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PERFORMANCE ANALYSIS OF TRANSPORT SYSTEMS IN THE SIBOVC SURFACE LIGNITE MINE BASED ON THE AHP-PROMETHEE APPROACH (KOSOVO)

Purpose. To evaluate the performance of continuous, truck-shovel and hybrid transport systems in the Sibovc surface lignite mine using an integrated multi-criteria decision-making framework and to determine the most appropriate technological alternative under variable geological and operational conditions.

Methodology. The study applies an integrated AISM-AHP-PROMETHEE framework. The AISM approach was used to structure the decision-making problem and define the evaluation criteria. AHP was applied to determine criterion weights, while PROMETHEE was used to rank the alternatives. Three systems were considered: continuous BWE, truck-shovel and hybrid BWE+TS. The assessment was based on a consolidated 3×9 decision matrix including effective capacity, plan fulfillment, availability, OPEX, energy consumption, CO_2eq emissions, flexibility, HSE performance and outages. The criteria were classified as benefit or cost indicators, with calibrated preference and indifference thresholds.

Findings. The PROMETHEE ranking showed that the HYBRID BWE + TS system is the most preferable alternative for the Sibovc mine. The final ranking was HYBRID BWE + TS > BWE > TS. The hybrid system obtained the highest positive flow and the only positive net outranking flow, $\phi = +0.220$, while the BWE and TS systems obtained $\phi = -0.055$ and $\phi = -0.165$, respectively. Its advantage is mainly associated with operational flexibility, higher availability and reduced outage intensity.

Originality. The study adapts the AISM-AHP-PROMETHEE approach to the operational conditions of the Sibovc surface lignite mine by integrating production, economic, energy, environmental, flexibility and HSE-related criteria into a unified decision-making framework. The use of calibrated thresholds and criterion contribution analysis enables justification of the hybrid system's priority through engineering interpretation.

Practical value. The results can support technological and investment planning in surface lignite mines. For the Sibovc mine, the hybrid system should be considered a gradual, selective solution, with the continuous BWE system remaining the primary production basis. At the same time, truck-shovel equipment is used in critical areas requiring additional flexibility. The framework can also be adapted to other surface lignite mines with similar geological and operational conditions.

Keywords: *surface lignite mine, Sibovc mine, bucket-wheel excavator, truck-shovel system, hybrid transport system, multi-criteria decision-making*

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Introduction. In countries where electricity is generated from fossil fuels, surface coal mining remains one of the most complex and strategically important activities in the mining industry. In Kosovo, lignite is not only the main raw material for energy production but also an important factor in economic, political and social stability, since more than 90 % of electricity is generated by thermal power plants supplied directly from the Kosovo lignite basin [1]. Therefore, the performance of the technological exploitation system has a direct influence not only on mining efficiency, but also on energy security, environmental management and socio-economic

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development. In this context, the environmental dimension of mining technologies should also be considered alongside land-use transformation, ecosystem functions and post-mining restoration priorities [2, 3]. In this context, environmental and industrial safety considerations during subsoil development also support the need to include ecological and HSE-related indicators in the evaluation of mining technological systems [4]. Environmental risk assessment in Kosovo mining regions also confirms the relevance of including environmental indicators in technological evaluation frameworks [5]. In a broader mineral-resource context, the evaluation of mining technologies should also be linked with systematic monitoring of the mineral resource base and the increasing role of strategic and critical minerals in raw material security and investment planning [6, 7].

The Kosovo coal basin is characterized by a complex geological and tectonic structure, expressed through heterogeneous lithological formations, variable geotechnical properties and spatial changes in overburden and lignite layers. Modern surface mines operate with heavy equipment, high production targets and strict requirements for coordinating excavation, transport, maintenance and environmental protection processes. Under such conditions, the difference between planned and actually achieved capacities can be considerable [8]. International mining practice also confirms that deviations between nominal and realized capacities are common in surface mining and are usually associated with geological limitations, insufficient coordination of work cycles, unplanned technical stoppages, changes in haulage distances, restrictions of mining fronts, and environmental or legal constraints [9, 10].

For this reason, the optimization of exploitation and transport systems in surface lignite mines cannot be reduced to a one-dimensional analysis based only on production capacity, operating cost or equipment productivity. The real mining system includes a set of interrelated technical, economic, energy, environmental, safety and organizational parameters. Consequently, selecting a technological system requires an integrated decision-making approach that balances engineering performance with the practical constraints of mine operations.

Analysis of recent studies and publications. The technological development of surface lignite exploitation has traditionally been associated with two main groups of systems: discontinuous systems based on truck-shovel operations and continuous systems based on bucket-wheel excavators and belt conveyors [9]. Continuous systems are generally considered suitable for large-scale deposits with stable geometry, high production volumes and standardized operating conditions, since the coordinated operation of flow-transport mechanisms is critical for maintaining stable material movement [11]. Their advantages include high capacity, lower specific operating costs and better energy performance under stable mining conditions. However, their efficiency may decrease in areas with variable geotechnical conditions, restricted working fronts or frequent changes in the direction and organization of mining operations.

Discontinuous truck-shovel systems, in contrast, provide greater operational flexibility and better adaptability to changing mining conditions. At the same time, their efficiency depends strongly on loading and hauling cycle time, equipment coordination and operational delays [12]. At the same time, they are usually associated with higher fuel consumption, higher operating costs, greater dependence on fleet management and route parameters, the technological state of haul trucks [13, 14] and haul road conditions, as well as a higher environmental impact [15]. Between these two technological approaches, hybrid systems combining bucket-wheel excavators, belt conveyors and truck-shovel equipment can be considered a compromise solution. Such systems enable the preservation of the volumetric and energy advantages of continuous mining while leveraging the flexibility of discontinuous equipment in technically difficult or geotechnically constrained areas [16, 17].

The advantages of each system, such as operational flexibility, production capacity or operating cost, may be accompanied by disadvantages related to occupational safety, energy consumption, environmental emissions or geotechnical stability [18, 19]. Therefore, the selection of a technological system for surface mining constitutes a typical multi-criteria decision-making problem, in which criteria are heterogeneous, partly conflicting and measured in different physical and economic units.

The scientific literature proposes a wide range of methods for solving multicriteria decision-making problems in mining, including the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the Analytic Hierarchy Process (AHP), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), fuzzy logic-based approaches, and outranking methods [20, 21]. In addition, the development of expert and decision-support systems in mining confirms the need for formalized tools capable of integrating heterogeneous technical, economic, environmental and safety-related criteria [22]. These approaches are useful for formalizing complex engineering decisions. However, their practical application in mining may be limited if the criteria are treated separately or if technical, economic, environmental and safety dimensions are not integrated into a single decision-making structure [23].

In this context, the PROMETHEE method is of particular interest because it enables direct pairwise comparisons of alternatives, uses preference and indifference thresholds, and preserves the engineering meaning of the criteria without excessive mathematical transformation [24]. The combination of AHP and PROMETHEE is especially relevant for mining problems where the relative importance of criteria must be justified. At the same time, the final ranking of alternatives should reflect the real dominance of one technological solution over another.

Unresolved aspects of the general problem. Despite the significant number of studies devoted to equipment selection, mining method selection and the application of multi-criteria decision-making methods in mining, several aspects remain insufficiently resolved for surface lignite mines operating under variable geological and operational conditions. First, many decision-making approaches still focus mainly on technical or economic indicators, while energy consumption, environmental impact, operational flexibility and HSE-related parameters are not always considered within a single evaluation framework. This creates the risk of selecting a sys-

tem that is optimal according to one criterion but unstable or inefficient under real operating conditions.

Second, the selection of transport systems in lignite mines is often considered separately from the operational variability of the mining field. In the case of the Sibovc mine, massive clay layers, lithological discontinuities and changes in the physical and mechanical properties of materials directly affect the stability of working fronts, equipment availability and production continuity. These conditions require a decision-making model that can evaluate not only nominal capacity but also the technological system's ability to maintain stable operation under constraints.

Third, the practical comparison of BWE, truck-shovel and hybrid BWE+TS systems requires a harmonized matrix of criteria that includes production, planning, operating time, cost, energy, environmental and safety indicators. Without such a matrix, the final decision may depend mainly on expert judgment or on separate operational indicators rather than on a transparent, reproducible analytical procedure.

Thus, the unresolved part of the general problem lies in the need to develop and apply an integrated multi-criteria framework that enables the comparative assessment of continuous, discontinuous and hybrid transport systems under the real operational conditions of the Sibovc surface lignite mine.

Purpose of the article and research objectives. The purpose of this article is to evaluate the performance of continuous, truck-shovel and hybrid transport systems in the Sibovc surface lignite mine using an integrated multi-criteria decision-making framework based on AHP weighting and PROMETHEE ranking.

To achieve this purpose, the following research objectives were formulated:

- to substantiate the need for an integrated assessment of technological transport systems in surface lignite mining under variable geological and operational conditions;
- to define the main alternatives for comparison: the continuous BWE system, the truck-shovel system and the hybrid BWE+TS system;
- to form a consolidated 3 × 9 decision matrix including technical, economic, energy, environmental, flexibility and HSE-related criteria;
- to apply AHP-derived criterion weights and PROMETHEE preference functions for ranking the technological alternatives;
- to interpret the obtained ranking in terms of operational efficiency, production stability, flexibility, energy consumption, environmental impact and practical applicability for the Sibovc mine.

The scientific contribution of the study consists of adapting the AHP-PROMETHEE procedure to the operational conditions of the Sibovc surface lignite mine by integrating production, cost, energy, environmental, flexibility and safety criteria into a unified decision-making framework. The practical value of the study lies in the potential to use the results to support the strategic planning of transport systems in surface lignite mines with similar geological, operational and managerial conditions.

Methods. ***Study area.*** The study was conducted at the Sibovc surface lignite mine in Kosovo, which is part of the Kosovo lignite basin and plays an important role in supplying lignite for thermal power generation. The mine is characterized by large-scale surface extraction, the use of continuous excavation and transport equipment, and variable geological and operational conditions that affect production stability.

The selection of this mine as the study area is justified by the need to evaluate transport system performance under real operating conditions, where production planning, equipment availability, downtime, energy consumption and operational flexibility are closely interrelated. These features make the Sibovc mine suitable for applying a multi-criteria decision-making approach to compare continuous, truck-shovel and hybrid transport systems. The location and satellite view of the study area are shown in Fig. 1.

As shown in Fig. 1, the study area includes active extraction zones, internal transport routes and surrounding land-use elements. This spatial configuration confirms the importance of transport organization in the mine, since the efficiency of material movement depends on the interaction between excavation areas, conveyor-based transport, truck access routes and operational infrastructure.

Therefore, the Sibovc mine represents a suitable case for evaluating technological alternatives not only based on production capacity, but also on flexibility, availability, outage intensity, energy consumption, environmental impact and HSE performance.

Research framework. The methodology of this study is based on the assumption that the optimization of transport systems in surface lignite mining is a multi-criteria decision-making problem within a complex mining system. In the MCDA literature, such problems are addressed using methods that preserve the heterogeneous structure of the criteria and allow alternatives to be compared transparently [25]. The performance of a mining transport system cannot be adequately evaluated by a single indicator only, because it depends simultaneously on productivity, operating cost, energy consumption, environmental impact, operational flexibility, availability and safety. For this reason, the study applies an integrated assessment framework combining AISM, AHP and PROMETHEE. The general sequence of the proposed methodological framework is shown in Fig. 2.

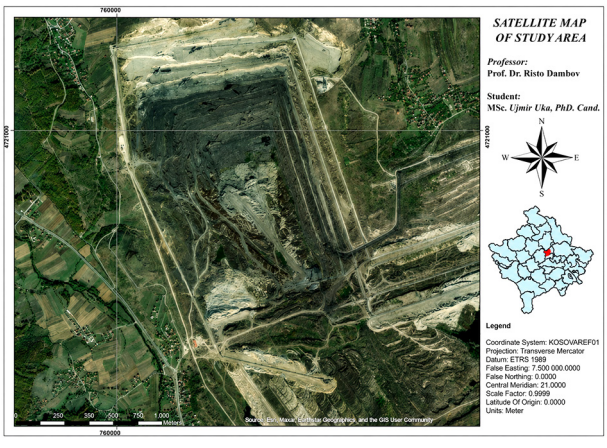

Fig. 1. Location and satellite view of the Sibovc surface lignite mine, Kosovo

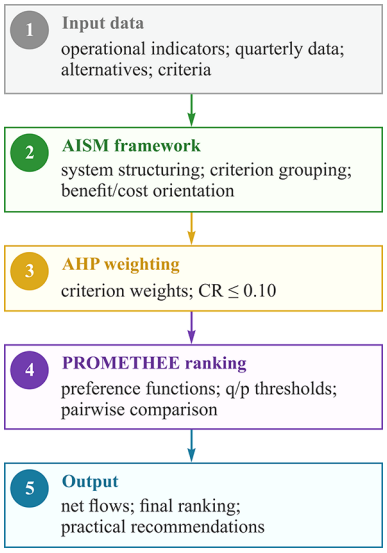

Fig. 2. Methodological framework of the AISM-AHP-PROMETHEE assessment

As shown in Fig. 2, the methodological procedure begins with the formation of the input dataset, including operational indicators, technological alternatives and evaluation criteria. Within the AISM framework, the decision-making problem is structured, the criteria are classified into benefit- and cost-oriented categories, and the assessment logic is defined. The AHP procedure is then applied to determine the relative importance of the criteria. At the same time, the PROMETHEE method is used for pairwise comparisons, the calculation of preference flows, and the final ranking of the alternatives. The framework's final output is the identification of the most appropriate transport system and the formulation of practical recommendations for the Sibovc mine.

Alternatives and evaluation criteria. Three technological alternatives were considered for the Sibovc surface lignite mine:

- A1 – BWE, representing the continuous system based on bucket-wheel excavators and belt conveyors;
- A2 – TS, representing the discontinuous truck-shovel system;
- A3 – HYBRID BWE+TS, representing the combined system in which the continuous system is supplemented by truck-shovel equipment in operationally difficult or geotechnically constrained areas.

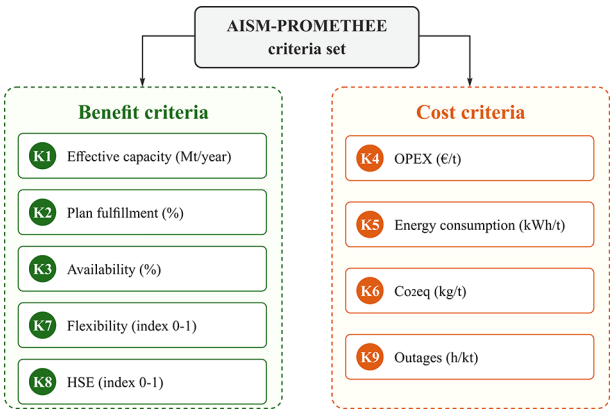

Fig. 3. Structure of benefit and cost criteria used in the AISM-PROMETHEE assessment of transport system alternatives

The criteria were selected to reflect the main dimensions of transport system performance in surface lignite mining. They include production capacity, plan fulfillment, availability, operating cost, energy consumption, environmental impact, operational flexibility, HSE performance and outage intensity. The inclusion of HSE performance is consistent with risk-oriented approaches to transport system assessment, where incident risk is considered through the interaction of technical, organizational and human factors [26]. Each criterion was assigned either a benefit or cost orientation (Fig. 3). For benefit criteria, higher values indicate better performance. For cost criteria, lower values indicate better performance.

As shown in Fig. 3, the evaluation criteria were divided into two groups according to their preference orientation. The benefit criteria include effective capacity, plan fulfillment, availability, flexibility and HSE performance, where higher values indicate better performance. The cost criteria include OPEX, energy consumption, CO_2eq emissions and outages, where lower values are preferred. This classification was used in the PROMETHEE procedure to determine the direction of preference for each criterion correctly. The use of these nine criteria enabled the formation of a consolidated 3 × 9 decision matrix, where the rows correspond to technological alternatives and the columns to evaluation criteria. The matrix itself is presented in the Results and Discussion section.

Operational basis and preprocessing logic. The empirical basis of the study was derived from consolidated operational indicators for the Sibovc surface lignite mine for the 2024 quarterly periods. These indicators reflect planning, production, operating time, downtime, cost, energy and environmental dimensions of the mining transport system. The values used for the comparative assessment were harmonized into a unified structure so that the continuous, discontinuous and hybrid transport systems could be evaluated under comparable conditions.

The consolidated values used in the decision matrix are within the ranges documented in the annual operational reports of the Sibovc mine and in literature-based models for similar lignite mining conditions. At the preprocessing stage, the indicators were checked according to three principles: the criterion's interpretability, consistency of measurement units and correct assignment to the benefit or cost type. Since the criteria are expressed in different units, such as Mt/year, %, €/t, kWh/t, kg/t and normalized indices, comparability was ensured through criterion typology, weighting and PROMETHEE preference functions rather than by direct comparison of raw values (Table 1).

This preprocessing logic was used to preserve the physical and engineering meaning of the criteria while making them suitable for multi-criteria comparison.

Criterion weighting using AHP. The relative importance of the criteria was determined using the AHP procedure. The use of expert-based approaches is appropriate when strategic and technological decisions depend on heterogeneous indicators and cannot be reduced to a single quantitative parameter [27]. In this study, the

Table 1

Operational basis and preprocessing logic of the evaluation criteria

Criterion	Unit	Operational basis	Preprocessing logic
K1 Effective capacity	Mt/year	Production and planning indicators	Conversion into comparable annualized production capacity
K2 Plan fulfillment	%	Planned and actual production indicators	Ratio between actual and planned production
K3 Availability	%	Operating time and downtime indicators	Share of available operating time in scheduled working time
K4 OPEX	€/t	Operating cost indicators	Specific operating cost per tonne of lignite
K5 Energy consumption	kWh/t	Electricity and fuel consumption indicators	Specific energy consumption per tonne of lignite
K6 CO_2eq emissions	kg/t	Energy use and emission-related indicators	Specific emissions expressed as CO_2eq per tonne
K7 Flexibility	index 0–1	Operational adaptability assessment	Normalized score reflecting the ability to adapt to mining conditions
K8 HSE performance	index 0–1	Safety and operational exposure assessment	Normalized score reflecting safety-related performance
K9 Outages	h/kt	Downtime and interruption indicators	Outage duration normalized per thousand tonnes of lignite

consistency of the weighting procedure was assessed using the consistency ratio (CR), with CR ≤ 0.10 accepted as the admissible limit [23, 28].

The following normalized vector of criterion weights was used

$$w = \{0.18, 0.12, 0.10, 0.14, 0.10, 0.08, 0.10, 0.08, 0.10\},$$

where

$$\sum_{i=1}^{9} w_i = 1.$$

The highest weights were assigned to effective capacity and OPEX, reflecting the importance of production performance and operating costs in assessing transport systems. The remaining criteria were included to account for availability, energy consumption, environmental impact, flexibility, HSE performance and outage intensity.

PROMETHEE ranking procedure. The final ranking of alternatives was performed using the PROMETHEE method. PROMETHEE is an outranking method based on pairwise comparison of alternatives for each criterion. It is suitable for this study because it enables the comparison of heterogeneous indicators and allows the calibration of preference and indifference thresholds to economic and operational tolerances.

Let

$$A = \{a_1, a_2, a_3\} = \{BWE, TS, HYBRID\ BWE + TS\},$$

be the set of alternatives, and

$$C = \{1, 2, 3, 4, 5, 6, 7, 8, 9\},$$

be the set of evaluation criteria. For each criterion i, the performance value of alternative a is denoted as $g_i(a)$, and the criterion weight is denoted as w_i.

For each pair of alternatives (a, b), the deviation for criterion i was calculated according to the criterion type

$$d_i(a,b) = \begin{cases} g_i(a) - g_i(b), & \text{for benefit criteria} \\ g_i(b) - g_i(a), & \text{for cost criteria} \end{cases}.$$

A linear V-type preference function with an indifference threshold q_i and a preference threshold p_i was applied

$$P_i(a,b) = \begin{cases} 0, & d_i \le q_i \\ \dfrac{d_i - q_i}{p_i - q_i}, & q_i < d_i < p_i \\ 1, & d_i \ge p_i \end{cases}.$$

The aggregated preference index of alternative a over alternative b was calculated as

$$\pi(a,b) = \sum_{i=1}^{9} w_i P_i(a,b),$$

where

$$0 \le \pi(a, b) \le 1.$$

The positive outranking flow, negative outranking flow and net outranking flow were calculated as follows

$$\phi^+(a) = \frac{1}{n-1} \sum_{b \ne a} \pi(a,b);$$

$$\phi^-(a) = \frac{1}{n-1} \sum_{b \ne a} \pi(b,a);$$

$$\phi(a) = \phi^+(a) - \phi^-(a),$$

where n is the number of alternatives.

The final ranking was determined according to the net flow $\phi(a)$. The higher the value of $\phi(a)$, the more preferable the alternative.

Preference and indifference thresholds. Preference and indifference thresholds were calibrated according to operational and economic tolerances of surface lignite mining. Differences below the indifference threshold q_i were treated as negligible. In contrast, differences equal to or greater than the preference threshold p_i were treated as sufficient to express a clear preference (Table 2).

The use of these thresholds enabled the ranking to avoid excessive sensitivity to insignificant numerical dif-

Table 2

Thresholds used in the PROMETHEE procedure

Criterion	Unit	q_i	p_i
K1 Effective capacity	Mt/year	0.1	0.3
K2 Plan fulfillment	%	1	3
K3 Availability	%	1	3
K4 OPEX	€/t	0.5	1.2
K5 Energy consumption	kWh/t	0.5	1.5
K6 CO_2eq emissions	kg/t	0.3	1
K7 Flexibility	index 0–1	0.05	0.15
K8 HSE performance	index 0–1	0.05	0.15
K9 Outages	h/kt	0.1	0.4

ferences and to reflect the practical tolerances typical of mining operations.

Results and discussion. ***Consolidated decision matrix.*** The first stage of the results was the formation of a consolidated decision matrix for the comparative assessment of the three technological alternatives considered for the Sibovc surface lignite mine. The matrix includes the continuous system based on bucket-wheel excavators and belt conveyors, the discontinuous truck-shovel system, and the hybrid BWE+TS system. Each alternative was evaluated according to nine criteria reflecting production, operational, economic, energy, environmental, flexibility and safety-related dimensions.

The selected criteria have different physical meanings and units of measurement. Therefore, their direct comparison is not possible without accounting for their criterion types. Effective capacity, plan fulfillment, availability, flexibility and HSE performance were treated as benefit criteria, where higher values indicate better performance. OPEX, energy consumption, CO_2eq emissions and outages were treated as cost criteria, where lower values indicate better performance. The consolidated values used for the multi-criteria assessment are presented in Table 3.

The matrix shows that none of the alternatives has absolute superiority across all criteria. The continuous BWE system demonstrates the lowest OPEX and energy consumption, which confirms its efficiency under stable operating conditions. However, it has the lowest flexibility index among the three alternatives. The truck-shovel system has the highest flexibility value, but it also has higher OPEX, energy consumption, CO_2eq emissions and outage intensity. The hybrid BWE + TS system occupies an intermediate or leading position for most criteria, combining relatively high effective capacity, plan fulfillment and availability with improved flexibility and lower outage intensity compared with the truck-shovel system.

Thus, the consolidated matrix reflects the multi-criteria nature of the technological choice. The final decision cannot be made based on a single indicator, since each alternative has both advantages and limitations. For this reason, the matrix was also used as the input dataset for the PROMETHEE procedure, in which the criterion weights, benefit/cost orientation, and calibrated preference thresholds were taken into account.

PROMETHEE ranking results. After forming the consolidated decision matrix, the PROMETHEE procedure was applied to determine the preference relations between the three technological alternatives. For each pair of alternatives, the preference index $\pi(a, b)$ is calculated by aggregating the weighted preference values over all nine criteria. This index expresses the degree to which alternative a is preferred to alternative b, taking into account the criterion weights, benefit/cost orientation and calibrated preference thresholds. The obtained preference matrix is presented in Table 4.

The values of the preference matrix indicate that the HYBRID BWE + TS system has the strongest pairwise dominance over the other alternatives. Its preference index equals 0.59 against the BWE system and 0.61 against the TS system. This means that, after applying the criterion weights and preference thresholds, the hybrid system demonstrates a more favorable aggregated performance than both the continuous and discontinuous alternatives.

The BWE system shows a moderate preference over the TS system, with $\pi(\text{BWE, TS}) = 0.46$, while the reverse preference $\pi(\text{TS, BWE}) = 0.39$. This indicates that the continuous system has an advantage over the discontinuous system, though it is not dominant across all criteria. In contrast, the TS system has the weakest preference position, especially in comparison with the HYBRID alternative.

Based on the preference matrix, the positive, negative and net outranking flows were calculated. The positive flow ϕ^+ characterizes the extent to which an alternative dominates the other alternatives. The negative flow ϕ^- characterizes the extent to which an alternative is dominated by the others. The net flow ϕ represents the balance between these two values and is used for the final ranking of alternatives.

Since three alternatives were compared, the number of pairwise comparisons for each alternative was $n - 1 = 2$. Therefore, the positive and negative outranking flows were calculated as the average values of the corresponding preference indices from the PROMETHEE preference matrix. The calculated PROMETHEE flows are presented in Table 5 and visualized in Fig. 4.

According to the net outranking flow, the final ranking of the technological alternatives is

$$HYBRID\ BWE + TS > BWE > TS.$$

The HYBRID BWE+TS system achieved the highest positive flow and the only positive net flow, $\phi = +0.22$, confirming its overall priority in the multi-criteria as-

Table 3

Consolidated decision matrix for the three technological alternatives

Alternative	K1	K2	K3	K4	K5	K6	K7	K8	K9
CONT (BWE)	7.40	96.20	88.00	2.80	3.20	4.50	0.35	0.78	0.90
TS	7.50	94.00	85.00	3.60	8.90	7.20	0.85	0.70	1.40
HYBRID (BWE+TS)	7.60	97.00	90.00	3.10	5.10	5.20	0.75	0.82	0.70

Table 4

PROMETHEE preference matrix π(a, b)

Alternative	BWE	TS	HYBRID
BWE	–	0.46	0.41
TS	0.39	–	0.35
HYBRID	0.59	0.61	–

Table 5

PROMETHEE flows and final ranking of alternatives

Alternative	ϕ^+	ϕ^-	ϕ	Ranking
HYBRID	0.600	0.380	0.220	1
BWE	0.435	0.490	–0.055	2
TS	0.370	0.535	–0.165	3

sessment. The BWE system ranked second, with a slightly negative net flow, $\phi = -0.055$, while the TS system ranked third, with the lowest net flow, $\phi = -0.16$. As shown in Fig. 4, the hybrid alternative is clearly separated from the other two systems by its positive net PROMETHEE flow.

Thus, the PROMETHEE ranking shows that the hybrid system provides the most balanced technological solution for the Sibovc mine conditions. Its advantage is not based on absolute superiority in every individual criterion, but on the integrated balance between production performance, flexibility, availability, HSE-related parameters, energy consumption, emissions and outage intensity. This result confirms the need to evaluate mining transport systems as multi-criteria engineering systems rather than as alternatives compared by a single productivity or cost indicator.

Contribution of individual criteria. To clarify the factors that determined the priority of the HYBRID BWE+TS system, the final PROMETHEE result was analyzed in terms of the individual criteria's contributions. This is important because the hybrid alternative's first position does not imply absolute superiority across all indicators. The ranking is based on the cumulative effect of several criteria, in which the advantages in flexibility, availability and outage reduction compensate for the moderate increase in operating cost and energy consumption compared with the purely continuous system.

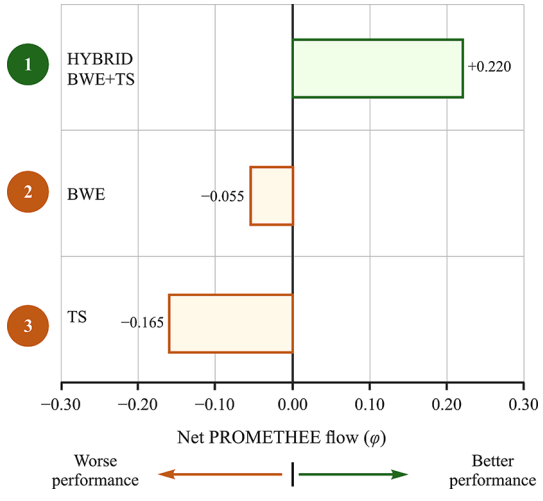

Fig. 4. Net PROMETHEE flow of the evaluated transport system alternatives

For this purpose, the aggregated preference index was decomposed into individual criterion contributions

$$C_i(a, b) = w_i \cdot P_i(a, b),$$

where w_i is the criterion weight; $P_i(a, b)$ is the preference value for criterion i. This decomposition allows distinguishing between determining, supporting and neutral criteria. Therefore, the PROMETHEE result is interpreted not only as a numerical ranking, but also as an engineering justification of the technological choice.

The average criterion contributions for the HYBRID BWE+TS system compared with the continuous and discontinuous alternatives are presented in Table 6 and Fig. 5.

As shown in Table 6 and Fig. 5, the largest contribution to the advantage of the HYBRID BWE+TS system is associated with operational flexibility. Criterion K7 has the highest average preference value and the greatest contribution, confirming its determining role in the final ranking. This is consistent with the hybrid system's technological nature, which combines the high-capacity operation of the continuous BWE system with the adaptability of truck-shovel equipment in geotechnically or organizationally challenging areas.

Availability and outage intensity also play an important role in the final result. Criterion K3 indicates that the hybrid system provides better operational continuity than the alternatives, while criterion K9 reflects the reduction of interruptions per unit of production. These criteria are especially important for the Sibovc mine, where production stability is directly related to the reliability of coal supply to thermal power plants. In this context, the hybrid system does not simply increase flexibility, but also provides a reserve operational mechanism to maintain production when the continuous system is constrained by front conditions, equipment synchronization or local geotechnical constraints.

The contribution of energy consumption and CO_2eq emissions should be interpreted as a balancing factor. The truck-shovel system is penalized by higher fuel and

Table 6

Average criterion contributions for the HYBRID BWE+TS system

Criterion	Type	w_i	$\bar{P}_i$	$\bar{C}_i = w_i \bar{P}_i$	Role
K1 Effective capacity	Benefit	0.18	0.30	0.054	Supporting
K2 Plan fulfillment	Benefit	0.12	0.10	0.012	Neutral
K3 Availability	Benefit	0.10	0.50	0.050	Defining
K4 OPEX	Cost	0.14	0.25	0.035	Supporting
K5 Energy consumption	Cost	0.10	0.45	0.045	Defining
K6 CO_2eq emissions	Cost	0.08	0.35	0.028	Supporting
K7 Flexibility	Benefit	0.10	1.00	0.100	Main determining
K8 HSE performance	Benefit	0.08	0.40	0.032	Supporting
K9 Outages	Cost	0.10	0.60	0.060	Defining
Σ	–	1.00	–	0.416	–

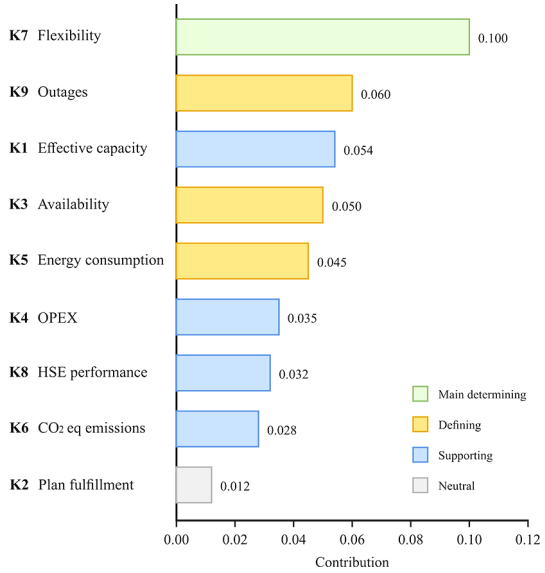

Fig. 5. Criterion contributions to the priority of the HYBRID BWE+TS system

energy intensity, while the hybrid system reduces this weakness by applying discontinuous equipment selectively rather than as the main production system. Therefore, the hybrid configuration limits the disadvantages of the TS system while preserving part of its flexibility. At the same time, it does not fully lose the structural advantages of the BWE system in terms of volume and operational regularity.

OPEX and HSE performance act as supporting criteria. The OPEX criterion indicates that the hybrid alternative does not offer the lowest specific operating cost, as the continuous BWE system remains more favorable under stable conditions. However, the difference in operating costs is offset by greater flexibility, higher availability and reduced outage intensity. The HSE criterion supports the hybrid alternative because the selective use of truck-shovel equipment can reduce the need to force the continuous system in critical areas and enable safer organization of interventions and maintenance.

The effective capacity criterion plays a supporting rather than a determining role. The three alternatives have relatively close effective capacities, so this criterion alone does not explain the final ranking. Similarly, plan fulfillment is interpreted as a neutral criterion, since the differences between alternatives are not sufficiently large to dominate the final result.

Thus, the ranking HYBRID BWE + TS > BWE > TS reflects a real technological compromise. The BWE system remains strong in terms of cost and energy performance, while the TS system provides high flexibility but is limited by higher operating cost, energy consumption, emissions and outages. The hybrid system occupies the most balanced position because it combines the advantages of both approaches and reduces their individual weaknesses under the operational conditions of the Sibovc mine.

The additional pairwise contribution of the hybrid system compared with the continuous system. In addition to the average contribution structure, a separate pairwise decomposition was used to compare the HYBRID BWE+TS system with the continuous BWE system. This comparison is important because the continuous system is the strongest conventional alternative for large-scale lignite mining and remains the main reference point for evaluating the practical value of hybridization (Table 7).

The pairwise contribution table shows that the preference of the HYBRID BWE+TS system over the continuous BWE system is mainly formed by three criteria: availability, flexibility and outages. Criteria K3, K7 and K9 each contribute 0.100, indicating that the main advantage of the hybrid system is not its nominal production capacity alone, but its ability to operate under variable mining conditions.

The OPEX criterion does not favor the hybrid alternative in this pairwise comparison. This means that the continuous BWE system remains more favorable in terms of specific operating cost under stable operating conditions. However, the absence of contribution from K4 is compensated by the strong effects of K3, K7 and K9. In engineering terms, this confirms that the hybrid system gains its advantage through operational stability and adaptability rather than through lower direct operating cost.

The contributions of K5 and K6 indicate that energy and environmental indicators play a moderate role in the comparison. The hybrid system does not fully eliminate the energy-related disadvantages associated with discontinuous equipment, but its selective use of truck-shovel operations helps control them. Therefore, the hybrid system remains more balanced than a fully discontinuous alternative.

Thus, the pairwise comparison with the continuous system confirms the same general tendency as the overall PROMETHEE ranking: the HYBRID BWE+TS system should be interpreted as a compromise solution that partially sacrifices the cost advantage of the continuous system, but gains important operational benefits in flexibility, availability and reduced interruption intensity.

Comparison with literature and operational reality. The evaluation of the obtained multi-criteria ranking should not be based only on the internal mathematical coherence of the PROMETHEE procedure. For this reason, the result was additionally interpreted in relation to the operational conditions of the Sibovc mine and compared with the conclusions of previous studies devoted to equipment selection, energy efficiency and technological organization in surface mining.

The obtained ranking is consistent with studies showing that truck-shovel systems are effective in con-

Table 7

Contribution of criteria in the HYBRID BWE+TS vs continuous BWE comparison

Criterion	P_i	w_i	C_i
K1	0.30	0.18	0.054
K2	0.10	0.12	0.012
K3	1.00	0.10	0.100
K4	0.00	0.14	0.000
K5	0.45	0.10	0.045
K6	0.35	0.08	0.028
K7	1.00	0.10	0.100
K8	0.40	0.08	0.032
K9	1.00	0.10	0.100
Σ	–	–	0.471

ditions where the mining front is variable and operational flexibility is required. However, their use as the primary technological system may be limited by higher operating costs, greater fuel and energy consumption, and greater reliance on fleet organization. This is especially important in lignite mines supplying thermal power plants, where production stability and continuity are critical. Previous studies on loading and hauling operations have also emphasized that energy efficiency depends not only on equipment type, but also on mine planning, haulage distance, operator performance and the organization of work cycles [13].

The second position of the continuous BWE system also corresponds to the general understanding of continuous mining systems in large-scale lignite extraction. Such systems are effective when mining conditions are stable, the deposit geometry is favorable, and the transport line can operate without frequent interruptions. Under these conditions, BWE systems usually provide high capacity, relatively low specific operating costs and better energy performance. However, the operational reality of the Sibovc mine includes geotechnical variability, lithological discontinuities and organizational limitations that can reduce the efficiency of a purely continuous system.

The first position of the HYBRID BWE + TS system agrees with studies indicating that combined configurations may represent a rational compromise when neither continuous nor discontinuous systems alone can simultaneously satisfy production volume, flexibility and operational stability requirements [9]. The hybrid system is particularly relevant for mines where the continuous system should remain the main production base, while truck-shovel equipment is used selectively in areas with difficult geotechnical conditions, restricted front development or temporary interruptions of conveyor-based operation.

In the case of the Sibovc mine, the final ranking is also compatible with the operational logic of lignite supply to thermal power plants. The continuous system remains important for maintaining the required production volume. Still, its effectiveness can be reduced by interruptions related to synchronization between bucket-wheel excavators, conveyor belts and the development of mining fronts. The truck-shovel system provides flexibility, but its full-scale use as the main system would increase energy intensity, OPEX and environmental pressure. Therefore, the hybrid system reflects the actual need to balance volumetric efficiency with adaptability to variable mining conditions.

Thus, the PROMETHEE ranking should be interpreted as an engineering compromise rather than as a formal mathematical result. The priority of the HYBRID BWE + TS system stems from its ability to preserve the structural advantages of continuous mining while mitigating the operational risks associated with limited flexibility. At the same time, the selective use of truck-shovel equipment allows avoiding the main disadvantages of a fully discontinuous system, especially in terms of operating costs, energy consumption and CO_2eq emissions.

Practical implications for the Sibovc mine. The obtained results have direct practical implications for the technological and organizational planning of the Sibovc surface lignite mine. The priority of the HYBRID BWE + TS system does not mean that the continuous system should be replaced by a discontinuous one. On the contrary, the continuous BWE system should remain the main technological basis for achieving annual production volumes, while truck-shovel equipment should be used as a flexible complementary component in critical areas.

From a technological standpoint, implementing the hybrid system should be gradual and selective. The truck-shovel component should be applied where the continuous system encounters local constraints due to geotechnical instability, limited working space, changes in mining front geometry, temporary conveyor interruptions or the need for flexible operational redistribution. Such an approach can reduce the risk of technological overlap and prevent unreasonable increases in capital and operating costs.

From an organizational point of view, the application of the hybrid system requires changes in maintenance, transport management and operational planning, since the efficiency of specialized transport systems depends not only on equipment parameters, but also on the selected management mode [29]. The presence of a flexible truck-shovel component creates reserve capacity that can be used during preventive maintenance, unplanned interruptions or temporary limitations of the continuous system. This can reduce the operational load on the BWE-conveyor system and improve the stability of lignite supply to thermal power plants.

From an economic point of view, the hybrid system should not be assessed only through OPEX per tonne. Although the continuous system may have a lower specific operating cost under stable conditions, the total cost of the mining system should also include losses caused by production interruptions, non-fulfillment of the production plan, equipment downtime and operational risk. In this context, the moderate increase in cost associated with the hybrid system can be justified if it improves production continuity and reduces the consequences of unplanned stoppages.

From an environmental and safety perspective, the hybrid system can help better control operational risks. The selective use of truck-shovel equipment in difficult areas may reduce the need to operate the continuous system under unfavorable conditions. This can improve HSE-related performance by enabling safer organization of maintenance and interventions. At the same time, limiting the use of discontinuous equipment only to areas where it provides real operational value helps control fuel consumption and CO_2eq emissions.

The practical value of the AISM-AHP-PROMETHEE framework is also related to decision-making transparency. The proposed approach allows mine management to compare technological alternatives not only by production capacity or cost, but also by a broader set of operational, energy, environmental and safety indicators. Therefore, the model can be used as a supporting tool for investment planning, technological modernization and the identification of weak points in the existing transport system. Its further application should be based on local operational data and careful calibration of criteria, weights and preference thresholds for each specific mining context.

Conclusions. The study confirmed that selecting a transport system for the Sibovc surface lignite mine

should be treated as a multi-criteria engineering problem rather than a single-criterion optimization task. The performance of the technological system depends not only on production capacity, but also on availability, operating cost, energy consumption, environmental impact, flexibility, HSE performance and outage intensity.

The application of the AISM-AHP-PROMETHEE framework enabled comparison of three technological alternatives: the continuous BWE system, the discontinuous truck-shovel system, and the HYBRID BWE + TS system. The final PROMETHEE ranking showed the following order of preference: HYBRID BWE + TS > BWE > TS. The hybrid system obtained the highest net outranking flow, $\phi = +0.220$, which indicates its overall priority under the considered operational conditions.

The priority of the HYBRID BWE + TS system is not caused by absolute superiority in all criteria. Its advantage is mainly formed by operational flexibility, availability and reduced outage intensity. These criteria are especially important for the Sibovc mine, where stable lignite supply to thermal power plants depends on the mining system's ability to operate under variable geological and organizational conditions.

The continuous BWE system remains effective in terms of production volume, operating cost and energy performance under stable conditions. However, its lower flexibility and higher sensitivity to interruptions reduce its overall preference when geotechnical variability, front limitations and synchronization of conveyor-based operation are considered.

The truck-shovel system provides high operational flexibility, but its full-scale use as higher OPEX, energy consumption, CO_2eq emissions and outage intensity limit the main technological alternative. Therefore, its most rational role in the Sibovc mine is not as a replacement for the continuous system, but as a selective complementary component within the hybrid configuration.

The practical value of the results lies in supporting a gradual, selective implementation of the HYBRID BWE + TS system. The continuous system should remain the main production basis, while truck-shovel equipment should be used in critical areas where additional flexibility is required. The proposed approach can also be adapted to other surface lignite mines with similar geological, operational and managerial conditions, provided that local data, criterion weights and preference thresholds are carefully calibrated.

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Аналіз ефективності транспортних систем на буровугільному кар'єрі Sibovc на основі підходу AHP-PROMETHEE (Косово)

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Мета. Оцінити ефективність безперервної, циклічної й гібридної транспортних систем в умовах буровугільного кар'єру Sibovc із використанням інтегрованого багатокритеріального підходу та визначити найбільш доцільну технологічну альтернативу за змінних геологічних і виробничих умов.

Методика. Дослідження виконано на основі інтегрованої схеми AISM-AHP-PROMETHEE. Підхід AISM використано для структурування задачі прийняття рішень і формування системи критеріїв оцінювання. Метод AHP застосовано для визначення ваг критеріїв, а метод PROMETHEE – для ранжування технологічних альтернатив. Розглянуто три системи: безперервну систему на базі роторного екскаватора й конвеєрного транспорту (BWE), циклічну екскаваторно-автомобільну систему (TS) і гібридну систему BWE+TS. Оцінювання виконано за консолідованою матрицею 3 × 9, що охоплює ефективну продуктивність, виконання плану, доступність обладнання, OPEX, енергоспоживання, викиди CO_2, гнучкість, показники HSE та простої. Критерії поділені на стимулюючі й дестимулюючі з урахуванням каліброваних порогів байдужості й переваги.

Результати. Ранжування за методом PROMETHEE показало, що найбільш доцільною альтернативою для умов кар'єру Sibovc є гібридна система HYBRID BWE + TS. Отримано такий порядок переваг: HYBRID BWE + TS > BWE > TS. Гібридна система має найбільший позитивний потік і єдине додатне значення чистого потоку переваги, $\phi = +0{,}220$, тоді як для систем BWE і TS отримані відповідно $\phi = -0{,}055$ та $\phi = -0{,}165$. Її перевага насамперед пов'язана із вищою операційною гнучкістю, кращою доступністю та зниженням інтенсивності простоїв.

Наукова новизна. Адаптовано підхід AISM-AHP-PROMETHEE до умов буровугільного кар'єру Sibovc шляхом об'єднання виробничих, економічних, енергетичних, екологічних, гнучкісних і HSE-критеріїв у єдину систему прийняття рішень. Використання каліброваних порогів і аналізу внеску окремих критеріїв дозволило обґрунтувати пріоритет гібридної системи не лише за числовим рейтингом, але й через інтерпретацію чинників, що формують її перевагу.

Практична значимість. Отримані результати можуть бути використані для технологічного й інвестиційного планування на буровугільних кар'єрах. Для кар'єру Sibovc гібридну систему доцільно розглядати як поступове й вибіркове рішення, за якого безперервна система на базі роторного екскаватора та конвеєрного транспорту залишається основою виробництва, а обладнання екскаваторно-автомобільної системи застосовується на ділянках, де потрібна додаткова гнучкість. Запропонований підхід може бути адаптований і для інших буровугільних кар'єрів зі схожими геологічними й експлуатаційними умовами.

Ключові слова: *буровугільний кар'єр, кар'єр Sibovc, роторний екскаватор, екскаваторно-автомобільна система, гібридна транспортна система, багатокритеріальне прийняття рішень*