2 "Roven-kivska"	0,28	1,76	0,74	0,71	0,90
Named after Dzerzhinsky	0,61	1,73	0,80	1,20	2,27
"Centrosoyuz"	0,69	4,26	1,85	1,36	5,15
"Luhanska"	0,03	1,43	0,70	0,40	0,08

The interest is sparked by the extreme values of the technological scheme's quality and its passport components. In the real conditions of the coal industry in Ukraine, for mines of the first type, the economic reliability parameter can reach a level of 2.0 [35]. The level of the innovative component reaches a value of 6.0, while the resource utilization level is 3.0. Considering that the probability of evolutionary development cannot exceed 1.0, the highest level of the technological scheme for Ukrainian mines can be calculated as (2+6+3)*1.0=12.

While this example is not conclusive evidence, it provides a basis to assert that in actual conditions, the maximum level of the privatization passport should not exceed 10-12 points. The closer this indicator is to 10, the more attractive the mine is for privatization and corporate development of reserves, requiring fewer expenses for each ton of capacity increment.

The essence of the technological passport lies in its ability to offer a comprehensive evaluation of the mine based on its technical level and the manifestation of topological features, including solutions for diversification of mining production, such as the processing of mining waste and beneficiation plants. Thus, the obtained tool is versatile and applicable in the conditions of mines operated by PJSC «DTEK Pavlogradvuhillia".

Conclusions

This work has introduced a novel approach to assess the innovative prospects of exploiting coal deposits. A comprehensive methodology was applied, relying on the incorporation of neoclassical production functions in the form of the Solow model for analyzing the state of the coal mining industry. Additionally, economic reliability was considered to develop recommendations for enhancing techno-economic indicators. It was established that the efficiency of enterprise functioning can be evaluated by the ratio of input (capital) to output (production level) resources, with a significant emphasis on the innovative component. Analyzing the relationships between these resource flows enables the selection of optimal development scenarios and the formulation of principles for designing production at various stages of development.

For the analysis of sustainable development prospects of the technological scheme of a mine, simulation modeling was employed to assess the dynamics of changes in the volume of reserves prepared for extraction. This approach practically aligns the simulation model with optimal programming models, making it versatile for analyzing the rules of mine object actions and their structures.

The comprehensive assessment of the state of the mine's technological scheme along four directions significantly increases the objectivity of the final results compared to using only one indicator, even if that indicator is relatively synthetic, such as the cost of coal production. Therefore, based on the obtained results, it can be argued that the maximum level of the privatization passport for the technological scheme, in real conditions, does not exceed 10-12 points. The closer this indicator is to 10, the more attractive the enterprise is for privatization and corporate development, with lower costs for each ton of capacity increment.

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