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RESEARCH ON DIVERSIFICATION SCENARIOS BASED ON COBB-DOUGLAS MODEL FOR COAL MINING ENTERPRISES

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ABSTRACT

This paper presents the research results of coal mining diversification scenarios. To achieve the purpose set, the Cobb-Douglas model is used, which takes into account the productive flows of a coal mine (coal, methane gas, rock, water). An algorithm for studying production scenarios has been developed, which includes the function logarithmization, determining elasticity coefficients, and studying scenarios. Four production scenarios have been analyzed, taking into account different production situations from the mutual influence of productive flows to the state when there is no coal mining. The obtained models have been validated for linear homogeneity. Coal as a productive flow has been found to have negative elasticity, which indicates direct influence on the efficiency level; that is, if it does not correspond to the rational level of mining, there is an uncontrolled curtailment in production capacity. The rock, like methane gas, has positive elasticity, indicating a constant return regardless of production volumes. Water has zero elasticity; however, in the absence of coal mining, it is the second most promising productive flow. Based on the scenario modeling, it has been found that under conditional production profitability of coal mining, the configuration of productive flows is constant, but when the level is reached. In the absence of coal mining, the most promising scenario is the recycling of coal mining waste. The hypothesis on the distribution of productive flows is confirmed by the AHP, PROMETHEE, ELECTRE, and VICOR hierarchy analysis methods. Appropriate software has been developed to implement the approach.

Keywords: decision support system, technological parameters, optimization, network model, hierarchy analysis methods, productive flows.

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INTRODUCTION

Diversification of business activities is an indispensable process in the evolution of coal enterprises. Diversification refers to the expansion of an enterprise's output to penetrate new activities and develop new types of production [1]. There are several scenarios for coal mining enterprises. These scenarios include the use of thermal and water resources [2, 3], coal seam gasification technology [4, 5], the use of rock mass energy [6, 7], beneficiation of mining waste [8], use of coal mining waste as raw materials for construction [9], creation of cultural complexes based on abandoned mines [10], construction of systems of alternative energy sources within the boundaries of an enterprise [11, 12].

There are a number of factors that encourage the creation of a model for studying diversification scenarios of coal mining enterprises. First, quality determines the feasibility of a scenario [13]. Quality is a philosophical category that refers to a set of characteristics regardless of the state [14]. In other words, the feasibility of mining a mineral is determined by the cost per tonne of rock mass. And depending on the cost, it is possible to choose scenarios, whether it is comprehensive mineral extraction from the rock mass or minimization of production waste. Secondly, the overall scenario cannot depend on the efficiency of a single process or the resulting decision [15]. For example, when mining coal, methane gas is released, rock is mined, and water is filtered into the underground space. These factors are, at first glance, complicating factors. This is true when considering in terms of ensuring safe working conditions on the gas factor [16], reducing water inrush into the underground space [17], and reducing the amount of rock raised to the surface [18]. However, the study [19] has proven that rock and gas have “positive elasticity” and due to this, it is possible to consider them as productive flows. That is why, in [20], productive flows of coal enterprises have been studied. Despite the scientific novelty of the research and its value, the recommendations and models obtained are proposed for operating and stably working enterprises.

A systemic crisis in the coal industry of Ukraine has emerged since the beginning of the 21st century [21, 22]. With the beginning of active military operations on the territory of Ukraine and, as a consequence, the destruction of the infrastructure of enterprises, the diversification scenario becomes inevitable. The search for decision-making tools is a complicating factor.

Based on a retrospective analysis of decision-making methods in the mining sector [23], three stages can be distinguished: the first stage (50s-80s of the 20th century), the second stage (90s of the 20th century - 10 years of the 21st century), and the third stage (from 2010 to the present). The first stage is characterized by the use of classical methods and decision-making models, which involve searching for an optimal decision in accordance with the parameter characteristics and restrictions [24, 25].

At the second stage of development of decision-making methods, quality indicators are widely implemented [26, 27]. That is, the resulting decision should be based on expert opinion. According to the expert opinion, the criteria are ranked hierarchically, within a hierarchy of priority, which further forms the overall assessment [28]. These methods are derived from the hierarchy analysis method [29] and, depending on the characteristic of the criterion (how it changes (linearly, logarithmically, exponentially, etc.), integer or fractional, absolute or relative, etc.), have different decision-making procedures [30, 31]. It is no longer a question of searching, but of making a decision. The decision is no longer optimal; it can be a compromise, Pareto-optimal, sufficient, rational within the limits set, acceptable for a certain expert group, or even high-quality from the point of view of business strategy [32]. At the third stage, the overall criterion is quality [33], and the search for a decision is based on considering scenarios and partitioning the macro task into micro ones [34, 35]. This is primarily because existing computing power makes this possible.

Thus, according to the analysis of works [23-35], it is possible to form requirements for the method of searching for the decision-forming scientific-practical research significance:

- To find the optimal decision, all productive flows should be considered, and their interrelationships should be taken into account. In other words, each ton of coal generates a certain amount of methane gas (depending on the coal seam gas capacity), rock (depending on the number of rock interlayers), and water (depending on the water capacity of the seam and adjacent rocks).
- It is necessary to explore alternative scenarios in the activities of enterprises. That is, scenarios should be developed: a) if all four flows (coal, gas, rock, water) determine the total economic effect; b) if the main flow, coal, is not available and the economic effect should be maximised; c) when there are different levels of the main flow - coal, that is (300 thousand tons/year for unprofitable enterprises; 600 thousand tons/year - for conditionally profitable; over 1000 thousand tons/year - for profitable).
- It is necessary to propose a decision support system, that is, the resulting method should not only be reliable, but also allow for a quick decision to be made without requirements to the decision-maker's qualification.
- Solving these problems will make it possible to recommend effective production diversification scenarios.

MATERIALS AND METHODS

Before outlining the general statements of the mathematical model, a description of the research area should be given. The scope of research is coal-mining enterprises of Ukraine, Eastern European countries (the Republic of Poland, the Czech Republic, the Republic of Slovakia), as well as those countries where coal is mined underground. The considered mines are characterized by the presence of a total or partial set of productive flows, that is, adverse hydrogeological conditions are probable, the presence of rock interlayers, and the presence of methane gas accumulations. Different sets of parameters or only a few may be taken into account.

The proposed model should comply with the following requirements:

a) The level of profit is the main criterion. This is not surprising that the activities and feasibility of the enterprise's existence depend on economic factors.
b) The model should be “elastic”. The term “elasticity” refers to the consideration of the influence of all productive flows on the level of the optimality criterion. Elasticity can be positive and negative. Positive elasticity means an unambiguous increase in the level of profit from an increase in flow volume [36], while negative elasticity means the presence of a restriction on the level of productive flow, that is, an increase in volume is reasonable according to a certain limit. With zero elasticity, the productive flow does not influence overall economic efficiency. “Zero” elasticity is common in mining operations, since the water inrush is conditionally constant and, regardless of the stage of the enterprise's development, there is a need for pumping out water. Even after the mine is closed, the water must be pumped out.
c) The mutual influence of flows should be taken into account. This was noted in the introduction.
d) Alternative scenarios need to be analyzed, namely: a) all productive flows are available; b) there is no main productive flow; c) one of the auxiliary productive flows is missing; d) different productive flow levels. The “main” productive flow refers to coal, since mining is now underway. “Auxiliary” refers to alternative productive flows: rock, methane gas, water.
e) The model should take into account the diversity of production levels and the potential for increasing the volumes of auxiliary productive flows.

The Cobb-Douglas model is used to develop the model [37, 38]. This model takes into account the total profit level depending on the number of productive flows and their elasticity [39]. In general terms, the Cobb-Douglas model can be described by the formula:

$$P = A \times C^{\alpha} \times M^{\beta} \times R^{\gamma} \times W^{\delta} \tag{1}$$

where P - is the profit level, monetary units; A - is the dimensionless scale factor; α, β, γ, δ, - elasticity of the respective flows, C - coal, M - methane, R - rock, W - water.

Formula (1) for the profit maximization case can be written as follows:

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$$\log(P) = \log(A) + \alpha \log(C) + \beta \log(M) + \gamma \log(R) + \delta \log(W) \quad (2)$$

Based on formulas (1)-(2), an algorithm for studying production diversification scenarios can be determined:

a) First, it is necessary to use logarithmization to represent the function (1) in the form of a linear formula. In the general definition, the Cobb-Douglas function is piecewise linear, but in most cases, logarithmization yields a linear function, which greatly simplifies the analysis.
b) Based on regression analysis, determine the elasticity coefficients.
c) Based on the coefficients, the maximum value of profit P can be calculated for different configurations of productive flows.

In the presented research, we analyse 4 scenarios. The first corresponds to the current production situation, when the volumes of productive methane and rock flows are formed by the level of coal mining. The second is that there are no restrictions on the level of rock and gas production; that is, methane production and rock beneficiation can be conducted in parallel. The third is to maximise profit and reduce the output of coal mining. Fourth - there is no coal mining, there are only auxiliary flows.

In the main part, the algorithm should be executed, and scenarios should be explored.

RESULTS

At the first stage, it is necessary to perform a logarithmization of expression (2) for the given four scenarios. Figures 1-3 show the results of logarithmization and the resulting dependences.

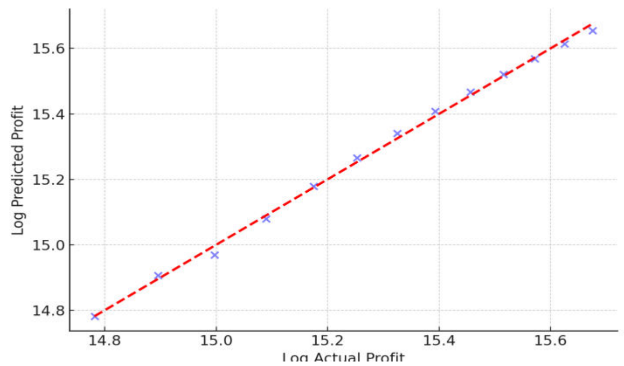

Figure-1. Graph of a change in overall production efficiency when forming the level of productivity flows of rock and methane gas through the main productive flow.

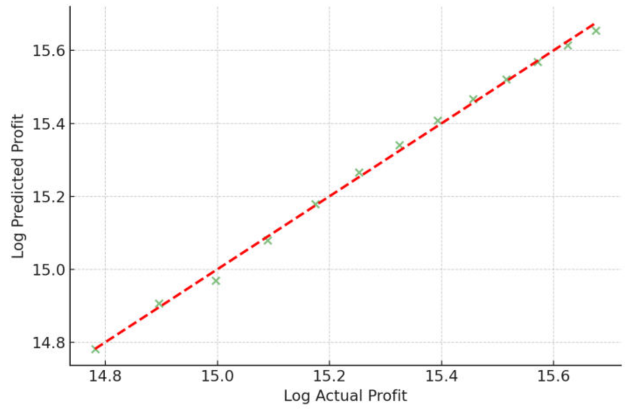

Figure-2. Graph of a change in overall production efficiency in the absence of restrictions on auxiliary productive flows.

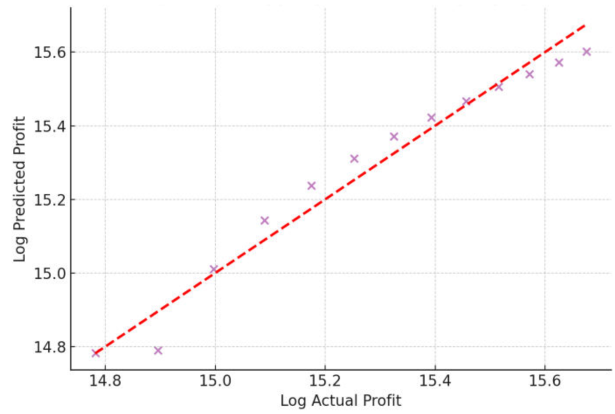

Figure-3. Graph of a change in overall production efficiency in the absence of the main productive Flow-coal.

As can be seen from Figures 1-3, the resulting model can be approximated by a linear function, and the approximation coefficient is R^2=0.96.

Based on logarithmization and regression analysis, the elasticity coefficients have been obtained (Table-1).

Table-1. Elasticity coefficients for different production diversification scenarios.

Productive flow	Scenarios 1 and 3	Scenario 2	Scenario 4
Coal	-44.72	-44.78	0.00
Methane	7.45	7.47	0.27
Rock	38.23	38.20	0.60
Water	0.00	0.00	0.00
Sum	1.00	0.98	0.97

As can be seen from Table-1, the sum of elasticity coefficients is equal to 1 or close to one. This indicates that the resulting model is linearly homogeneous,

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that is, there is a constant return when production volumes and productive flows change.

The negative elasticity for coal in Scenarios 1 and 3, as well as 2, may indicate a decrease in profit when the output of coal mining increases. This result may be data specific or reflect certain economic conditions.

Methane and rock have a positive elasticity, indicating a positive influence on profit.

Water has zero elasticity in all scenarios, indicating no influence on profit in this model.

In Scenario 4, where coal is not included, methane has very little positive elasticity, while rock has a positive elasticity. This indicates that in the absence of coal mining, a promising direction is the recycling and beneficiation of coal mining waste in the form of rock.

Based on the comparison of productive flows using the AHP method, it has been found that coal and water have the greatest advantage. This is not surprising that coal is the main productive flow and the overall efficiency depends on it, while water is a constant productive flow and is the most environmentally sound.

Based on the PROMETHEE method, it has been found that coal and rock do indeed tend to negative elasticity, that is, the overall production efficiency depends on the volume of mining.

Based on the ELECTRE method, the hypothesis about the elasticity of coefficients in the model based on the Cobb-Douglas function has been confirmed.

Based on the VICOR method, it has been found that when the main flow decreases, it is the rock recycling that is the most feasible diversification scenario.

To confirm the hypotheses about the elasticity of productive flows, a flow analysis has been performed using four decision-making methods [40-45]: AHP, PROMETHEE, ELECTRE, VICOR (Figure-4). The AHP method considers the weight of the criteria and provides a clear structure for assessing alternatives, but it can be sensitive to the choice of weights [46, 47]. The PROMETHEE method takes into account the advantages between alternatives and can take into account different types of advantage functions. The ELECTRE method uses agreement and disagreement matrices, which allow the advantages and disadvantages of alternatives to be considered. The VIKOR method takes into account both maximizing advantages and minimizing disadvantages, which allows for a compromise between alternatives [48, 49].

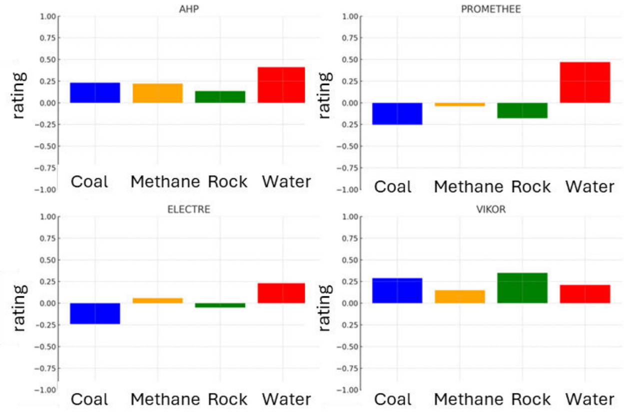

Figure-4. Summary analysis of productive flows using four methods of hierarchy analysis.

To automate the process of analyzing production scenarios, software has been developed. Figure-5 shows the working window of the program. The program allows you to specify levels of change in productive flows. Scenarios are also analyzed automatically. The results of the analysis of scenarios 1, 2, and 4 are displayed in the working window immediately. And also in increments of 50 thousand tons, the results of Scenario 3 - that is, a gradual reduction in coal mining and redistribution of productive flows, are displayed (Figure-6).

Based on the study of the scenario of a gradual reduction in coal mining [50, 51], we see that at the first stage, the configuration of productive flows remains almost unchanged - up to the production level of 300 thousand tons/year - the level of uncontrolled curtailment in production capacities. With a reduction in coal mining, the flow-rock is the most promising, and in second place is water (Figure-7).

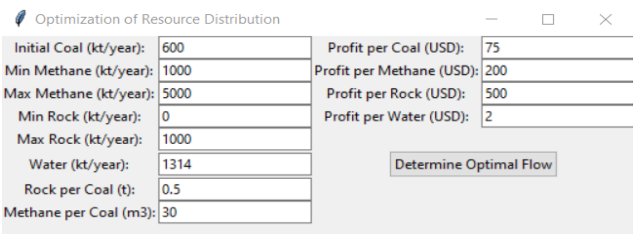

Figure-5. Working window of the program for studying production diversification scenarios.

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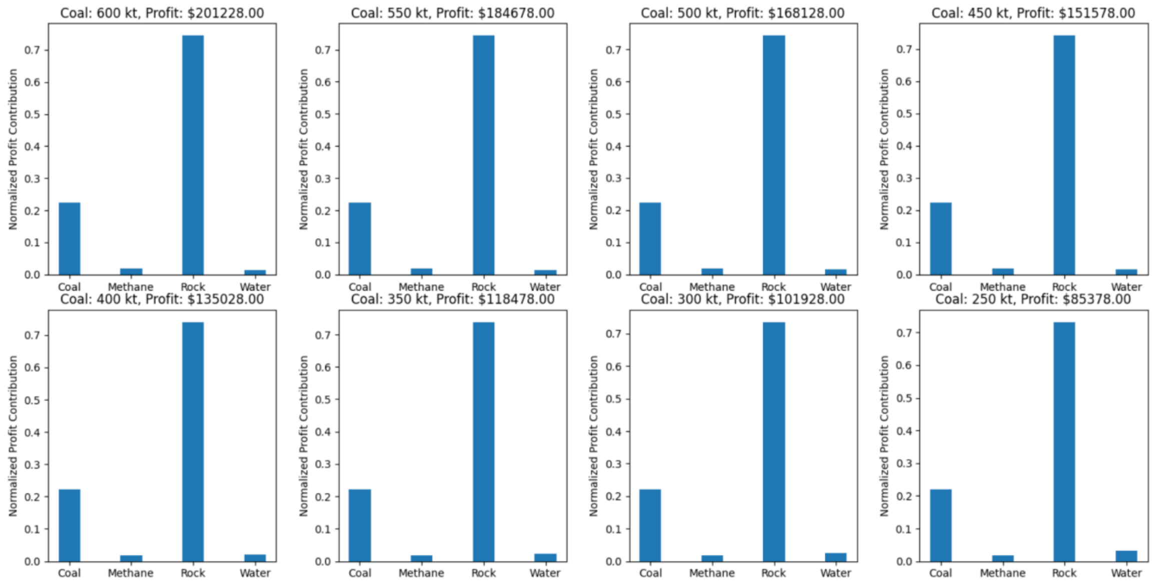

Figure-6. Fragment of the scenario analysis for a gradual reduction in coal mining and achieving economic efficiency through auxiliary flows.

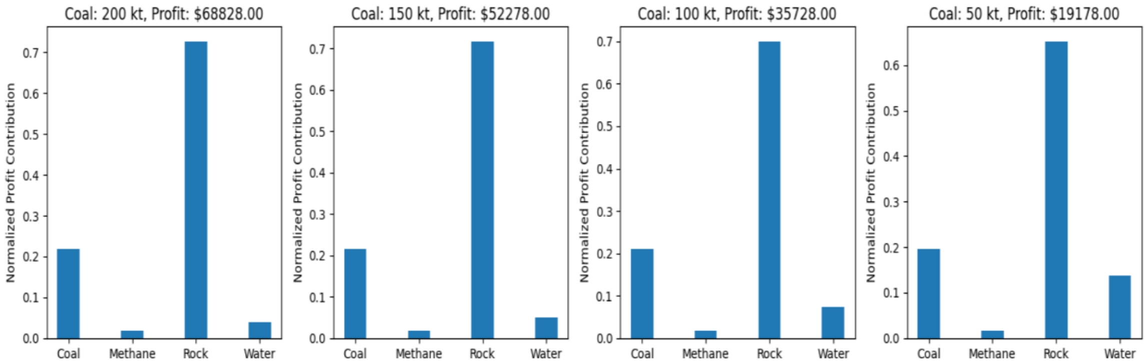

Figure-7. Fragment of the scenario analysis for a gradual reduction in coal mining and achieving economic efficiency through auxiliary flows at the final stage.

Thus, the study of different production diversification scenarios allows us to assert that rock recycling is a promising productive flow, but only after reducing the level of coal mining to an economically unviable level. Wastewater treatment is also a promising direction, because it is a productive flow with zero elasticity, that is, it does not have a negative influence on the level of production efficiency, but has potential for growth.

CONCLUSIONS

The study of different production diversification scenarios for coal mines has revealed that each productive flow: coal, gas, rock, water, has some influence on the overall economic efficiency. However, this influence varies depending on the production scenario. The level of influence is determined by the elasticity coefficient. For coal, the elasticity coefficient is always negative. This is explained by the fact that auxiliary flows are also dependent on coal mining. Moreover, economic efficiency is only possible with a reasonable mining level. A study of scenarios for a gradual reduction in coal mining has determined that at the production level of 300 thousand tons/year, there is an uncontrolled curtailment of production capacities, and the main scenario is rock recycling. Methane gas has positive elasticity; however, scenario modeling shows the futility of switching mine operations solely to methane pumping. This is explained by high pumping costs, as well as the variability of the localization of methane accumulations. Rock has positive elasticity and can definitely become an effective mechanism for ensuring the stability of the enterprise in the context of diversification. Water, despite its zero elasticity, is a significant productive flow and, in the absence of coal mining, is a source of additional profit.

The linear dependences obtained in the paper have been validated for homogeneity. Based on the analysis results, the elasticity coefficient values have been confirmed, which indicates the reliability of the results obtained in the paper.

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