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THE PROBLEM OF MULTIPLE CRITERIA SELECTION OF THE SURFACE MINING HAUL TRUCKS

PROBLEM WIELOKRYTERIALNEGO DOBORU WOZIDEŁ W KOPALNIACH ODKRYWKOWYCH

Vehicle transport is a dominant type of technological processes in rock mines, and its profitability is strictly dependent on overall cost of its exploitation, especially on diesel oil consumption. Thus, a rational design of transportation system based on haul trucks should result from thorough analysis of technical and economic issues, including both cost of purchase and its further exploitation, having a crucial impact on the cost of minerals extraction. Moreover, off-highway trucks should be selected with respect to all specific exploitation conditions and even the user's preferences and experience.

In this paper a development of universal family of evaluation criteria as well as application of evaluation method for haul truck selection process for a specific exploitation conditions in surface mining have been carried out. The methodology presented in the paper is based on the priciples of multiple criteria decision aiding (MCDA) using one of the ranking method, i.e. ELECTRE III. The applied methodology has been allowed for ranking of alternative solution (variants), on the considered set of haul trucks. The result of the research is a universal methodology, and it consequently may be applied in other surface mines with similar expoitation parametres.

Keywords: selection of mining machines, haul trucks, surface mining, multiple criteria decision aiding, ELECTRE III method

Transport samochodowy jest dominującym rodzajem transportu w procesach technologicznych w kopalniach surowców skalnych; jego opłacalność jest ściśle powiązana z kosztami ekploatacji parku maszynowego, w tym ze zużyciem oleju napędowego. Racjonalny dobór systemu transportowego z wykorzystaniem wozideł, powinien wynikać z dokładnej analizy aspektów techniczno-ekonomicznych, inwestycyjnych oraz eksploatacyjnych. Ponadto, wozidła powinny być dobierane z uwzględnieniem wszystkich istotnych parametrów w określonych warunkach eksploatacyjnych, a nawet preferencji użytkownika.

W niniejszej pracy opracowano uniwersalny zbiór kryteriów oceny oraz zastosowano metodę oceny w zakresie doboru wozideł technologicznych dla odkrywkowych kopalń surowców skalnych. Przedstawiona w pracy metodyka wyboru wykorzystuje nurt wielokryterialnego wspomagania decyzji (*WWD*), a w szczególności jedną z jego metod – ELECTRE III. Zastosowane narzędzie pozwoliło na uszeregowanie

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alternatywnych propozycji rozwiązań – wariantów, w analizowanym zbiorze wozideł technologicznych. Zaproponowana metodyka ma charakter uniwersalny i może być zastosowana w innych zakładach górniczych o podobnych warunkach eksploatacyjnych.

Słowa kluczowe: dobór maszyn górniczych, wozidła technologiczne, górnictwo odkrywkowe, wielokryterialne wspomaganie decyzji, metoda ELECTRE III

1. Introduction

Road transport carried out by off-highway trucks is a dominant one, and sometimes it is the only one possible mode of transportation in surface mines of rock materials. This approach is justified primarily by the mineral deposits sourcing technology, based largely on the mining with explosives. In addition, this mode of transport also determines less frequently used system of rock materials' exploitation, based on direct mining by hydraulic mining shovel, or as a result the loading process of output carried out by backhoe loaders or by excavators directly to the off-highway dump trucks.

The transport of the output carried out by off-highway trucks to points of destination and its unloading, is also imposed by the stationary processing plants located at some distance from the output loading place. Often, mining and geological conditions of the surface mines preclude the use of the other type of transport technology. The size and the type of the off-highway trucks have a significant effect on the efficiency of extraction and they determine the loading process – different for haul tracks and articulated haulers.

At the same time, the development of the building and construction industry and the policy of the European Union toward Poland within the National Cohesion Strategy, somehow force the further expansion of infrastructure. On the other hand, the fluctuation of prices of fuels has a direct impact on the rational and cost-effective use of the off-highway trucks constituting the main component of the mine machine system.

The share of transport expenditures in the mining companies indicates on how important role the transport plays in the overall mining process. The high costs generated by the output transport, both in terms of investments and further exploitation, are estimated at around 60% of total operational costs (Czaplicki, 2006, 2009). On average, investment in transport technology constitute 20 to 30% of total expenditures for the construction of the mine, and the transport costs are formed in the range of 60% of the extraction cost, depending on the distance of transportation, the depth of mining activity and the other conditions (Czaplicki, 2006, 2009). Thus, the costs of technological transport in some mines account for more than a half of the extraction costs. The condition for the effective transport processes is the selection of appropriate means of transport.

The profitability of vehicle transport is characterized by parameters depending on its energy consumption and other operating costs; they are closely related to the prices and volume of diesel oil consumption. It should be emphasized that despite of the widespread use of the off-highway trucks, it has not been developed universal criteria for selecting these modes of transport (Gałkowski et al., 1994; Marijew et al., 2004; Czaplicki, 2006, 2009).

The increasing demand for rock materials, the variety of off-highway trucks produced, their high prices and operating costs, and a large diversity of mining and geological conditions in the opencast mines, make it necessary and urgent to develop rational multiple criteria method for selecting these off-highway dump trucks, taking into account the scientific evidence; it inspired the authors to take this issue.

2. Principles of Multiple Criteria Decision Aiding and ELECTRE III method as a basis for off-highway truck selection

2.1. The essence of Multiple Criteria Decion Aiding

Multiple Criteria Decision Aiding (MCDA) is a field of research, which aims at giving a person called *decision maker,* some tools and methods in order to enable him to solve complex decision problem. The analyzed decision problem very often does not have a formal mathematical structure; therefore, it is not possible to carry out optimization techniques. On the other hand, many often contradictory points of view, are taken into account. Consequently, when using MCDA it is impossible to obtain objectively optimal solutions, that are the best from all points of view at the same time. Therefore, the problem of this type of decision maker is based on a limited set of solutions – usually set of variants.

Based on the research proposed by several authors (e.g. Roy, 1990a, 1990b; Roy & Vanderpooten, 1995; Vincke, 1992, 1999) three crutial groups of MCDA methods can be distinguished, i.e.: multiattribute utility theory methods, outranking relation methods and interactive methods. On the other hand all the typical multiple criteria problems can be divided into three subsets, i.e.: selection problems, sorting problems and ranking problems.

The problem solved in this article has been formulated as a ranking of considering variants, and to solve the problem one of the representative outranking relation based multiple criteria decision aiding method, i.e. ELECTRE III, has been applied.

2.2. The principles of ELECTRE III method

The ELECTRE III method allows to rank the finite set A of variants, evaluated by a coherent family F_j of j-criteria, where $j > 1$. The cohesiveness of the family of criteria is assesed on the basis of three conditions (e.g. Roy, 1999; Sawicka, 2012):

- *exhaustiveness*, the set of criteria takes into account all aspects of the considered decision problem,
- *cohesiveness*, each of the criteria globally form the decision makers preferences,
- *non-redundancy*, the set of criteria is chracterized by unique range of meaning.

The ranking of set of variants is based on outranking relation, denoted by S. It is assumed that variant a outranks variant b, denoted by aSb, if the available information of decision maker's preferences, the quality of variants' evaluation and the nature of the problem, provide enough arguments to state that variant a is at least as good as b in the absence of significant reasons to reject this assumption (Vincke, 1992, 1999). The calculation procedure of ELECTRE III method can be divided into four stages, which are as follows:

- construction of the decision maker's model of preferences regarding particular criteria, composed of the definition of weights of criteria and threshold values,
- construction of the valued outranking relation – S,
- ordering of variants based on the outranking relations,
- construction of final ranking of variants.

2.3. Construction of the decision maker′s model of preferences

The decision maker, while comparing two variants *a* and *b* with an application of ELECTRE III method, considers four states of preferences, i.e.:
- indifference of variants, denoted by *aIb*,
- weak preference of variant *a* over variant *b*, denoted by *aQb*,
- strong preference of variant *a* over variant *b*, denoted by *aPb*,
- incomparability of variants *a* and *b*, denoted by *aJb*.

Three thresholds are used to model these states of preferences, and are determined separately for each *j*-criterion: indifference threshold – q_j, preference threshold – p_j and veto threshold – v_j. In addition, it is assumed to distinguish the importance of individual criteria, in the form of weighting factors – k_j.

Each of the four possible states of preferences (I, Q, P, J) satisfies the following conditions:

$$aIb \Leftrightarrow g_j(b) \le g_j(a) \le g_j(b) + q_j\big(g_j(b)\big) \tag{1}$$

$$aQb \Leftrightarrow g_j(b) + q_j\big(g_j(b)\big) < g_j(a) \le g_j(b) + p_j\big(g_j(b)\big) \tag{2}$$

$$aPb \Leftrightarrow g_j(b) + p_j\big(g_j(b)\big) < g_j(a) \le g_j(b) + v_j\big(g_j(b)\big) \tag{3}$$

$$aJb \Leftrightarrow \; g_j(a) > g_j(b) + v_j\big(g_j(b)\big), \quad \forall j \in F, \quad g_j \in R > 0 \tag{4}$$

where: $g_j(a)$ and $g_j(b)$ denotes the value of citerion *j* for the variant *a* and *b*, respectively.

2.4. Construction of the valued outranking relation

The construction of the outranking relation involves the definition of the outranking degree, denoted as $S(a, b)$ for each pair of variants (a, b). The outranking degree of variants is determined on the basis of the two values: concordance index – $c(a, b)$ and discordance index – $d_j(a, b)$, (see Fig. 1). The first one is defined by the equation (5), as:

$$c(a,b) = c_1(a,b) + c_2(a,b) \tag{5}$$

wherein:

$$c_1(a,b) = \frac{1}{K} \sum_{j \in C(aSb)} k_j, \text{ where } K = \sum_{j \in F} k_j \tag{6}$$

and

$$c_2(a,b) = \frac{1}{K} \sum_{j \in C(bQa)} \psi_j k_j, \text{ where } \psi_j = \frac{g_j(a) + p_j\big(g_j(a)\big) - g_j(b)}{p_j\big(g_j(a)\big) - q_j\big(g_j(a)\big)} \tag{7}$$

The discordance index $d_j(a,b)$ is based on the value of veto threshold and it is defined by equation (8) as follows:

$$d_j(a,b)=\begin{cases}0 & \text{if } g_j(b)-g_j(a)\le p_j\left(g_j(a)\right)\\ \dfrac{g_j(b)-g_j(a)-p_j\left(g_j(a)\right)}{v_j\left(g_j(a)\right)-p_j\left(g_j(a)\right)}, & \text{if } p_j\left(g_j(a)\right)<g_j(b)-g_j(a)\le v_j\left(g_j(a)\right)\\ 1 & \text{if } g_j(b)-g_j(a)>v_j\left(g_j(a)\right)\end{cases} \quad (8)$$

The final form of the outranking relation is defined by the following formula:

$$S(a,b)=\begin{cases} c(a,b) \text{ if } d_j(a,b)\le c(a,b)\\ c(a,b)\cdot \prod\limits_{j\in J(a,b)} \dfrac{1-d_j(a,b)}{1-c(a,b)}, \ \forall j\end{cases} \quad (9)$$

where: $J(a,b)$ is a set of criteria for which $d_j(a,b) \ge c(a,b)$.

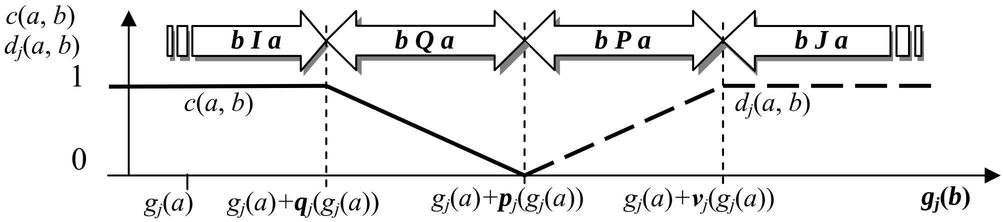


Fig. 1. The four-state model of decision maker's preferences (indifferences relation I, weak preference relation Q, strong preference relation P and incomparability relation J) built on the basis of thresholds q_j, p_j, v_j (Sawicki, 2001)

2.5. Ordering of variants based on the outranking relations

Ordering of variants based on the degree of outranking relation $S(a,b)$ starts from the definition of the following value:

$$\lambda = \max_{a,\, b\in A} S(a,b) \quad (10)$$

The valued outranking relation $S(a,b)$ is the essential element of the two complete preorders construction, based on classification algorithm. According to Roy (1990a, 1999) the complete preorder corresponds to a situation, where the relation S is transitive and complete. On the one hand, the computational procedure assumes that the descending preorder is constructed by the selection, in the first instance, of the best solution or indifference solutions, from the set of variants A, ending the worst solutions. The second preorder – ascending, begins to organize the solution or solutions from the worst. The calculation procedure is based on the constructed matrix of criteria vaules, including the family of evaluation criteria defined previously and the set of competitive variants. Finally, based on the outranking relations *S*, the position of variants is located, whence in the next step of the procedure, the descending and ascending distillations of all variants are constructed. The first distillation starts from choosing the best variant and it ends at the worst one, while the second distillation is arranged in the opposite direction. The variant, which is incomparable to the set of the other variants, is placed at the bottom of the descending distillation, and at the top of the ascending distillation. The variants, which are considered to be indifferent (within the indifference classes), are located on an equal place, regardless of the distillation type.

The outranking relation $S(a,b)$ indicates the degree of reliability of the hypothesis that variant *a* outranks variant *b*, i.e. *aSb*. Mutual relations are checked by the concordance tests. They are based on checking the relations between each pair of variants *a* and *b*, i.e. *aSb* and/or *bSa*. The concordance tests are made for each of the variants and for the hipothesis that *aSb* and *bSa*; they involve comparing two variants of each of the criteria. The advantage of using valued outranking relation is relatively low sensitivity to parameters' changes made arbitrary, sometimes out of necessity.

Final ranking of variants in ELECTRE III method is based on the joining descending and ascending distillations. The result is one complete preorder, in the form of graph, which is the final ranking of the analyzed variants, presenting the relations between them (Roy, 1990a, 1990b; Vincke, 1992, 1999).

3. The methodology for a comprehensive evaluation and selection of off-highway trucks in surface mines of rock materials

3.1. Research assumptions

During the construction of the family of criteria and the selection of a set of variants, as well as taking into account the selection of ranking method and implementation of decision makers' models of preferences, the following aspects have been considered:

- complex and multifaceted nature of the family of evaluation criteria,
- implementation of several models of decision makers' preferences, forming a team of independent experts,
- models of decision makers' preferences that consider the weights of the criteria, as well as weak preference, strong preference and indifference relations between variants,
- decision makers' uncertainty in terms of the incomparability of variants and preference thresholds,
- key role and crucial nature of the course of decision process modeling, requiring the use of many reliable and authoritative analysis.

3.2. Evaluation criteria of the haul trucks and the transport system environment in the surface mines of rock materials

3.2.1. The general characteristic of the family of evaluation criteria

The coherent family of criteria, characterizing the problem of evaluation and selection of the off-highway trucks in the surface mines of rock materials in the most eminent degree, is presented below. The set of criteria can be used to solve discrete multiple criteria decision problems, such as ranking problems, using MCDA methods. The proposed family of criteria consists of 10 criteria and is divided into 3 subsets, inlucing: i) economic, ii) technical-construction, iii) exploitation and reliability aspects.

3.2.2. Subset of economic criteria

Total investment costs – F_1, is minimized criterion, aggregating all relevant components of the investment costs, related to the present, in real terms or capitalized at the date of the analysis. The criterion includes all cost components that bind to sustained investment in technological road transportation, such as the purchase of the off-highway dump trucks, preparation of operating facilities, roads, loading and unloading points, etc. This criterion is expressed in monetary units [PLN][1].

Total operating costs – F_2, is minimized criterion, aggregating all relevant components of the operating cost, assigned to the various technological means of off-highway trucks. It includes the major components of operating costs, such as: fuel costs, tires, fluids, maintenance and technical services, and repair (including the purchase of service and own work) and spare parts. The components of operating costs are also the expenditures on road maintenance, operators' and supervisors' salaries, insurance and transport taxes, depreciation, and other administrative fees.

This criterion aggregates all operating costs related to the transportation work done during 5,000 engine hours. Measure adopted for this criterion is expressed in relative units in the form of [PLN/5,000 engine hours].

3.2.3. Subset of technical-construction criteria

Maximum power – F_3, is maximized criterion, determining the catalog value (available in the manufacturer's technical-movement documentation) of the maximum power generated by the haul truck. The value of the criterion is expressed in [kW].

Maximum torque – F_4, is a maximized criterion, determining the value of the directory maximum torque, generated by the propulsion system of the vehicle. The value of the criterion is expressed in [Nm].

Minimum turning radius – F_5, is a minimized criterion, determining the catalog value of the off-highway truck turning radius. The value of the criterion is expressed in [m].

Payload capacity – F_6, is maximized criterion, determining maximum capacity of the vehicle declared by the manufacturer of the vehicle, taking into account the permissible overload. The value of the criterion is expressed in [T].

[1] Polish currency, i.e. 1 Euro ≈ 4 PLN

3.2.4. Subset of exploitation and reliability criteria

Unit energy consumption – F_7, is minimized dimensionless criterion, expressing theoretical formulas (11) and (12):

$$F_7 = \frac{E}{G_u L} = \left(1 + 2\frac{G_o}{G_u}\right) f\cos\alpha + \sin\alpha + \left[\left(1 + 2\frac{G_o}{G_u}\right) \cdot \frac{1}{2gL} + \frac{2k_x F}{G_u}\right] v^2 + \frac{h_c}{L} \tag{11}$$

wherein:

$$\begin{aligned} E &= L\left[\left(G_u + G_o\right) \cdot \left(f\cos\alpha + \sin\alpha\right) + G_o\left(f\cos\alpha - \sin\alpha\right)\right] + \left(\frac{G_u + 2G_o}{2g} + 2Lk_x F\right) v^2 + G_u h_c \\ &= L\left[\left(G_u + 2G_o\right) f\cos\alpha + G_u \sin\alpha\right] + \left[\left[\frac{G_u + 2G_o}{2g} + 2Lk_x F\right]\right] v^2 + G_u h_c \end{aligned} \tag{12}$$

where:

- E — the vehicle energy consumption [J],
- F — the surface area of the front of the vehicle [m^2],
- g — the standard acceleration due to gravity [m/s^2],
- G_o — kerb weight [N],
- G_u — load weight [N],
- f — the drag coefficient associated with a particular surface area and it takes the values: from 0.01 (on the concrete surface) to 0.3 (on the loose, dry sand surface),
- h_c — the platform's center of gravity vertical raising height, with the output during unloading [m],
- k_x — the drag coefficient [kg/m^3], equal to $c_x\rho/2$,
- c_x — the conefficient depending on the shape of the coachwork,
- ρ — air density under normal conditions [kg/m^3],
- α — the angle of transport road to the horizontal path [°],
- L — the length of transport road, i.e. the distance between loading and unloading point [m],
- v — the nominal vehicle speed [m/s].

Criterion F_7 recognizes the unit energy consumption of the various types of the off-highway trucks, adopted as the work required to overcome all movement resistance and giving the nominal speed related to the unit of transported output on the distance of 1 [m] road.

Reliability index – F_8, is maximized relaibility criterion, determining the probability that at any point in time the off-highway truck is in a state of roadworthiness and does the transport work. The criterion is determined for each variant as the average reliability index of individual vehicles, and described by the formula (13). The value of this criterion is expressed in [%].

$$F_8 = \frac{\sum_{i=1}^{n} t_i^{op}}{\sum_{i=1}^{n} t_i^{op} + \sum_{i=1}^{n} t_i^{re}} \tag{13}$$

where:

- t_i^{op} — the time of efficient vehicle operation in the i-th operation day [h],

t_i^{re} — the total time of renewal, expressed in [h]; it includes: the vehicle downtime within the effective repair, the external service corrective action time and the operation downtime in the service workshop (idle waiting for repair).

The time of efficient vehicle operation is considered as the time at which the haul truck is in a state of roadworthiness and performs the task of transport. In contrast, the time at which the haul truck is in a state of roadworthiness, but it is not used for execution of the transport tasks, nor is in reserve.

The efficient recovery time is that one in which the haul truck is repaired, unlike the time when it is broken-down and is waiting for repair, i.e. operation downtime in the service workshop. The description of above operating conditions, excluding states of work, stop and repair, was to expand and to refine the analysis of all the states, in which the vehicle is operating in practice. The purpose of this analysis, in addition to specifying the possible states, is to determine the components of the associated costs. This allows performing more complex and precise evaluation of the considered variants. In addition, completion of the above operating conditions was associated with the reliability index adjustment to the manner of recording operational information in some mines. The external service corrective action time is interpreted as the time in which the repair is performed by an authorized service of vehicle's manufacturer. In the analyzed time of renewal (repair) the times of repairs performed by capital (internal service) and the authorized service of vehicle's manufacturer are distinguished. This involves a clarification of all components of the off-highway dump trucks operating costs.

Stream damage parameter – F_9, is minimized criterion characterizing the number of the off-highway truck exclusions of the transport system due to breakdown, and it also allows to determine the average number of service requests, for the same vehicle, for renewal system, neglecting recharge time. Stream damage parameter is determined by the analyzed off-highway trucks individual population down time mean value per interval of the total worktime (5,000 engine hours). The value of this criterion is expressed in [damages/engine hours].

$$F_9 = \frac{\Delta n_l}{N_o \cdot L_p} \tag{14}$$

where:

Δn_l — the number of registered damages in the l-th range of the analyzed mileage [damages],

N_o — the number of specific type of vehicles in the analyzed population [units],

L_p — the total length of the range of the analyzed mileage (5,000 engine hours).

Ergonomics and driver comfort – F_{10}, is maximized criterion, describing the subjective feeling of comfort and workplace adaptation to the anatomical characteristics of the operator (driver). The criterion value is determined on the basis of a survey conducted among operators, using a checklist modeled on the Dortmund Checklist – ESAC[2]. This study covers the aspect of the off-highway trucks equipment, affecting the comfort and the ergonomics of the driver's working environment, including: spaciousness, visibility, insulation and air-conditioned cabins, type of a dashboard and the driver's seat, as well as ROPS, FOPS safety systems, etc. The value of this criterion is expressed in [points].

[2] Ergonomic System Analysis Checklist.

3.3. Designing of decision variants

The analyzed set of variants was defined *a'priori* – it was inalterable during the decision procedure, and based on the existing fleet of different types and manufacturers of the off-highway trucks; utilised in two selected raw rock mines K_1 and K_2. Twenty-one vehicles accepted for analysis, represented seven different decision variants in numerous's different populations. When defining the variants, the mines' similar exploitation conditions were included, as well as the specificity of the transport environment, i.e.:

– mining-geological conditions,
– mineral deposits operating system,
– transport distance,
– type of road surface (bituminous surface, hard-macadam surface, mixed road surface),
– size of differences in the levels of transport load,
– the amount of output transported during one transport cycle,
– the nature and quality of sourced minerals,
– weather and road changing conditions in the seasons.

Depending on the size of extraction, all of the analyzed vehicles perform tasks at the mines K_1 and K_2.

The haul trucks with a similar mileage and technical condition were adopted for the analysis; for all types of the off-highway trucks, regardless of the size of the variant's population, the following analysis, based on real data obtained from mines K_1 and K_2 for the assumed mileage range – 5,000 [engine hours], had been previously made: the unit energy consumption – F_7, the stream damage parameter – F_9, the reliability index – F_8. Furthermore, all the essential components of operating costs of every off-highway trucks in the assumed range of mileage, have been assigned and aggregated. The initial investment of each vehicle has been measured and capitalized on January 1, 2013, apart from the mode of acquisition and credits.

3.4. Construction of the family of criteria

Constructing a family of criteria, a special attention was paid to the issue of their complementarity, characterizing variants as a whole, completeness and evaluation consistency and non-redundancy. A decision problem was defined as a multiple criteria ranking of variants, i.e of the off-highway trucks. Therefore, an analyst with the participation of decision-makers (the group of experts), constructed a set of criteria for evaluating the analyzed variants (see section 3.2). In this analysis, new parameters in addition to these already in use, were suggested, which – according to the authors, better characterize the vehicles making deliveries in quarring.

Economic criteria have been intentionally divided into two components – the total investment costs and the total operating costs, because of their great importance for the majority of decision makers.

3.5. Models of decision makers′ preferences adopted for the analysis

Proceeding with modeling sensitivity of the analysis in ELECTRE III method, the characteristic for this method thresholds vaules (q_j, p_j, v_j) were used, taking into account the features of the decision problem. The range of equivalence (indifference of variants) was brought to decision makers' attention, as well as weak preference between variants, bounded below by indifference threshold q_j and bounded above by preference threshold p_j. In addition, the range of the strong preference between variants, in this method bounded below by preference threshold p_j and bounded above by veto threshold v_j, and the range of incomparability understood as drastic and not acceptable advantage of one variant over the other.

In the performed analysis, it was decided to constitute a group of decision-makers, representing selected, independent of each other, team of experts – presenting them the matrix of criteria values for the adopted decision variants (see Table 1).

The team consisted of three academic experts and two mining managers (including one who is also an academic expert in the field of surface mining technology), managing traffic and technology, and the selection of machines in opencast mines, as well.

The first academic expert is specializing in the analysis of work and terms of the technological equipment selection in surface mining, specifically mineral deposits. The second and third deal with the analysis of the operation and reliability of complex technical systems, and one of them with the decision-making process modeling, as well. Preferences of decision makers formulated within the research are presented in Tables 2-6. There are also included directions of preferences – dir_j of each of the criterion (min or max), pointing to minimize or maximize the value of the criterion. Values of weights of criteria relative importance are accepted in accordance with the decision makers preferences.

TABLE 1

Matrix of criteria values for the analyzed variants (Bodziony, 2013)

No.	Criteria		Variants						
	Name	**Unit**	A_1	A_2	A_3	A_4	A_5	A_6	A_7
1.	Total investment costs	thous. PLN	740	815	1,018	1,959	1,262	1,844	1,610
2.	Total operating costs	thous. PLN / 5,000 eng. hours	2,509	1,982	2,326	2,381	2,576	2,456	2,106
3.	Maximum power	kW	448	440	522	533	371	522	520
4.	Maximum torque	Nm	2,237	2,350	2,731	3,326	2,167	2,739	3,091
5.	Minimum turning radius	m	10.2	10.0	9.0	8.5	7.2	9.6	9.6
6.	Payload capacity	T	45.0	42.0	55.0	64.0	45.0	63.1	64.9
7.	Unit energy consumption	—	0.831	0.797	0.827	0.790	0.54	0.877	0.851
8.	Reliability index	%	66	61	61	92	92	57	85
9.	Stream damage parameter	damages / 1,000 eng. hours	7.18	9.36	15.0	6.46	6.15	9.10	6.46
10.	Ergonomics and driver comfort	points	43.7	38.2	82.8	116.1	96.0	72.7	98.2

where: A_1 – Bielaz 7547-3, A_2 – Bielaz 7548-D, A_3 – Bielaz 7555, A_4 – Komatsu HD605-7, A_5 – Komatsu HD405-7, A_6 – Euclid R60, A_7 – EH 1100-3

TABLE 2

Preferences of a decision maker, Expert 1 – an academic expert in the field of surface mining machinery (Bodziony, 2013)

No.	Criteria		Parameters of the model of preferences of Expert 1				
	Name	**Unit**	dir_j	k_j	q_j	p_j	v_j
1.	Total investment costs	thous. PLN	min	5	20	500	1,000
2.	Total operating costs	thous. PLN /5,000 eng. hours	min	10	50	100	350
3.	Maximum power	kW	max	5	5	20	100
4.	Maximum torque	Nm	max	5	200	500	800
5.	Minimum turning radius	m	min	2	1.0	1.5	2.5
6.	Payload capacity	T	max	15	2	10	15
7.	Unit energy consumption	—	min	8	0.05	0.15	0.25
8.	Reliability index	%	max	20	5	10	20
9.	Stream damage parameter	damages / 1,000 eng. hours	min	10	0.5	1.5	5.0
10.	Ergonomics and driver comfort	points	max	20	5	20	50

where: dir_j – direction of preferences, k_j – weighting factor, q_j – indifference threshold, p_j – preference threshold, v_i – veto threshold

TABLE 3

Preferences of a decision maker, Expert 2 – an academic expert in the field of operation of machines and vehicles (Bodziony, 2013)

No.	Criteria		Parameters of the model of preferences of Expert 2				
	Name	**Unit**	dir_j	k_j	q_j	p_j	v_j
1.	Total investment costs	thous. PLN	min	10	100	300	500
2.	Total operating costs	thous. PLN /5,000 eng. hours	min	20	50	200	400
3.	Maximum power	kW	max	6	50	70	100
4.	Maximum torque	Nm	max	9	100	400	600
5.	Minimum turning radius	m	min	10	1	2	3
6.	Payload capacity	T	max	14	3	8	12
7.	Unit energy consumption	—	min	7	0.01	0.03	0.10
8.	Reliability index	%	max	11	10	15	20
9.	Stream damage parameter	damages / 1,000 eng. hours	min	8	0.2	3.0	5.0
10.	Ergonomics and driver comfort	points	max	5	10	20	30

TABLE 4

Preferences of a decision maker, Expert 3 – a contract manager of the mine and an academic expert in the field of surface mining, as well (Bodziony, 2013)

No.	Criteria		Parameters of the model of preferences of Expert 3				
	Name	Unit	dir_j	k_j	q_j	p_j	v_j
1.	Total investment costs	thous. PLN	min	30	50	200	500
2.	Total operating costs	thous. PLN /5,000 eng. hours	min	20	20	100	200
3.	Maximum power	kW	max	10	20	100	150
4.	Maximum torque	Nm	max	2	100	200	500
5.	Minimum turning radius	m	min	1	2	3	5
6.	Payload capacity	T	max	10	5	10	20
7.	Unit energy consumption	—	min	7	0.01	0.03	0.10
8.	Reliability index	%	max	10	10	15	20
9.	Stream damage parameter	damages / 1,000 eng. hours	min	5	0.3	0.5	1.0
10.	Ergonomics and driver comfort	points	max	5	5	10	50

TABLE 5

Preferences of a decision maker, Expert 4 – a quarry manager for the production technology (COO) (Bodziony, 2013)

No.	Criteria		Parameters of the model of preferences of Expert 4				
	Name	Unit	dir_j	k_j	q_j	p_j	v_j
1.	Total investment costs	thous. PLN	min	5	100	200	1 000
2.	Total operating costs	thous. PLN /5,000 eng. hours	min	30	70	150	250
3.	Maximum power	kW	max	2	50	70	200
4.	Maximum torque	Nm	max	8	50	100	800
5.	Minimum turning radius	m	min	3	0.5	1.0	2.5
6.	Payload capacity	T	max	15	5	10	20
7.	Unit energy consumption	—	min	10	0.015	0.010	0.150
8.	Reliability index	%	max	15	7	10	30
9.	Stream damage parameter	damages / 1,000 eng. hours	min	5	0.2	5.0	10.0
10.	Ergonomics and driver comfort	points	max	7	20	30	50

TABLE 6

Preferences of a decision maker, Expert 5 – an academic expert in the field of operation and reliability of machines (Bodziony, 2013)

No.	Criteria		Parameters of the model of preferences of Expert 5				
	Name	**Unit**	dir_j	k_j	q_j	p_j	v_j
1.	Total investment costs	thous. PLN	min	16	50	150	300
2.	Total operating costs	thous. PLN /5,000 eng. hours	min	21	30	60	100
3.	Maximum power	kW	max	6	15	50	100
4.	Maximum torque	Nm	max	6	50	100	300
5.	Minimum turning radius	m	min	5	1.0	2.0	5.0
6.	Payload capacity	T	max	10	5	15	30
7.	Unit energy consumption	—	min	10	0.05	0.10	0.30
8.	Reliability index	%	max	10	5	15	30
9.	Stream damage parameter	damages / 1,000 engine hours	min	10	0.5	2.0	5.0
10.	Ergonomics and driver comfort	points	max	6	5	20	40

The above presented models of experts' preferences were constructed in a total independence of experts from each other, i.e. models were not consulted each other. In addition, each asked to take part in the analysis specialist, did not work under time pressure, third parties or persons analyst. The role of the analyst was to identify and explain the decision-making problem and to create a mathematical model that describes it, having regard to the field of knowledge and experience of decision makers, as well as the selection of all the methods and tools that allowed to solve this problem. As a result of the calculation procedure five final rankings were generated, individualy for each of the accepted models of decision maker's preferences (see from Fig. 2 to Fig. 6).

The final ranking shows that based on the model of 1st expert's preferences i.e., the academic expert of surface mining, see Fig. 2, two variants (K605 and H1100) outrank all others, and are the best variants. At the same time, these variants are mutually equivalent (indifferent), i.e. the variants are presented in one square. A similar relation is between B7548 and K405 variants, which are at a lower position in the final ranking. The ranking matrix contains final relations that exist between variants. There can be noticed a preference *P*, for example variant K405 is preferred to B7547 and B7555 variants. P^- refers to the inverse preference, i.e. ER60 variant is not preferred to the K405. And also, the already mentioned indifference relation *I*. Based on the concordance matrix, the K405 variant is 0.87 degree at least as good as the B7547 variant and a variant H1100 is 0.95 degree at least as good as the B7555 variant. In contrast, the credibility matrix shows the strength of the outranking relation between variants. In this model of the expert's preferences, there were no incomparable solutions (variants).

The final ranking of the analysis carried out, based on the accepted model of the 2nd expert's preferences (an academic expert in the field of operation and reliability of machines and vehicles), see Fig. 3, illustrates three variants B7548, K605 and H1100, which outrank all others

Final ranking

Ranking matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	*I*	P^-	P^-	P^-	P^-	P^-	P^-
B7555	*P*	*I*	P^-	P^-	P^-	P^-	P^-
B7548	*P*	*P*	*I*	P^-	*I*	*P*	P^-
K605	*P*	*P*	*P*	*I*	*P*	*P*	*I*
K405	*P*	*P*	*I*	P^-	*I*	*P*	P^-
ER60	*P*	*P*	P^-	P^-	P^-	*I*	P^-
H1100	*P*	*P*	*P*	*I*	*P*	*P*	*I*

Credibility matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.17	0	0	0	0	0
B7555	0	1	0	0	0	0	0
B7548	0.86	0.12	1	0	0	0	0
K605	0	0.94	0	1	0.94	0.99	0.87
K405	0.87	0	0	0	1	0	0
ER60	0	0.78	0	0	0	1	0
H1100	0.95	0.95	0.85	0.70	0.29	1	1

Concordance matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.44	0.90	0.21	0.51	0.54	0.23
B7555	0.87	1	0.78	0.30	0.55	0.79	0.29
B7548	0.86	0.57	1	0.23	0.46	0.57	0.25
K605	0.95	0.94	0.85	1	0.94	0.99	0.87
K405	0.87	0.63	0.81	0.45	1	0.65	0.65
ER60	0.69	0.78	0.83	0.34	0.37	1	0.35
H1100	0.95	0.95	0.85	0.70	0.83	1	1

Fig. 2. The set of results, incl.: final ranking, the ranking matrix, the credibility matrix and the concordance matrix of the model of the decision maker's preferences – an academic expert in the field of surface mining (Bodziony, 2013)

and are the best solutions. At the same time the best variants are indifferent (indistinguishable). A similar relation exists between the B7555 and K405 variants, which are at the lower level in the final ranking. In this model of the expert's preferences, there were no incomparable solutions (variants).

The final ranking, based on the presented analysis, shows that the accepted model for the 3rd expert's preferences, i.e. a quarry manager of production and transport technology, see Fig. 4, variant H1100 outranks all others and is the best solution. Moreover, the next variants K605 and B7548 in the ranking, are incomparable. In addition, K605 variant is incomparable with variants B7547, B7555 and K405. The incomparability relation *J* between variants is graphically illustrated by separated and unconnected squares at the same level. At the same time, variants K405 and B7547, are indifferent (indistinguishable).

Based on the final ranking, and the analysis for the adopted model of the 4th expert's preferences, who is manager and an expert on rock surface mining of raw materials, and contract manager

Final ranking

Ranking matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	*I*	P^-	P^-	P^-	P^-	*P*	P^-
B7555	*P*	*I*	P^-	P^-	*I*	*P*	P^-
B7548	*P*	*P*	*I*	*I*	*P*	*P*	*I*
K605	*P*	*P*	*I*	*I*	*P*	*P*	*I*
K405	*P*	*I*	P^-	P^-	*I*	*P*	P^-
ER60	P^-	P^-	P^-	P^-	P^-	*I*	P^-
H1100	*P*	*P*	*I*	*I*	*P*	*P*	*I*

Credibility matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0	0	0	0	0	0
B7555	0	1	0	0	0	0	0
B7548	0.94	0	1	0	0	0	0
K605	0	0	0	1	0	0.99	0.7
K405	0	0	0	0	1	0	0
ER60	0	0	0	0	0	1	0
H1100	0	0	0	0.84	0.11	1	1

Concordance matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.46	0.73	0.29	0.65	0.66	0.34
B7555	0.83	1	0.6	0.46	0.64	0.78	0.37
B7548	0.94	0.67	1	0.42	0.59	0.66	0.47
K605	0.9	0.89	0.7	1	0.8	0.99	0.7
K405	0.82	0.44	0.62	0.47	1	0.62	0.51
ER60	0.78	0.72	0.63	0.56	0.49	1	0.37
H1100	0.87	0.85	0.73	0.84	0.73	1	1

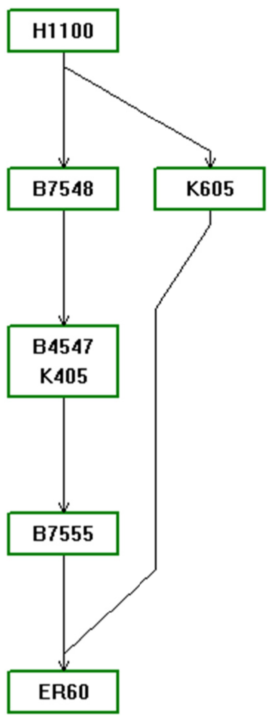
Fig. 3. The set of results, incl.: the final ranking, the ranking matrix, the credibility matrix and concordance matrix of the model of the decision maker's preferences – an academic expert in the field of operation and reliability of machines and vehicles (Bodziony, 2013)

in mine, at the same time, (Fig. 5) it appears that variant H1100 outranks all others, providing the best solution. In addition, the next variants K605 and B7548 in the ranking are incomparable. Like the relation between variants B7555 and B7548, which in turn is incomparable with K405 variant, and B4547 variant is incomparable with ER60 variant. The incomparability relation *J* between variants is graphically illustrated by separated and unconnected squares at the same level.

The final ranking in the presented analysis shows that for the accepted model of the 5th expert's preferences (an academic expert in the field of operation of machines and vehicles), see Fig. 6, variant H1100 outranks all others, providing the best solution. It is a better solution than B7548 variant, and worse solutions are variants B7555, K405 and K605. In addition, K605 variant is incomparable with variants B7555 and K405, which in turn are indifferent (equivalent). The worse solution is variant ER60.

The results of all analysis, clearly show the advantage of the variant H1100 over other options. H1100 variant meets almost all of the most important criteria accented by the experts in

Final ranking



Ranking matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	*I*	*P*	P^-	*J*	*I*	*P*	P^-
B7555	P^-	*I*	P^-	*J*	P^-	*P*	P^-
B7548	*P*	*P*	*I*	*J*	*P*	*P*	P^-
K605	*J*	*J*	*J*	*I*	*J*	*P*	P^-
K405	*I*	*P*	P^-	*J*	*I*	*P*	P^-
ER60	P^-	P^-	P^-	P^-	P^-	*I*	P^-
H1100	*P*	*P*	*P*	*P*	*P*	*P*	*I*

Credibility matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.0062	0	0	0	0	0
B7555	0	1	0	0	0	0	0
B7548	0	0.41	1	0	0	0	0
K605	0	0	0	1	0	0.87	0
K405	0	0	0	0	1	0	0
ER60	0	0	0	0	0	1	0
H1100	0	0	0	0.86	0.071	1	1

Concordance matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.56	0.73	0.33	0.72	0.68	0.41
B7555	0.65	1	0.38	0.63	0.73	0.89	0.48
B7548	0.89	0.75	1	0.59	0.72	0.75	0.6
K605	0.7	0.61	0.5	1	0.63	0.87	0.5
K405	0.51	0.28	0.42	0.53	1	0.58	0.58
ER60	0.58	0.38	0.43	0.57	0.43	1	0.22
H1100	0.67	0.65	0.43	0.86	0.62	1	1

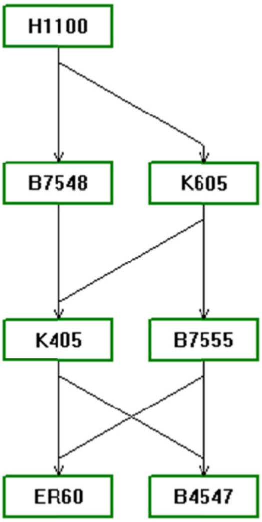
Fig. 4. The set of results, incl.: the final ranking, the ranking matrix, the credibility matrix and the concordance matrix of the model of the decision maker's preferences – a quarry manager of production and transport technology (Bodziony, 2013)

the field of opencast mining technology, as well as the experts of machines' operation. Moreover, this variant gets a high position in terms of equally important criterion (with the highest relative importance) for all decision makers, namely operating costs, giving way to only one variant B7548. Therefore, the decision about its possible application reduces capital expenditures (compared with variants ER60 and K605), but most of all operating expenditures, while ensuring driver-operator ergonomic and comfortable working conditions.

It should also be paid special attention to the high position of the variant B7548 in all anlysis carried out and its relations to K605 variant. Regardless of the experts specialization the presented variants above occupy both high and ambiguous classification level in final rankings, despite the fact that their technical level differs.

Variant B7548 is an old construction characterized by high fuel consumption, high failure rate and unacceptable levels of ergonomics and comfort. However, due to low investment costs, especially operational cost, it may be an alternative to other off-highway trucks. Although

Final ranking



Ranking matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	*I*	P^-	P^-	P^-	P^-	*J*	P^-
B7555	*P*	*I*	*J*	P^-	*J*	*P*	P^-
B7548	*P*	*J*	*I*	*J*	*P*	*P*	P^-
K605	*P*	*P*	*J*	*I*	*P*	*P*	P^-
K405	*P*	*J*	P^-	P^-	*I*	*P*	P^-
ER60	*J*	P^-	P^-	P^-	P^-	*I*	P^-
H1100	*P*	*P*	*P*	*P*	*P*	*P*	*I*

Credibility matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.2	0	0	0	0.41	0
B7555	0.9	1	0	0	0	0.86	0.016
B7548	0.98	0.5	1	0	0	0	0
K605	0	0.95	0	1	0.89	0.99	0
K405	0.9	0	0	0	1	0.16	0
ER60	0	0.46	0	0	0	1	0
H1100	0.94	0.93	0.6	0.84	0.19	1	1

Concordance matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.35	0.6	0.25	0.67	0.68	0.22
B7555	0.9	1	0.58	0.5	0.7	0.86	0.27
B7548	0.98	0.65	1	0.47	0.69	0.68	0.5
K605	0.95	0.95	0.65	1	0.89	0.99	0.65
K405	0.9	0.4	0.55	0.45	1	0.56	0.45
ER60	0.8	0.68	0.57	0.54	0.62	1	0.34
H1100	0.94	0.93	0.7	0.84	0.82	1	1

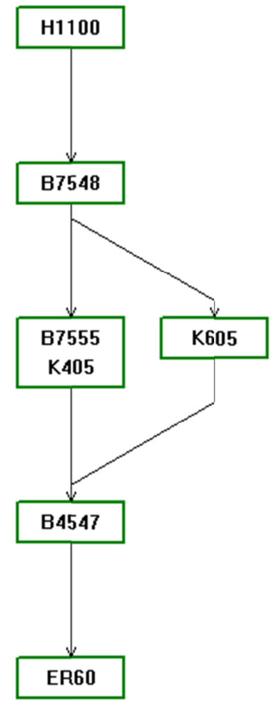
Fig. 5. The set of results, incl.: the final ranking, the ranking matrix, the credibility matrix and the concordance matrix of the model of the decision maker's preferences – an expert on rock surface mining of raw materials, and contract manager in mine, at the same time (Bodziony, 2013)

it is not produced in the analyzed version, it is still available as a so-called *vehicle after the reconstructtion*. In addition, it may be modified by an appropriate retrofitting, with relatively low investments.

High ranking position of K605 variant should be interpreted in a quite different manner. In contrast to the B7548, it is a new construction (the highest reliability index – F_8 of the analyzed off-highway dump trucks population – 92.14%, and the lowest stream damage parameter – F_9), providing the driver a high level of ergonomics and comfort (the highest score in the survey of drivers' subjective feelings). However, this variant is characterized by the highest investments of all comparable vehicles, as well as high operating costs associated with servicing and relatively high fuel consumption. What is noteworthy, discussed variants have very similar unit energy consumption – F_7.

Vehicle occupying the last position in almost all rankings is ER60, which turned out to be *the worst* variant. This is due to both the high investment costs, operational costs, and above

Final ranking



Ranking matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	*I*	P^-	P^-	P^-	P^-	*P*	P^-
B7555	*P*	*I*	P^-	*J*	*I*	*P*	P^-
B7548	*P*	*P*	*I*	*P*	*P*	*P*	P^-
K605	*P*	*J*	P^-	*I*	*J*	*P*	P^-
K405	*P*	*I*	P^-	*J*	*I*	*P*	P^-
ER60	P^-	P^-	P^-	P^-	P^-	*I*	P^-
H1100	*P*	*P*	*P*	*P*	*P*	*P*	*I*

Credibility matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0	0	0	0	0	0
B7555	0	1	0	0	0	0	0
B7548	0.86	0	1	0	0	0	0
K605	0	0	0	1	0	0.9	0
K405	0	0	0	0	1	0	0
ER60	0	0	0	0	0	1	0
H1100	0	0	0.84	0	0	5	1

Concordance matrix

	B4547	B7555	B7548	K605	K405	ER60	H1100
B4547	1	0.55	0.73	0.36	0.7	0.56	0.4
B7555	0.74	1	0.53	0.64	0.68	0.87	0.44
B7548	0.86	0.74	1	0.49	0.69	0.72	0.52
K605	0.84	0.66	0.63	1	0.82	0.9	0.63
K405	0.55	0.46	0.51	0.51	1	0.57	0.57
ER60	0.71	0.61	0.57	0.39	0.43	1	0.31
H1100	0.84	0.84	0.62	0.84	0.68	1	1

Fig. 6. The set of results, incl.: the final ranking, the ranking matrix, the credibility matrix and the concordance matrix of the model of the decision maker's preferences – an academic expert in the field of operation of machines and vehicles (Bodziony, 2013)

all, high level of damage, which according to the expressed preferences of all decisiom makers, regardless of their specialization, resulted in a lack of its acceptance.

As can be seen, the experts in the field of opencast mining paid particular attention to the parameters associated with the transport process technology (capacity) and to criteria related to the off-highway dump trucks operations (emphasizing the essential: the reliability index – F_8, the operating costs – F_2, and subsequently the unit energy consumption – F_7). The results of final rankings indicate that significance of construction features and technical parameters is low.

Specialists in the field of machines and vehicles operation focused on two areas of criteria. The first one, covering the technical-reliability parameters, with an emphasis on construction features, as well as indicators describing the technical readiness and failure. The second important area is the economic issue, including both investment and primarily operating costs.

Representatives of the mine management presented polarized position on the investment costs (recognizing weighting factors at the level, respectively 30 and 5). However, they have recognized operating cost as a criterion with the highest relative importance. Moreover, the construction features proved to be important, with an emphasis on capacity.

Notably, universal and equally important parameter for all expert, are operating costs, but their greatest significance, within proposed criteria, is evidenced by high weights given by all the experts.

According to the analyst, the experts didn't tie sufficient importance to the unit energy consumption parameter, which as a criterion aggregates a large number of extremely important sub-criteria (components) associated with mining and geological conditions of the mine and its transport surrounding.

4. Conclusions

The authors presented the practical application of multiple criteria decision aiding (MCDA) methods and one of these methods – ELECTRE III, to solve the problem of the evaluation and selection of the off-highway dump trucks in specific operating conditions of opencast mining of rock materials.

The proposed methodology is universal and can be used in many mines, especially in the case of replacement of the of off-highway dump trucks fleet. Notably, on the mentioned versatility affect:

- constructing (specifying) universal set of reliable criteria, allowing for a comprehensive, multi-faceted analysis of off-highway dump trucks;
- performing complex process modeling and aggregation of interdisciplinary decision criteria, in order to obtain a meaningful assessment of their value and properly define the nature and their ranges;
- solving the analyzed decision problem with an application of MCDA method – ELECTRE III, extremely useful in this type of issues;
- carrying out the analysis of the decision makers preferences, representatives of diverse groups of experts, and drawing attention to the crucial role of the models of decision makers preferences in the decision making process by defining the importance of each decision criteria (assigning weights) and determining the sensitivity of the decision makers experts to change their values (setting preference thresholds).

In addition, the carried out analysis show that it is possible to significantly reduce the efforts, both investment and operating costs, while providing ergonomic and comfortable driver's working conditions by the application of MCDA methods in the problem of the off-highway dump trucks in opencast mining selection.

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