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Application of the Analytical Hierarchy Process to Select the Most Appropriate Mining Equipment for the Exploitation of Secondary Deposits

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Abstract: A methodology is outlined for equipment selection for the extraction of secondary deposits, supported by the Multiple Criteria Decision Making (MCDM) tool based on the Analytic Hierarchy Process (AHP) method and applied to evaluate its impact on the mining system's performance and the viability of the rock mining project. The equipment selection analysis affords us the means to explore selected options, taking technological and economic parameters into account, and opening the way for making the decision to begin or discontinue mining operations. The simulation results show how maintaining the mining site in a good condition impacts on the actual duty cycle of mining equipment, the time required to complete the hauling task and the operating costs.

Keywords: MCDM; raw materials; mining equipment; secondary deposit

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1. Introduction

In large number of surface mines and quarries, there are secondary deposits left alongside the currently mined deposits. The presence of these secondary sections makes further exploitation of the target deposit a difficult task, mostly due to the presence of numerous karst interlayers. Up to now, these have been regarded as extractive waste and hauled away to the dumping sites, or, when they do not preclude the excavation of the target deposit, they have been left undisturbed. Both scenarios give rise to major losses, in terms of the economic, engineering and environmental aspects. Usually, there are plans to commence secondary mining operations, particularly in hard coal deposits [1–3]. In most cases, however, mining operations will not recommence and, in the case of rock deposits, leaving undisturbed sections containing waste rock and dirt gives rise to difficulties in target deposit mining, generating considerable losses [4].

Exploitation of extractive waste may prove profitable, as there is no need to haul the whole section of the deposit to the dumping site. Actually, it is only the portion of the deposit that cannot be further utilised that has to be dumped. It is worth mentioning that the analysis presented in this study aimed to support the selection of the optimal mining equipment for limestone extraction from deposits of strategic significance. Recently, this issue has gained importance because the perpetual demand for rock and stone for the construction and road-building industry calls for an increase in production, including from secondary deposits. Another important aspect is the sustainability of rock excavation, promoting its optimal utilisation through selective exploitation [4–8]. Taking care of all available deposit resources allows the excavation site to be reduced, which results in limiting dumping sites and reducing the amount of waste rock and dirt [5].

The issues described apply to all rock materials. This article presents an example of a limestone deposit.

A solution to a decision problem is sought according to a set of specified coherent criteria that best characterise the problem of evaluating and selecting the mining equipment to be used in rock mines and quarries in considering the exploitation of the secondary deposits. The proposed criteria can be applied to solve discrete decision-making problems, such as ranking the machines and equipment, recalling the MCDM approach. The set of criteria includes nine coherent criteria, taking the environmental, economic and engineering aspects into account.

The applications of MCDM for solving the problems of sustainable development and/or re-exploitation of waste deposits (mining waste) are currently an important research topic and have been described by Dino et al. [4], Stenis and Hogland [5], Kaźmierczak et al. [6,7], Rakhmangulov et al. [8], Cegan et al. [9] and Petronijević et al. [10]. As regards the exploitation of secondary deposits, it is recommended that a sustainable mining method should be selected and that the whole deposit should be mined, including the secondary deposit portion, to improve the productivity rates and extend the mine's life [11–13]. Moreover, the amount of waste rock to be dumped and the size of the dumping sites will be thus reduced, which translates into lower waste generation and the long-term sustainable management of the deposit [10,14–16].

For that reason, environmental issues and the energy consumed by the mining equipment were taken into consideration when defining the criteria characterising the decision-making model. Moreover, the selection of mining equipment should account for all key elements specific to the mining process as described by Stojanovic et al. [17], Yavuz [18] and Dayo-Olupona et al. [19].

The AHP method used in this study has been applied and implemented more widely than other MCDM methods in studies of similar problems in related fields, especially in mining engineering equipment selection (ESP). Selection of the optimal layout of the equipment and improvement of the limestone processing transfer to mobile devices were studied by Teplická and Straka [20] The process of multicriterial decision-making for supporting the solution of selection problems in the extractive and mineral processing industry was explored by Sitorus et al. [21], Bodziony et al. [22] and Kluge and Malan [23]. Burt and Caccetta [24] recommended the optimal mining equipment for surface mining operations, as did Bascetin [25] and Nolan and Kecojevic [26]. Kazakidis et al. [27] applied the analytical hierarchy process to assist in selecting the optimal mining method according to productivity, cost-effectiveness and environmental criteria. This approach was also adopted by Ataei et al. [28], Bogdanovic et al. [29] and Gupta and Kumar [30]. The work of [31] described the selection of the mining method in a salt mine in terms of the priorities determined by the fuzzy analytical hierarchy process (AHP) technique. This technique was adopted in the analyses of mining equipment selection reported by [32–34]. A combination of two methods, AHP and TOPSIS, was presented by Spanidis et al. [35] and was implemented to support the reclamation of lignite mine sites. The combined AHP and ELECTRE methods were used to support the selection of the optimal mining technology for an open-cast coal mine by Stojanovic et al. [17]. ELECTRE methods were used to support the selection of the optimal equipment for surface mining by [16,36]. Analyses based on the AHP method describing applications in coal mining and mine water factors were described in other works [37–41]. Moreover, multicriterial analysis by the AHP method enabled the identification of the operations in rock mining and quarrying with the highest potential [6,7,21,26,34,42–45].

For that reason, the criteria that characterise the decision-making model include the environmental factors and the energy consumed by mining machinery and equipment.

This study outlines the methodology for optimal equipment selection to exploit secondary deposits, supported by the MCDM tool based on the AHP approach. The study demonstrated how the quality of useful mineral determines the cost-effectiveness and operational efficiency of the undertaking with regard to the engineering and economic parameters, highlighting the impacts of the waste rock content in the mined material.

2. Materials and Methods

An analysis was conducted for supporting the selection of mining equipment with the predetermined output of 600 Mg/h to be used in exploration and extraction of the limestone deposits in one of the surface mines in the northwest of Poland. The deposit features numerous karst interlayers, which is why 20–30% of the deposit is regarded as off-spec material and thus treated as waste rock. Up to now, this material has not been processed and has been categorised as useless waste. Moreover, this rock material has to be hauled to the dumping site, which increases the production costs and leads to expansion of the dumping sites. In the analysed portion of the deposit, the useful mineral content approaches 70%, and thus 30% is regarded as waste rock. In order to separate the waste rock from useful mineral, the mined material is crushed in a primary crushing process.

This study investigates a decision-making model based on the multicriteria analysis (AHP, Analytic Hierarchy Process) introduced by Saaty [46]. The method allows one to solve multicriterial decision-making problems and for the incorporation of expert opinions in the decision-making process, yielding a quantitative measure characterising the analysed attributes [9,21,43,46]. As a multicriterial approach, the AHP method is based on a compensatory strategy of modelling preferences, assuming the variants to be comparable. The key feature of the AHP approach is that it allows for the manifestation of user preferences and subjective perceptions. Actually, the variations in preferences from one person to another are regarded as normal and natural in judgements based on decision-makers' experience. The AHP procedure involves four stages [46]:

- Stage 1—Hierarchy construction, presentation of the model and formulating the criteria for the ranking of the variants;
- Stage 2—Evaluation of the relative weights of the criteria, subcriteria and decision factors through pairwise comparisons;
- Stage 3—Determining the interrelationships and relative weights (priority) of the criteria and decision factors. Verification of the adequacy of the outcomes (matrix consistency testing);
- Stage 4—Synthesis of alternative preference sequencing, based on a normalised decision matrix (classification of the decision variants).

3. Designing the Decision Variants

The configurations of the decision variants for the analysis are collated in Figures 1 and 2. These include the selected equipment and the conditions of the surroundings, such as the configuration of haulage roads in the context of the exploitation of secondary deposits. In formulation of the decision variants, the operational efficiency of the analysed equipment and the waste rock contents in the analysed batch of the material being mined were of particular importance.

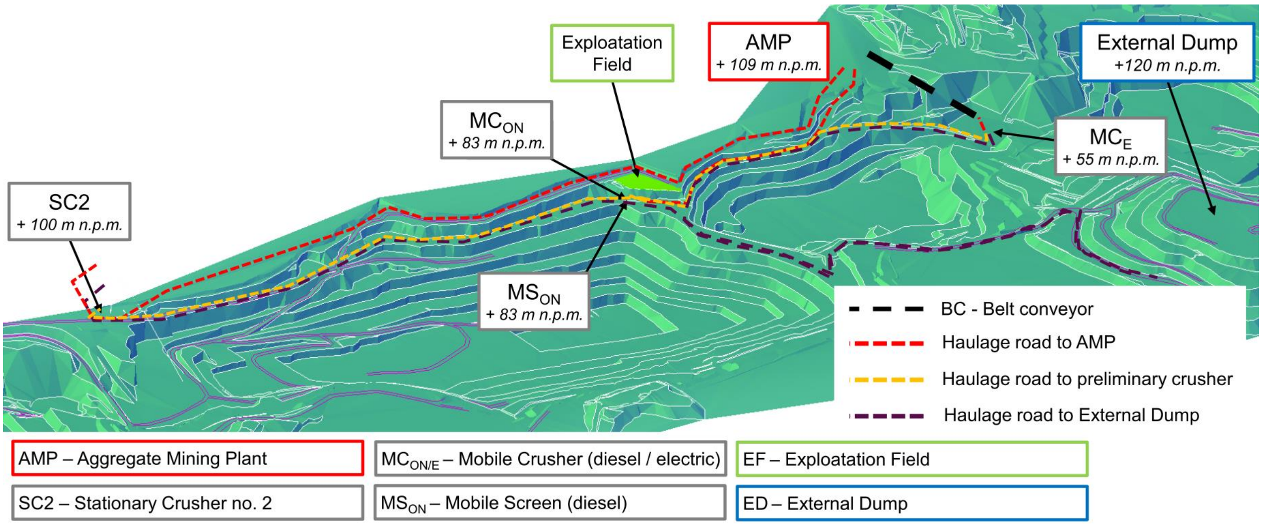

Figure 1. Configuration of the decision variants and the operating conditions of the analysed mine.

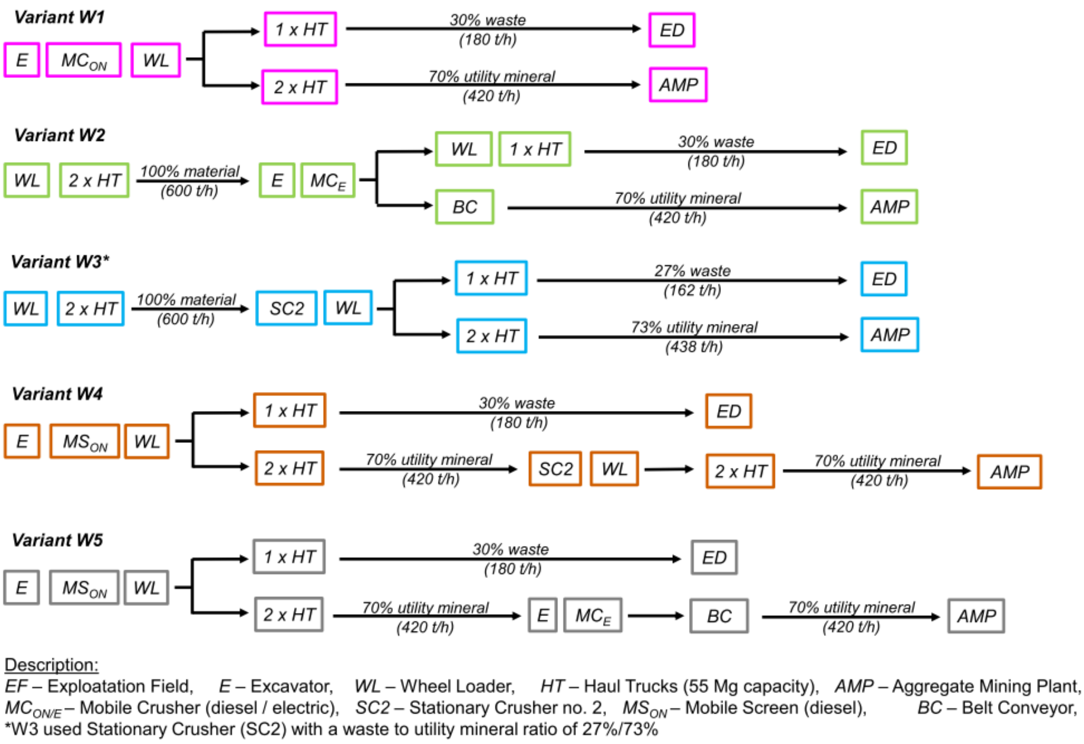

Figure 2. Configuration of the mining equipment in various decision variants.

4. Criteria for Selecting and Evaluating the Equipment for Secondary Deposit Mining

A set of criteria was proposed (see below) to assist in selecting and reliably evaluating the equipment for mining secondary deposits. To facilitate a comprehensive analysis of the decision problem, coherent sets of criteria were aggregated to account for engineering (technological), economic and environmental factors.

- K1—length of haulage roads;
- K2—the number of deployed machines;
- K3—the size of work crew;
- K4—factors that adversely impact on the implementation of the mining operations;
- K5—energy consumed by the machinery and mining equipment;
- K6—distance from the crushing unit to residential buildings;

- K7—amount of dumped material;
- K8—net profit;
- K9—waste rock content in the deposits.

4.1. Technological Criteria

(K1) Length of haulage roads—a quantitative criterion where the problem is to select the minimal value, defining the total distance travelled by the haul truck during two work shifts, in km.

(K2) Number of deployed machines—a quantitative criterion where the problem is to select the minimal value, defining the total number of deployed loading and hauling machines (the decision variant necessary for the implementation of the mining operation), expressed as the number of items.

(K3) Size of work crew—a quantitative criterion where the problem is to select the minimal value, defining the total number of machine operators in the given variant of the load–haul system during two work shifts, given as the number of people (headcount).

(K4) Factors adversely affecting the implementation of the mining process—a qualitative criterion expressed as a score, expressing the likelihood of unplanned downtime (Table 1) due to the formation of a flyrock zone in the wake of blasting or long queues of haul trucks, as well as other factors affecting the safety and continuity of operations, including loading, hauling and primary crushing of the mined material. This criterion indicates how the location of the primary crusher determines the occurrence of unplanned downtime.

Table 1. Possibility of unplanned downtime due to the location of the crushing unit.

	W1	W2	W3	W4	W5
Technological problems caused by mining operations					
Is the crushing and sorting unit located within the flyrock zone?	1	0	0	0.5	0.5
Is the haul truck trip delayed by the blasting operations in order to keep a safe distance?	1	0	0	0.5	0.5
Problems caused by difficult terrain					
Does the location of the crushing unit give rise to disruptions in the haul trucks' movements in its vicinity?	0.5	1	0.5	0	0.5
Does the location of the crushing unit lead to gridlock and congestion of the haul trucks being loaded, those carrying the load and those heading towards the loading yard?	1	0.5	0	0.5	0.5
Does the location of the crushing unit lead to filling in and bulldozing of the existing yards, thus precluding further production?	1	0	0	1	0.5
Sum	**4.5**	**1.5**	**0.5**	**2.5**	**2.5**

0 pts—problem does not occur; 0.5 pts—problem may occur; 1.0 pts—problem occurs. The lower the score, the more desirable the option.

4.2. Environmental Criteria

(K5) Energy consumed by the machinery and equipment—a quantitative environmental criterion where the objective is to select the minimal value, defining the total energy consumption of all machinery and equipment making up the load–haul–dump system (variant), expressed in MJ/day. It also indicates which piece of equipment is environmentally friendly, in other words which variant would ensure the lowest energy consumption, the lowest flue gas/greenhouse gas emission levels and the smallest carbon footprint per two working shifts.

(K6) Distance of the crushing unit from residential buildings—a quantitative environmental criterion where the problem is to select the maximal value, defining the distance between the initial location of the crusher and the nearest residential buildings, expressed in m. This is the basis for delineating the zone affected by noise, vibration and dust exposure, and is expressed as the distance between the crusher and the nearest residential buildings, neglecting the effects of wind.

(K7) The amount of mined material to be dumped—a quantitative environmental criterion where the objective is to select the minimal value, defining the amount of waste rock (mostly karst) per working shift, in tonnes. This strongly impacts the haulage and dumping costs, and also has to be considered in the context of mining royalties and the required protective measures. Reducing the amounts of waste rock/dumped material helps to reduce the area occupied by dumping sites as well as their volume, which may result in a reduction in the mining royalties to be paid.

4.3. Economic Criteria

(K8) Net profit—a quantitative economic criterion, where the objective is to select the maximal value; expressed in the units of currency (EUR). It is an item in the revenue and expense account defining the actual value of the financial results. It is used to evaluate the viability of the applied production system.

(K9) Waste rock content in the deposit—a quantitative economic and environmental criterion where the objective is to select the maximal value, given as a percentage, expressing the critical (maximal) waste (karst) rock contents in the deposit section being mined while production still remains profitable. This parameter determines the break-even point and viability of mining operations.

For the purpose of AHP-based MCDM analysis, a decision matrix of the criteria was formulated for the adopted decision variants (Table 2).

Table 2. Decision matrix of the criteria in the decision variants considered.

	Designation	**K1**	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**
Designation	Criterion	Length of haulage roads	Number of deployed machines	Size of work crew	Factors adversely affecting the implementation of the mining process	Energy consumed by machinery and equipment	Distance of the crushing unit from residential buildings	The amount of mined material to be dumped	Net profit	Waste rock content in the deposit
	Unit	km/day	pcs.	pcs.	pts.	MJ/day	m	t	EUR/t	%
	Preference direction	min	min	min	min	min	max	min	max	max
W1		594	6	10	4.50	111,979	2192	2520	2.41	59%
W2		783	8	14	1.50	135,090	1190	2520	2.07	53%
W3		2469	8	18	0.50	179,620	1975	2268	1.87	52%
W4		2140	10	20	2.50	205,210	1975	2520	1.59	51%
W5		689	9	14	2.50	138,215	1190	2520	2.21	59%

Figure 3 illustrates the relevance of the variants considered, expressing the preference of the given variant with respect to each criterion/assessment of the decision variant's relevance. Decision Variant W1 appears to be the preferred option with respect to criteria K1, K2, K3, K5, K6, K8 and K9, ex aequo with Variant W5. In regard to Criteria K4 and K7, Variant W3 appears to be the optimal alternative. In terms of the criteria considered, Variant W4 is the least favoured while Variant W2 ranks as second, third or fourth.

The relevance of the adopted criteria with respect to the decision variants was evaluated in a pairwise comparison process, and the respective priorities (thresholds of significance) in relation the criteria and decision variants were determined by the AHP method. Criteria K1–K3, K5, K6, K8 and K9 were found to be the most relevant with respect to Variant W1, while Variant W2 ranks as second or third in terms of nearly all criteria. Variant W3 appears to be the favoured option in terms of Criteria K1 and K7, while Variant W4 ranks as fourth or fifth in terms of nearly all criteria, and Variant W5 seems highly relevant with respect to Criteria K9, K1 and K8.

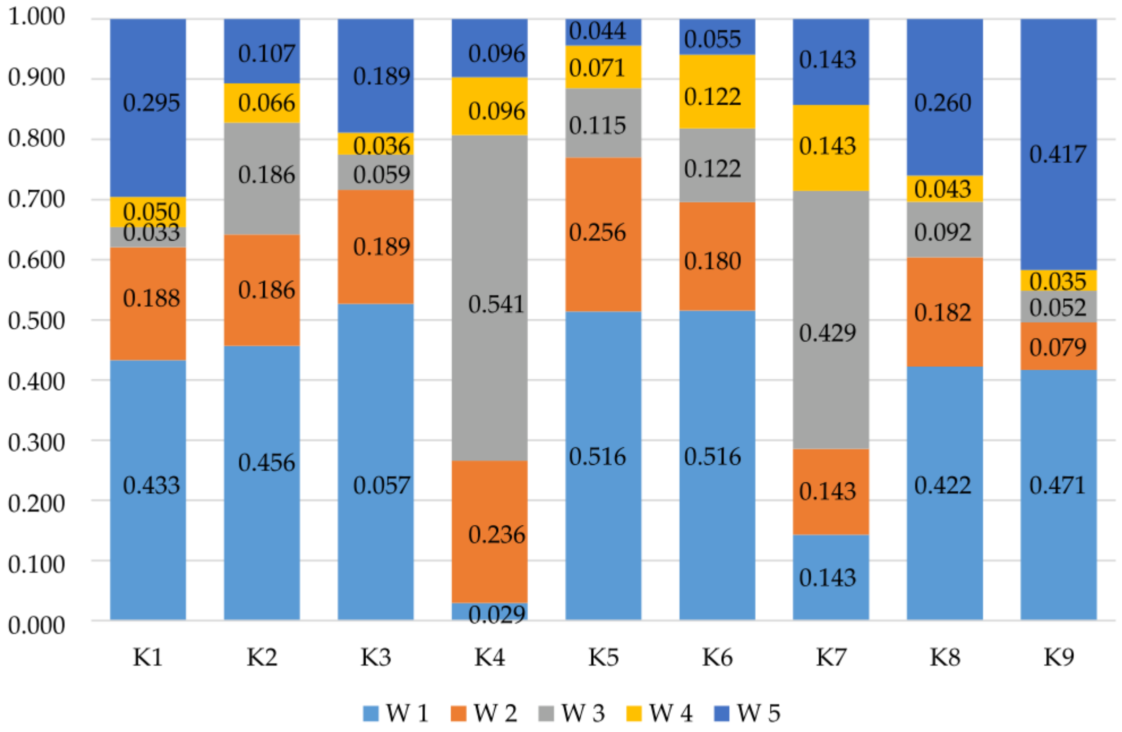

Figure 3. Weight coefficients calculated by the AHP analysis.

As input data, the results of the pairwise comparison process and the weight coefficients obtained by the AHP-based ranking analysis are summarised in Figure 3.

AHP allows for the incorporation of subjective judgements and preferences into the decision-making process. In this study, a dedicated group of decision-makers included a team of independent experts: two specialists in surface mining technology with an academic background (one of them also being a mining manager) and four mining managers responsible for mining operations. The university experts are specialists in the field of operation and maintenance of surface mining machinery and in equipment selection problems.

The experts' judgements and evaluations are given in Tables 3–8, summarising the weighted criteria and their ranking list, the most preferred alternative being indicated. Finally, the averaged weights of the criteria are summarised and the final ranked list is given, with an indication of the most favourable variant, taking all the experts' judgements into consideration.

Table 3. Ranked list of the final weight distributions of the respective equipment variants according to Expert 1.

E1	K1	K2	K3	K4	K5	K6	K7	K8	K9	Priority Vector	Ranking
w_i	**0.043**	**0.020**	**0.019**	**0.242**	**0.043**	**0.286**	**0.035**	**0.181**	**0.130**		
W1	0.433	0.456	0.527	0.029	0.514	0.516	0.143	0.422	0.417	**0.351**	1
W2	0.188	0.186	0.189	0.236	0.256	0.180	0.143	0.182	0.079	**0.183**	3
W3	0.033	0.186	0.059	0.541	0.115	0.122	0.429	0.092	0.052	**0.216**	2
W4	0.050	0.066	0.036	0.096	0.071	0.122	0.143	0.043	0.035	**0.083**	5
W5	0.295	0.107	0.189	0.096	0.044	0.059	0.143	0.260	0.417	**0.167**	4

Table 4. Ranked list of the final weight distributions of the respective equipment variants according to Expert 2.

E2	K1	K2	K3	K4	K5	K6	K7	K8	K9	Priority Vector	Ranking
w_i	**0.033**	**0.041**	**0.027**	**0.216**	**0.014**	**0.189**	**0.035**	**0.232**	**0.211**		
W1	0.433	0.456	0.527	0.029	0.514	0.516	0.143	0.422	0.417	**0.350**	**1**
W2	0.188	0.186	0.189	0.236	0.256	0.180	0.143	0.182	0.079	**0.172**	**4**
W3	0.033	0.186	0.059	0.541	0.115	0.122	0.429	0.092	0.052	**0.200**	**3**
W4	0.050	0.066	0.036	0.096	0.071	0.122	0.143	0.043	0.035	**0.073**	**5**
W5	0.295	0.107	0.189	0.096	0.044	0.059	0.143	0.260	0.417	**0.206**	**2**

Table 5. Ranked list of the final weight distributions of the respective equipment variants according to Expert 3.

E3	K1	K2	K3	K4	K5	K6	K7	K8	K9	Priority Vector	Ranking
w_i	**0.029**	**0.284**	**0.173**	**0.155**	**0.070**	**0.149**	**0.070**	**0.034**	**0.035**		
W1	0.433	0.456	0.527	0.029	0.514	0.516	0.143	0.422	0.417	**0.390**	**1**
W2	0.188	0.186	0.189	0.236	0.256	0.180	0.143	0.182	0.079	**0.191**	**3**
W3	0.033	0.186	0.059	0.541	0.115	0.122	0.429	0.092	0.052	**0.209**	**2**
W4	0.050	0.066	0.036	0.096	0.071	0.122	0.143	0.043	0.035	**0.077**	**5**
W5	0.295	0.107	0.189	0.096	0.044	0.059	0.143	0.260	0.417	**0.132**	**4**

Table 6. Ranked list of the final weight distributions of the respective equipment variants according to Expert 4.

E4	K1	K2	K3	K4	K5	K6	K7	K8	K9	Priority Vector	Ranking
w_i	**0.019**	**0.026**	**0.053**	**0.093**	**0.217**	**0.097**	**0.050**	**0.262**	**0.183**		
W1	0.433	0.456	0.527	0.029	0.514	0.516	0.143	0.422	0.417	**0.406**	**1**
W2	0.188	0.186	0.189	0.236	0.256	0.180	0.143	0.182	0.079	**0.183**	**3**
W3	0.033	0.186	0.059	0.541	0.115	0.122	0.429	0.092	0.052	**0.151**	**4**
W4	0.050	0.066	0.036	0.096	0.071	0.122	0.143	0.043	0.035	**0.066**	**5**
W5	0.295	0.107	0.189	0.096	0.044	0.059	0.143	0.260	0.417	**0.194**	**2**

Table 7. Ranked list of the final weight distributions of the respective equipment variants according to Expert 5.

E5	K1	K2	K3	K4	K5	K6	K7	K8	K9	Priority Vector	Ranking
w_i	**0.022**	**0.025**	**0.026**	**0.186**	**0.079**	**0.194**	**0.040**	**0.232**	**0.195**		
W1	0.433	0.456	0.527	0.029	0.514	0.516	0.143	0.422	0.417	**0.366**	**1**
W2	0.188	0.186	0.189	0.236	0.256	0.180	0.143	0.182	0.079	**0.176**	**4**
W3	0.033	0.186	0.059	0.541	0.115	0.122	0.429	0.092	0.052	**0.190**	**3**
W4	0.050	0.066	0.036	0.096	0.071	0.122	0.143	0.043	0.035	**0.074**	**5**
W5	0.295	0.107	0.189	0.096	0.044	0.059	0.143	0.260	0.417	**0.194**	**2**

Table 8. Ranked list of the final weight distributions of the respective equipment variants according to Expert 6.

E6	K1	K2	K3	K4	K5	K6	K7	K8	K9	Priority Vector	Ranking
w_i	**0.119**	**0.020**	**0.083**	**0.041**	**0.050**	**0.047**	**0.040**	**0.363**	**0.239**		
W1	0.433	0.456	0.527	0.029	0.514	0.516	0.143	0.422	0.417	**0.413**	1
W2	0.188	0.186	0.189	0.236	0.256	0.180	0.143	0.182	0.079	**0.163**	3
W3	0.033	0.186	0.059	0.541	0.115	0.122	0.429	0.092	0.052	**0.109**	4
W4	0.050	0.066	0.036	0.096	0.071	0.122	0.143	0.043	0.035	**0.053**	5
W5	0.295	0.107	0.189	0.096	0.044	0.059	0.143	0.260	0.417	**0.261**	2

4.4. Expert 1: Mining Manager, CEO in a Mining Company

According to Expert 1, the three most vital criteria are K6 (distance of the crushing unit from residential buildings; 28.6%), K4 (factors adversely affecting the implementation of the mining process; 24.2%) and K8 (net profit; 18.1%). Those with the least significance are K3 (size of the work crew; 1.9%), K2 (the number of deployed machines and equipment; 2.0%) and K7 (3.5%); see Figure 4.

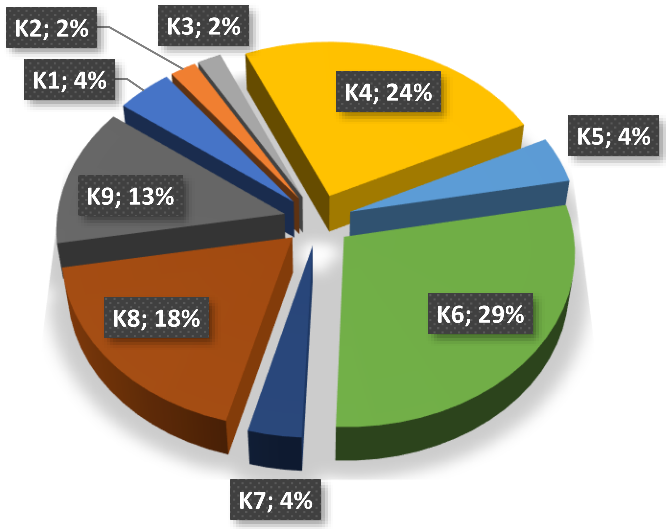

Figure 4. Weighted criteria expressed as percentages, according to Expert 1.

According to Expert 1, Variant W1 is the most favoured, producing a result in the order of 0.351; Variant W3 (0.216) Variant W2 (0.183) and Variant W5 (0.167) are next in line. The least favoured is Variant W4, yielding a result of 0.083.

4.5. Expert 2: Mining Manager, CEO in a Mining Company

According to Expert 2, the most relevant criteria are K8 (net profit; 23.2%), K4 (factors adversely affecting the implementation of the mining process; 21.6%) and K9 (the critical level of useful mineral contents; 21.1%). Those considered to be the least important factors are K5 (energy consumed by the machinery and equipment; 1.4%, K3 (the size of the work crew; 2.7%) and K1 (length of haulage roads; 3.3%); see Figure 5.

According to Expert 2, the most favourable variant is W1 (0.350), with Variant W5 (0.206), Variant W3 (0.200) and Variant W2 (0.172) coming next in line, while Variant W4 (0.073) appears to be the least favourable.

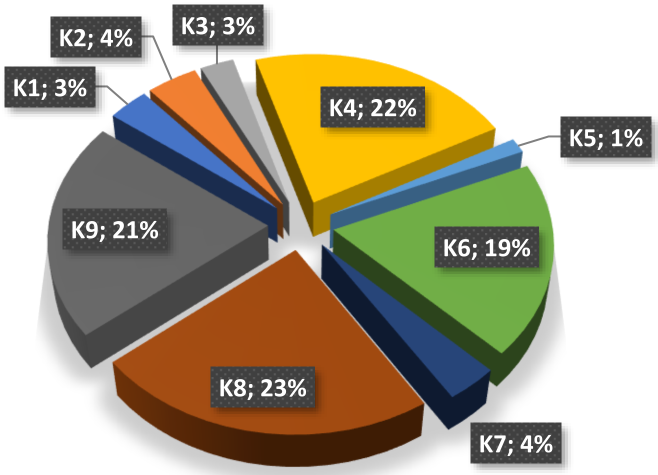

Figure 5. Weighted criteria expressed as percentages, according to Expert 2.

4.6. Expert 3: Mining Manager, CEO in a Mining Company

According to Expert 3, the most relevant criteria include K2 (number of deployed machines and equipment; 28.4%), K3 (the size of the work crew; 17.3%), K4 (factors adversely affecting the implementation of the mining process; 15.5%) and K6 (nuisance caused by mining operations; 14.9%). The least relevant ones are K1 (length of haulage roads; 2.9%), K8 (net profit; 3.4%) and K9 (critical level of useful mineral content in the deposits; 3.5%); see Figure 6.

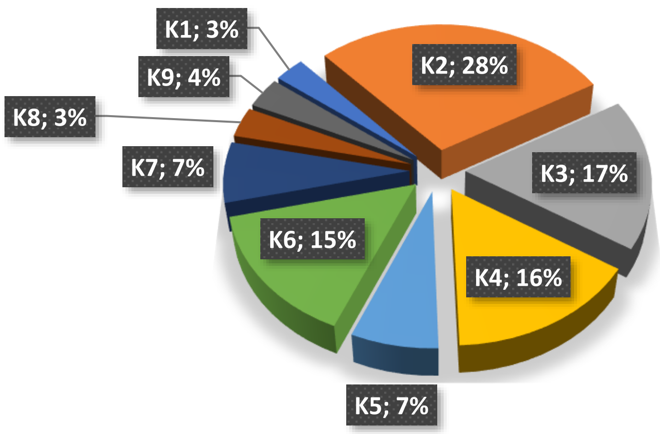

Figure 6. Weighted criteria expressed as percentages, according to Expert 3.

According to Expert 3, the most favourable variant is W1 (0.390), with Variant W3 (0.209), Variant W2 (0.191) and Variant W5 (0.132) coming next in line, while Variant W4 with 0.077 appears to be the least favourable.

4.7. Expert 4: Mining Manager

According to Expert 4, the most relevant criteria are K8 (net profit; 26.2%), K5 (energy consumed by the machinery and equipment; 21.7%) and K9 (the critical level of useful mineral content; 18.3%). Those considered to be the least relevant are K1 (length of haul age roads; 1.9%) and K2 (the number of deployed machines and equipment; 2.6%); see Figure 7.

According to Expert 4, the most favourable variant is W1 (0.406), with Variant W5 (0.194), Variant W2 (0.183) and Variant W3 (0.151) ranked next in line, while Variant W4 (0.066) appears to be the least favourable.

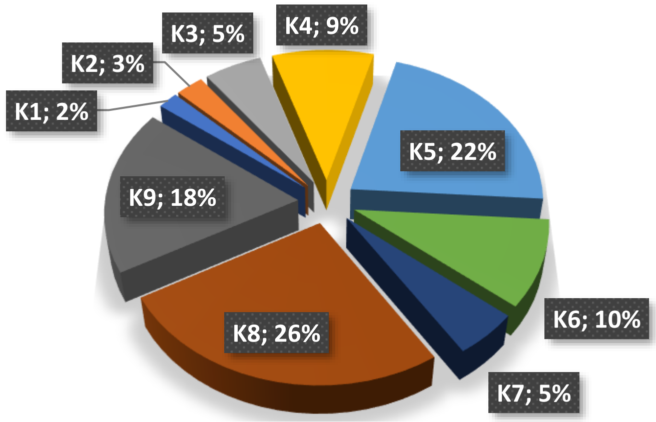

Figure 7. Weighted criteria expressed as percentages, according to Expert 4.

4.8. Expert 5: Mining Manager and Academic Expert in the Field of Surface Mining Technology

In the opinion of Expert 5, the most relevant criteria are K8 (net profit; 23.2%), K9 (the critical level of useful mineral content; 19.5%), K6 (nuisance caused by mining operations; 19.4%) and K4 (factors adversely affecting the implementation of the mining process; 18.6%). Those considered to be the least important factors include K1 (length of haulage roads; 2.2%), K2 (the number of deployed machines and equipment; 2.5%) and K3 (the size of the work crew; 2.6%); see Figure 8.

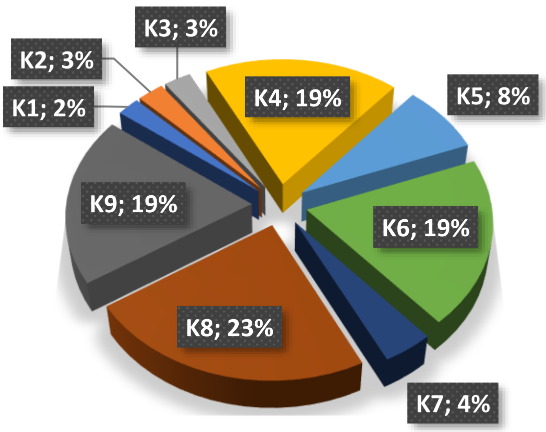

Figure 8. Weighted criteria expressed as percentages, according to Expert 5.

According to Expert 5, the most favourable variant is W1 (0.366), Variant W5 (0.194), Variant W3 (0.190) and Variant W2 (0.176) rank as next in line, whilst Variant W4 (0.074) appears to be the least favourable.

4.9. Expert 6: Academic and Specialist in the Field of Surface Mining

According to Expert 6, the most relevant criteria are: K8 (net profit; 36.3%) and K9 (the critical level of useful mineral content; 23.9%). The one considered to be the least important is K2 (the number of deployed machines and equipment; 2.0%); see Figure 9.

According to Expert 6, the most favourable variant is W1 (0.413), with Variant W5 (0.261), Variant W2 (0.163) and Variant W3 (0.109) ranked next in line, while Variant W4 (0.053) is considered the least favourable.

The AHP-based evaluation model incorporating the subjective expert opinions was implemented in the equipment selection problem, and the most favourable Variant W1 was obtained accordingly. Decision Variant W4 was considered the least favourable. However, determining the ranked list of other decision variants was not a straightforward task.

That is why the priority values of the respective variants evaluated by experts had to be averaged, thus yielding the final ranked list of equipment variants, shown in Table 9.

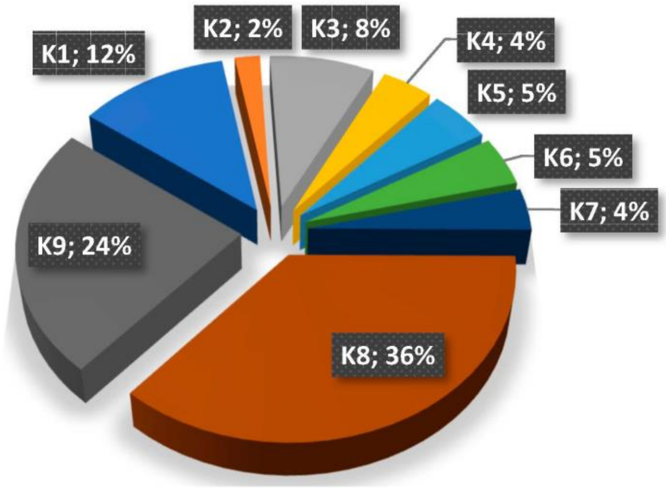

Figure 9. Weighted criteria expressed as percentages, according to Expert 6.

Table 9. Final ranked list of decision variants based on expert scoring.

	E1	E2	E3	E4	E5	E6	Average	Ranking
W1	0.351	0.350	0.390	0.406	0.366	0.413	0.379	1
W2	0.183	0.172	0.191	0.183	0.176	0.163	0.178	4
W3	0.216	0.200	0.209	0.151	0.190	0.109	0.179	3
W4	0.083	0.073	0.077	0.066	0.074	0.053	0.071	5
W5	0.167	0.206	0.132	0.194	0.194	0.261	0.192	2

For better clarity of presentation and to demonstrate predominance of the most favoured alternative, Figure 10 shows the relevance of the decision factors (expressed as percentages) based on the experts' evaluation of all decision variants in the equipment selection problem.

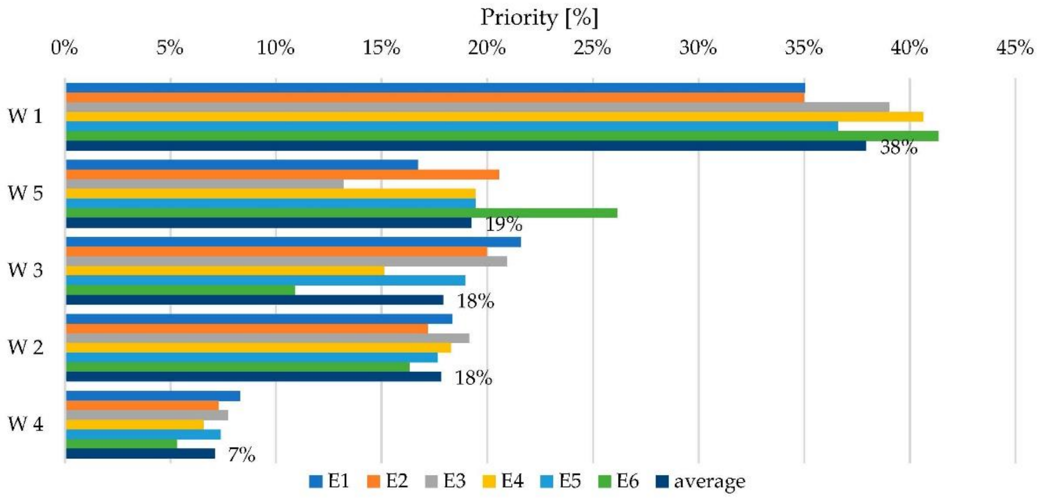

Figure 10. Ranked list of relative priority weights in the analysed decision variants based on experts' scoring (the outcome of the computation procedure).

5. Discussion

The results of the AHP-based procedure show Variant W1 to be nearly two (1.82) times more favourable than Variant W5, ranking as second in the hierarchy of relevance. Variants W5, W3 and W2, coming next in line, featured similar levels of relevance: 19.2%, 17.9% and 17.8%, respectively. The least relevant variant appears to be W4, as its averaged relevance was 7.1%.

The relative weights (expressed as percentage fractions) with regard to the criteria were formulated by the team of experts. According to five out of six experts, Criteria K8 and K9 were first in the order of relevance, while Criteria K4 and K6 were assessed as the most relevant by four experts. Only Expert 3 founds Criteria K2 and K3 to be the most relevant, though these were regarded by the remaining experts as being of little significance. The criteria found to be the most relevant in the study of the equipment selection problem were K8, K6, K4 and K9 (see Figure 11).

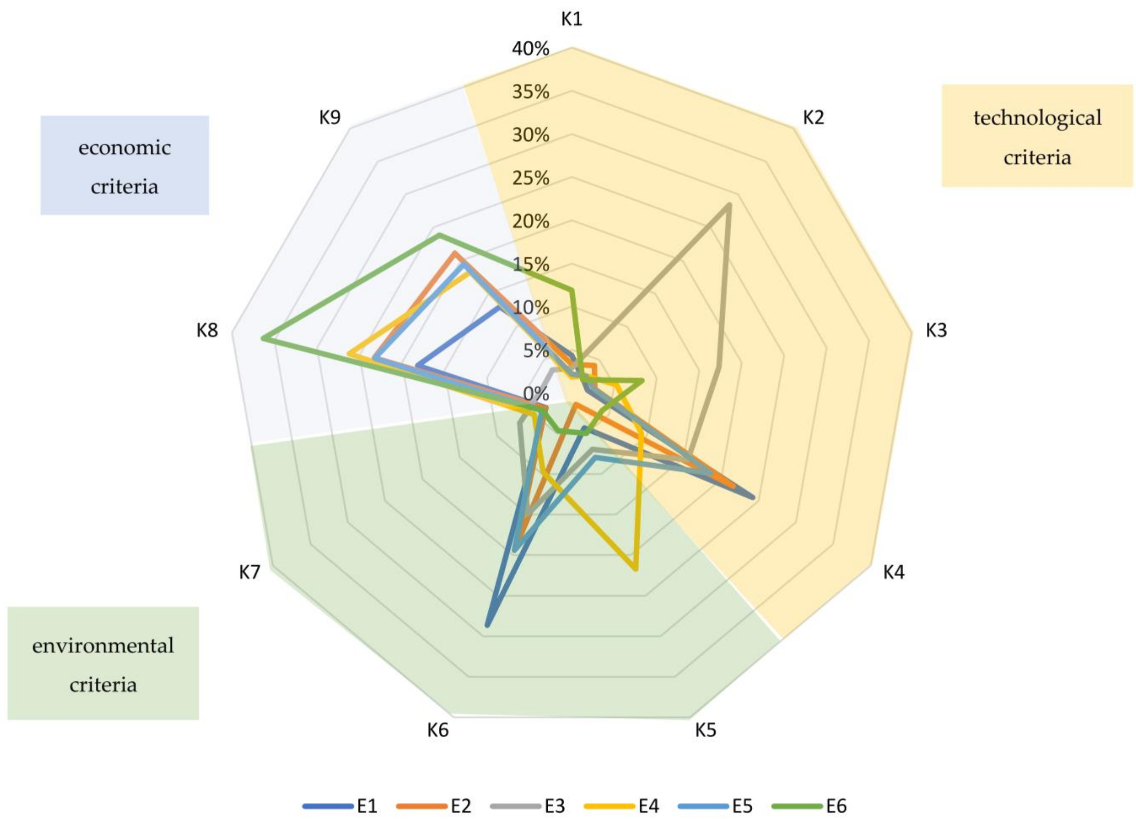

Figure 11. Expert's preferences with regard to the criteria (relevance of the criteria in the AHP-based procedure).

It appears that Criterion K8 comes first in the order of relevance (21.8 %), outranking K9, K6 and K4, with levels of relevance of 16.5%, 16.1% and 15.6%, respectively. These criteria will largely impact on the selection of alternatives in the analysed decision-making procedure. The set of criteria found to be of medium and low relevance includes K5, K3 and K2 (7.9%, 6.9% and 6.3%, respectively). Those that affect the expert priority analysis to the lesser degree are K7 and K1. It is readily apparent that the economic criteria were considered by all experts.

6. Conclusions

The methodology outlined in this study enables the practical application of multi-criterial decision-making analysis and the AHP-based tool to support the selection of surface mining equipment under the specified working conditions and in the context of secondary deposit mining. This aspect has not received much analysis so far, though it may prove to be a vital issue in terms of the sustainability and viability of mining projects.

The proposed methodology is universal and may be widely applied in mining companies, particularly to support evaluations of the existing machinery and equipment and the purchase of new equipment. The universal aspects of the outlined methodology are:

- Formulation of a set of reliable criteria allowing a comprehensive and multi-aspect analysis of feasible methods of secondary deposit mining;
- Implementation of a complex model and aggregation of interdisciplinary decision factors (criteria) to enable a reliable multi-aspect evaluation of feasible alternatives of mining equipment systems;
- Incorporation of real operational conditions in the modelling procedure, prompting the development of a schematic procedure to support the decision-making process.

Hitherto, MCDM methods have been mostly applied in studies aiming to improve the performance of mining companies through enhancing the operational efficiency of machinery and equipment, while secondary mining operations seem to have been omitted or neglected. Selection of the optimal equipment in the context of secondary deposit mining poses a challenge, as it is affected by a number of unrelated or even conflicting factors. The main purpose of the analysis was to define the decision model so that secondary deposit mining would be feasible and profitable, and so mining the entire deposit would be a sustainable process and the environmental aspects should be duly accounted for.

To showcase the potential application of the AHP approach, the analysis was conducted with different configurations of the mining equipment. The decision-making procedure relied on nine criteria (the maximal number allowable in the AHP method), including engineering, economic and environmental factors. The AHP approach allowed us to determine the relative weights of the criteria so that the final score embraces all the considered criteria, no matter how diverse and hard to compare.

Thus, the methodology outlined in this study may be readily adapted to reflect the unique operating conditions in a surface mine where secondary deposits are to be exploited. Modifying the relative weights and basic parameters enables the sensitivity analysis with respect to the selected factor, which is another advantage of the AHP method.

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