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Multi-Criteria System's Design Methodology for Selecting Open Pits Dump Trucks

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Abstract: The sustainable development and operation of mining enterprises as major sources of economic growth in many countries is determined by both a balance of economic, environmental, and social objectives and the resources required to achieve these objectives. Transportation is one of the main resources at open pits. It accounts for up to 70% of open pit operating expenses. Various parameters of transportation means should be coordinated both with the parameters of the open pit and meet the conditions of its operation. The problem of selecting a dump truck model in the paper is solved using a universal system of selection criteria developed using an original methodology. The two-level system of criteria includes all currently known selection criteria. The peculiarity of the methodology is the use of the multi-criteria FUCOM method for ranking the criteria. In addition, it is proposed to differentiate the criteria evaluations according to the experts' competence levels. Sets of criteria for evaluation by experts of different levels are proposed. The obtained criterion ranks are recommended to be used by managers of mining enterprises to choose a dump truck model. The presented methodology is suitable for the development of new systems of criteria, considering significant changes in operating conditions or the emergence of factors not considered in this study. Evaluation of all models of dump trucks on the market using the developed system of criteria is envisaged by the authors in a future study.

Keywords: open pit; dump track; multi-criteria system; MCDM; FUCOM

1. Introduction

The largest volume of transportation of rock mass in open-pits is carried out all over the world by dump-trucks of various carrying capacities [1,2]. The cost of transporting rock mass increases by 20-30% on average for every 100 m of depth in deep pits. The share of these costs reaches 70% or more of field development total cost [3–5]. At the same time, the maximum transportation distance is 10 km for deep open pits.

Cost reduction is achieved by combining modes of transport. The combination of automobile and conveyor transport or cyclical-and-continuous method is the most common in open pits [6,7]. Most researchers consider this method promising for deep open pits [8,9]. The implementation of this method requires the creation of transshipment points. The effectiveness of schemes with combined transport depends on the depth of the transshipment points in the open pit. Nevertheless, the share of transportation by dump trucks remains considerable in this case [10,11].

Many alternative options for the layout of the open pit transport system have appeared in mining enterprises currently. This is due both to an increase in the carrying capacity of new models of mining dump trucks, and the number of dump truck manufacturers. The tendency to increase the carrying capacity of dump trucks to ensure the required cargo turnover is especially relevant for large and deep open pits [12,13]. The maximum carrying capacity of modern mining dump trucks has reached 450 tones [3]. According to [14], nine major manufacturers of mining dump trucks are represented on the world market. However, their number tends to increase. In addition, the range of mining equipment is constantly expanding.

These factors are the reason for a significant variety of applied technical and technological solutions. The results of 13 open pit projects carried out by the authors show that the most common differences are the following: the load capacity of dump truck models in the same open pit – 5 times; the estimated width of the transport berm – 1.5-3 times; the depth, and angles of the conveyor in

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different open pits – 2–4 times; the number of dump trucks for various transport complex layout options, but for the same open pits depth and productivity – up to 10 times [10] (Figure 1).

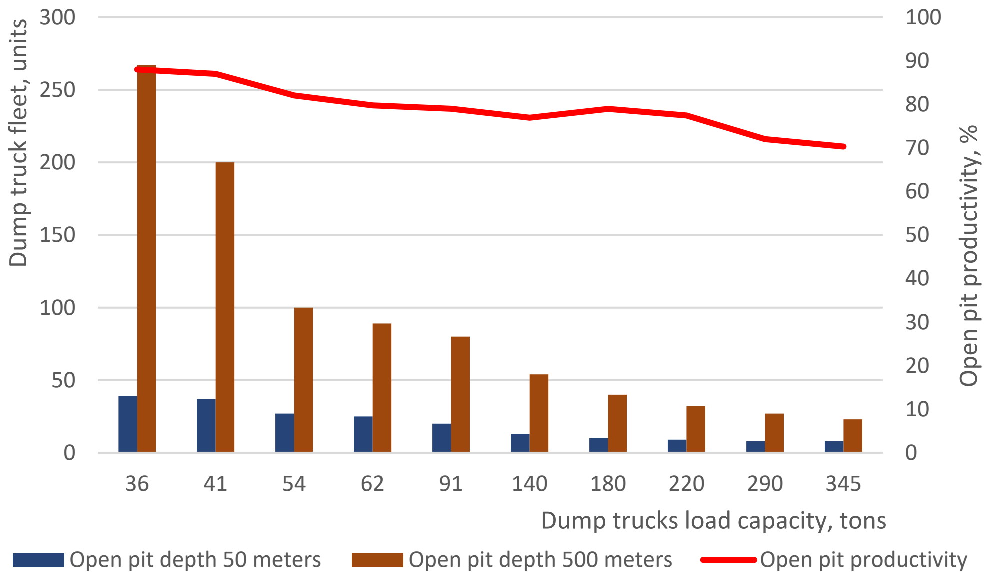

Figure 1. Change in the number of dump truck fleet of the depth and productivity of the open pit.

Table 3. dump trucks account for one mining excavator at a depth of open pits up to 200 meters, and at a depth of 200–600 meters – 10 or more dump trucks. Moreover, open pit transport constitutes the bulk of the equipment and is 2.1-3.7 times higher than the number of all other types of equipment for the main technological processes (Figure 2).

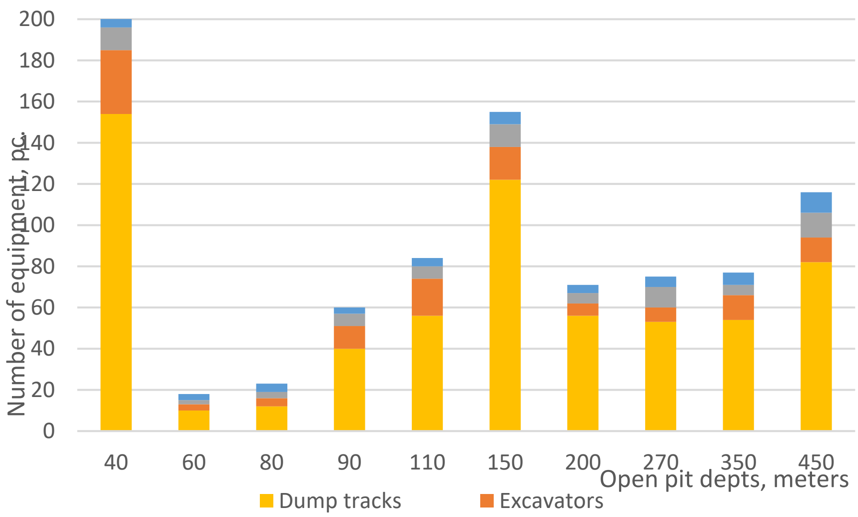

Figure 2. The amount of equipment in different depths open pits.

The negative impact of the mining enterprise on the environment forces as the number of equipment increases. Especially relevant are the issues of the negative impact of equipment operation on the atmosphere in deep open pits. The main negative impact from open pit equipment is emissions from the operation of dump truck engines and dust during the transportation of rocks [15]. Dump trucks account for 60 to 75% of emissions (Figure 3). The presented results of these author's studies do not consider the volume of emissions during the production of blasting. These emissions are not permanent and do not affect the work of personnel and equipment in the open pit, since until the complete dispersion of the dust-gas cloud, after blasting, the resumption of work in the open pit is not allowed.

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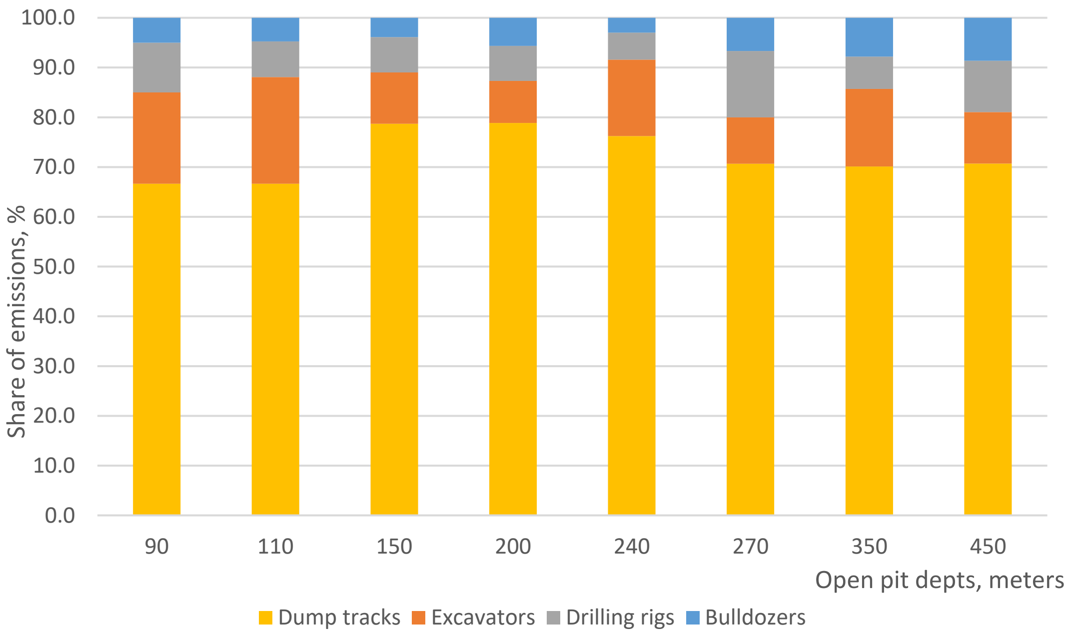

Figure 3. Contribution of different types of equipment to open pit emissions.

In this regard, environmental issues acquire a significant influence on the design decisions for deep open pits [16–19].

Improving the efficiency of deep open pits operations requires the consideration of many alternative solutions in such conditions. One of the most important decisions is the selection of a specific dump truck model. The presence of numerous factors and options makes the selection issue complex and multi-criteria.

The main goal of this study is to develop a methodology for the multi-criteria selection of a dump truck model.

The rest of the paper is organized as follows. A literature review of studies on the factors, methods, and criteria for selecting a dump truck model is presented in Section 2. The original system of criteria for selecting a dump truck model and the selection methodology using the multi-criteria FUCOM method is presented in Section 3. Section 4 contains a case study on the proposed methodology effectiveness. Finally, conclusions and recommendations for the application of the selection methodology and future research are presented in the Conclusion.

2. Literature review

2.1. Factors for Selecting a Dump Truck Model

One of the main factors is the excavator model, the choice of which, in turn, depends on the height of the ledge, the physical and mechanical properties of the rocks and the required productivity of the open pit [20]. However, numerous variants of dump truck models are possible for the same excavator model.

The authors [21] propose to consider the properties of rocks, the distance of transportation, the amount of work and the rate of the deposit development when selecting a dump truck model. The authors of the study [22] consider the ratio of the dump truck body capacity to the capacity of the excavator bucket, which should be in the range from 4-6 to 7-8, to be the most important factor. In addition, they suggest selecting higher capacity models as the open pit deepens, transport distances increase, and rock mass transport volumes increase. Three factors are proposed to be considered in the paper [23]. The first factor is the maneuverability of the dump truck, which depends on its technical characteristics, including the load capacity and size of the dump truck. The second factor is

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the carrying capacity, which must correspond to the transportation volumes. Finally, the third factor is safe working conditions.

Many studies are devoted to the choice of a rational model of a dump truck based on economic factors. The competitiveness coefficient, which considers the prices of compared models, as well as several technical characteristics, was proposed in [24]. The indicator of the efficiency of transport work is studied in [25]. This indicator considers changes in mining conditions and the economic situation. The value of the total discounted costs for the acquisition and operation of dump trucks [3] is one of the common indicators for evaluating dump truck models. Economic losses from downtime of dump trucks [26], including because of their breakdowns [27], are considered when choosing dump trucks. Options for using fuel [28] and other energy sources [15,29] are determining the amount of operating expenses for various models of dump trucks. Researchers in [30–32] suggest considering the possibility of using conveyors in an open pit when selecting dump truck models. The choice is also made based on an economic comparison of the options in these studies.

The cost of buying dump trucks and subsequent operating expenses are major factors in business practice. To perform the corresponding calculations, various software tools are used, for example, PTV Vissim [33] in the method [34].

However, the emphasis mainly on economic indicators does not allow considering the environmental friendliness and safety of operation of dump trucks. Progressive mining enterprises are beginning to shape their mission in accordance with the concept of sustainable development. Social and environmental factors, as well as factors of automation of transportation and production processes, begin to influence decision-making [35–37] at such enterprises.

The systematic consideration of these factors is especially difficult when selecting a model of dump trucks for deep open pit conditions. This is because the fleet of dump trucks is completely replaced as the open pit deepens.

Thus, technical, technological, economic, environmental, geological, and organizational factors must be considered when selecting dump truck models to ensure the efficient operation of deep open pits.

2.2. Multi-Criteria Decision-Making Methods

Numerous influencing factors, as well as the specifics of work at great depths, predetermines the need for a multifactorial and multicriteria approach to solving the problem of selecting mining dump trucks. Therefore, we propose to use multi-criteria methods to select a dump truck model. These methods are based on expert ranking of criteria for evaluating alternatives, followed by ranking of alternatives in accordance with the rank of criteria. This approach allows considering many conflicting factors and requirements. Currently, such methods are widely used in mining and in the choice of transport and handling systems for open pit mining. We performed an analysis of the experience of using MCDM to identify the most used methods. The result of the analysis is presented in Table 1.

Table 1. MCDM for the selection of transportation and loading-handling systems in mining.

Systems	Research Area	MCDM	Source
Sustainable transportation system	The selection of sustainable vehicles in the mining industry	AHP-DEA	[28]
	Selection of open pit dump trucks	AHP	[38]
	Selection of open pit dump trucks	ELECTRE III	[39]
	Selection of open pit dump trucks	APEKS	[40]
Transportation system	Selection of dump trucks for transporting ore from the mine	WPM, ELECTRE I, PROMETHEE II	[41]
	Selection of open pit dump trucks	AHP-Fuzzy WSM	[42]

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	Selection of open pit dump trucks	Fuzzy TOPSIS	[43]
	Selection of ore transportation option	AHP	[31]
	Selection of loading-hauling systems for open pit mining	Fuzzy AHP	[44]
	Selection of mobile surface mining machines for excavating, transporting, and loading coal or ore	AHP	[45]
	Selection of dump trucks, wheel loaders, crawler excavators, bulldozers, and blast hole drilling rigs	AHP-TOPSIS	[46]
Loading-hauling systems	Selection of loading-hauling equipment for open pit mining	Fuzzy AHP	[47]
	Selection of loading-hauling equipment for open pit mining	Fuzzy AHP-Fuzzy TOPSIS	[32]
	Selection of loading-hauling systems for open pit mining	AHP-Fuzzy TOPSIS	[48]
	Selection of loading-hauling systems for open pit mining	AHP	[49]
	Selection of loading-hauling equipment	Fuzzy ANP-Fuzzy PROMETHEE	[50]

The Analytic Hierarchy Process (AHP) or fuzzy AHP method, as well as its combinations with other methods (TOPSIS, PROMETHEE, ELECTRE) is used most often for the selection of dump trucks and loading and unloading systems in open pits. The analyzed methods (Table 1) are widely used in various research areas, use both quantitative and qualitative evaluation criteria, are relatively simple, and are also implemented in convenient software.

The main disadvantage of the considered methods is many pairwise comparisons of criteria. This makes the procedure of multi-criteria evaluation time-consuming with numerous criteria. Several researchers in the field of MCDM have proposed more efficient methods for multi-criteria evaluation of [51–53]. Full Consistency Method (FUCOM) [54] is the most promising according to the authors. However, we were unable to find studies on the application of this method in mining. Given the large number of factors influencing the choice of dump trucks for open pits, we suggest using FUCOM.

3. Models and Methods

3.1. Methodology of Forming a System of Criteria for Selecting a Dump Truck Model

We have developed a methodology, the result of which was the original universal system of criteria for selecting a model of mining dump trucks. The methodology consists of the following 5 stages.

Stage I. Analysis of research in the field of selecting mining equipment, dump trucks, optimizing the operation of mining vehicles. Identification of factors and formation of a list of selection criteria.

Stage II. Primary grouping of criteria according to factors influencing the selection of a dump trucks. Grouping is done by establishing relationships between factors and criteria.

Stage III. Formation of an initial data set. We suggest the following list of data: the range of values, the unit of measure, the target value of the criterion. In addition, the description of the criterion should contain its name, a brief explanation, the name of the corresponding group of criteria, and an indication of the source of data on the range of quantitative values of the criterion. An example of the initial data collection form is presented in Table 2.

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Table 2. Form for criteria initial data presentation (example).

Criteria group	Criteria	Brief explanation	Unit	Data source	Range of values	Target value
Technica l	Useful life	Manufacturer-guaranteed useful life	Years	Dump truck technical indicators	3-7	max

Stage IV. Secondary grouping of criteria. This grouping is recommended to equalize the number of criteria in the groups. Such adjustment is necessary for the correct ranking of criteria by the FUCOM method. Secondary grouping is carried out by combining similar criteria in terms of meaning, units of measurement, range of acceptable values and target values. In addition, it is allowed to combine groups of criteria according to the similarity of the relevant factors. In addition, we recommend excluding conditionally constant parameters, as well as dependent parameters, from consideration. For example, the technical indicator "duration of unloading a dump truck" is excluded, since it is conditionally the same for all mining dump trucks and the time spent on unloading does not exceed 1% of the total duration of the trip. Another technical indicator, "average rolling resistance," is also excluded, since its value depends on other criteria already included in the group of technical criteria.

Thus, we received four groups of criteria: technical, technological, environmental, economic and organizational. In addition, we recommend excluding conditionally constant parameters, as well as dependent parameters, from consideration. For example, the technical parameter "duration of unloading a dump truck" is excluded, since it is conditionally the same for all mining dump trucks and the time spent on unloading does not exceed 1% of the total duration of the trip. Another technical parameter, "average rolling resistance," is also excluded, since its value depends on other parameters already included in the group of technical criteria.

Thus, we received four groups of criteria: technical, technological, environmental, economic and organizational.

Stage V. Distribution of criteria by expert competence levels for further ranking of criteria by the FUCOM method. Such a distribution is necessary to obtain the most objective and qualitative assessment of the criteria. We proceeded from the assumption that the most qualitative assessment of the criteria can be given by experts with competencies that best match the content of the criterion. We propose to allocate three levels of expert competence, namely, strategic, design, and optimization.

Level 1 – Strategic. Experts of this level have competencies in the field of strategic management of a mining enterprise. These experts evaluate the criteria that determine the company's financial performance and reputation. We classified owners or presidents of companies, key executives, general, commercial, and technical directors, as well as their deputies, as first-level experts.

Level 2 – Design. The second level experts evaluate the criteria that are used in making design decisions. The experts at this level are the heads and specialists of the design and engineering department, chief engineers, miners, geologists, mine surveyors, heads and specialists of planning and economic departments, heads of labor protection and environmental departments.

Level 3 – Optimization. At the third level, experts evaluate the criteria directly related to the process of operation and maintenance of dump trucks in an open pit. Such experts include mechanics, power engineers, heads of open pits, transport departments and shift supervisors.

A flowchart of the proposed methodology for systematizing the selection criteria for dump trucks is shown in Figure 4.

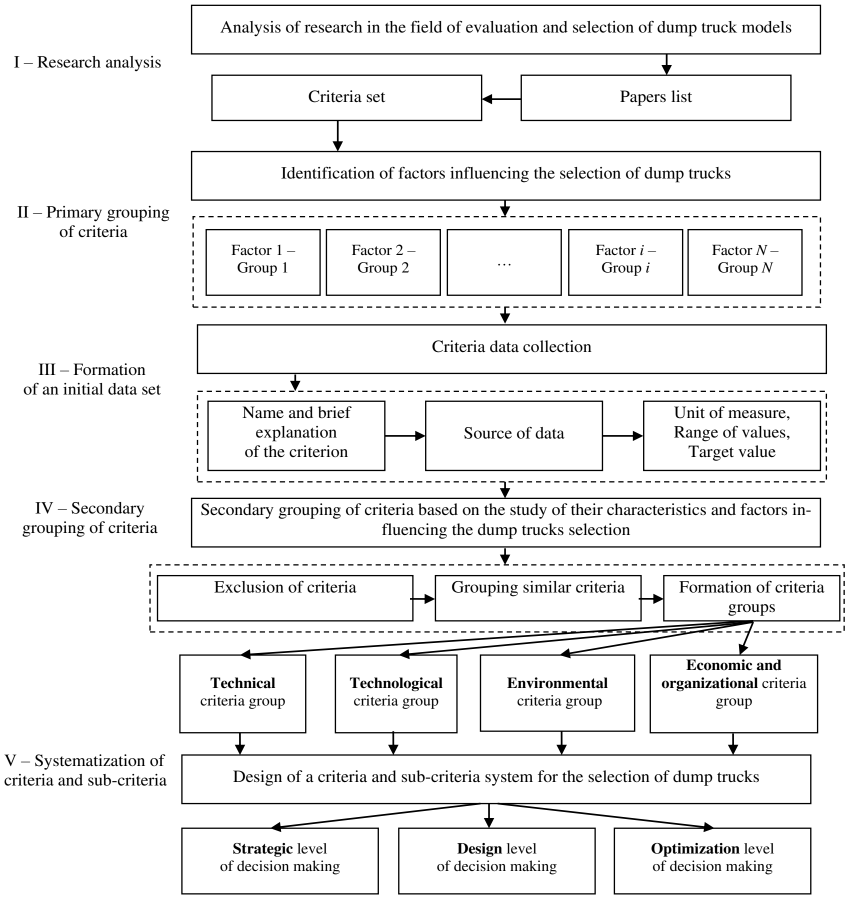

Figure 4. Methodology of the criteria system design for the dump trucks selection.

The presented methodology is general for solving the criteria system design problem. The initial data are scientific publications and the results of surveys of industrial experts. Nevertheless, the authors propose to use the developed system of criteria (see Section 4) as a base one, since it is the result of an analysis of all currently known factors considered when choosing models of dump trucks.

2.2. FUCOM Method for Calculating Criterion Weights

The Full Consistency Method (FUCOM) [43] was chosen to calculate the weight of the criteria that determine the selection of dump trucks. The choice of the FUCOM method is justified by the fact that in comparison with AHP, ANP and BWM, it provides the following advantages [54–56]:

- Minimum number of pairwise comparisons of criteria equal to (n -1), compared to AHP (n(n - 1)/2), and to BWM (2n - 3).
- Simple algorithm is used for prioritization of criteria by decision makers.
- High reliability of the result.
- Allows obtaining optimal weighting factors with the possibility of validating them, showing the consistency of the results.

Thus, the FUCOM method, unlike AHP and BWM, provides an opportunity to perform model checking by calculating the error size for the obtained criterion weight vectors, to determine the degree of consistency and thus adequately reflect errors in expert judgments.

The FUCOM method has been used in transportation to evaluate and select: alternative fuel vehicles [57], human resources of a transportation company [58] and others. In the mining industry — to assess the mineral potential of new deposits [56].

The basic steps of the FUCOM method are:

Step 1. Ranking of criteria $C = \{C_1, C_2, \ldots, C_j, \ldots, C_n\}$ according to their significance, starting from the criterion that will have the highest weight to the criterion of the lowest significance. Each j-th criterion is assigned a rank k

$$C_{j(1)} > C_{j(2)} > \ldots > C_{n(k)} \tag{1}$$

Step 2. Comparison of ranked criteria and determination of comparative priority Φ for criteria

$$\varphi_{k/(k+1)}, k = 1,2 \ldots, n, \tag{2}$$

$$\Phi = (\varphi_{1/2}, \varphi_{2/3}, \ldots, \varphi_{k/(k+1)}). \tag{3}$$

Step 3. Calculation of the final values of the weight coefficients of the evaluation criteria forming the transposed matrix $\omega = (\omega_1, \omega_2, \ldots, \omega_j, \ldots, \omega_n)^T$. The values of the matrix ω must satisfy the following two conditions.

The ratio of weighting coefficients should be equal to the comparative priority of criteria $\varphi_{k/(k+1)}$ determined at the second step

$$\frac{\omega_k}{\omega_{k+1}} = \varphi_{k/(k+1)}. \tag{4}$$

- The final values of weight coefficients should satisfy the condition of mathematical transitivity

$$\varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)} = \varphi_{k/(k+2)} \tag{5}$$

Considering (4) and (5) we obtain

$$\frac{\omega_k}{\omega_{k+1}} \otimes \frac{\omega_{k+1}}{\omega_{k+2}} = \frac{\omega_k}{\omega_{k+2}}. \tag{6}$$

Thus, we obtain a new condition, which must be satisfied by the final values of the weight coefficients of the evaluation criteria

$$\frac{\omega_k}{\omega_{k+2}} = \varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)} \tag{7}$$

Step 4. Solution of the model for calculating the values of weighting coefficients of evaluation criteria. The model minimizes the value of deviation χ from the full consistency of the results

$$min\, \chi, \tag{8}$$

$$\chi = \left|\frac{\omega_{j(k)}}{\omega_{j(k+1)}} - \varphi_{k/(k+1)}\right|, \forall j, \tag{9}$$

$$\chi = \left|\frac{\omega_{j(k)}}{\omega_{j(k+2)}} - \varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)}\right|, \forall j, \tag{10}$$

$$\sum_{j=1}^{n} \omega_j = 1, \forall j, \tag{11}$$

$$\omega_j \geq 0, \forall j. \tag{12}$$

As a result of solving the model (8-12), the values of evaluation criteria are obtained $\omega = (\omega_1, \omega_2, \ldots, \omega_j, \ldots, \omega_n)^T$.

The proposed methodology for determining the weights of criterion groups and criteria for selecting dump trucks using the FUCOM method is presented in Figure 6.

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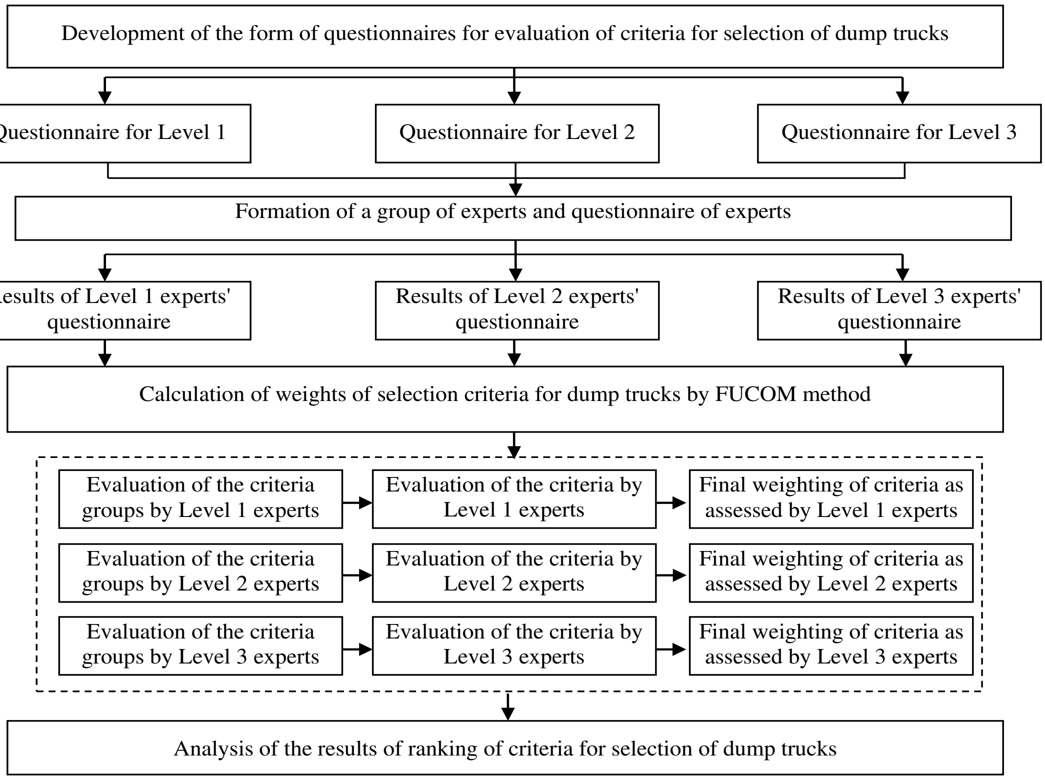

Figure 5. Methodology for ranking criteria for selection of dump trucks.

4. Results

4.1. Data Collection and Formation of a Universal System of Dump Truck Selection Criteria

The selection of a dump truck model using multi-criteria methods requires the definition of a criterion set for evaluating various models. We analyzed 49 studies to identify the criteria used to address this issue. We analyzed studies on the selection of a dump trucks, equipment complexes for open pits, as well as studies on the features of transport operation in deep open pits. The results of the analysis are presented in Table 3.

Six groups of criteria (Stage 2) were initially identified: technical, technological, geological, economic, environmental, and organizational. The number of criteria in the initial groups turned out to be uneven, from 4 to 26.

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Table 3. The result of criteria data collection for selecting dump trucks*.

№	Criteria	References																																														
		[59]	[60]	[61]	[44]	[28]	[45]	[46]	[47]	[32]	[30]	[31]	[12]	[38]	[34]	[62]	[63]	[64]	[65]	[66]	[39]	[67]	[43]	[24]	[68]	[69]	[40]	[70]	[41]	[42]	[71]	[72]	[48]	[49]	[25]	[1]	[3]	[15]	[73]	[29]	[74]	[26]	[75]	[76]	[27]	[12]	[77]	[78]	[79]	[80]
	Technical Criteria Group																																																	
1	Useful life	+			+				+	+				+											+				+		+	+	+		+				+				+		+	+			+	+
2	Grade		+		+											+	+							+					+		+		+				+	+	+		+	+				+	+			
3	Fuel efficiency (fuel consumption)			+		+	+			+				+		+					+			+		+	+		+							+	+	+	+						+		+			
4	Production				+					+		+													+							+	+		+	+	+	+	+	+		+	+							+
5	Average rolling resistance				+											+				+													+	+							+		+		+	+	+			
6	Mobility				+									+																			+										+							
7	Net to Tare Ratio				+											+				+													+		+					+										
8	Safety (Technology and safety systems)					+	+		+	+		+	+	+												+			+																					
9	Vibration and impact	+																											+						+	+						+				+				+
10	Comfort (ergonomics)					+	+		+					+							+								+						+	+													+	+
11	Ease of maintenance						+		+			+		+																											+									
12	Maneuverability								+																																					+				
13	Power selection (Maximum power)													+							+								+																					
14	Altitude limitation													+																																				
15	Reliability													+							+																													
16	Visibility													+																																				
17	Maximum torque																				+																													
18	Minimum turning	+																			+			+			+																							
19	Payload capacity																			+	+	+	+				+		+	+	+																			
20	Manufacturer of Engine																						+						+																					
21	Gearbox																												+																					
22	Truck box features																						+																											
23	Truck suspension system	+																					+																											
24	Hill Climbing Ability																						+																											
25	Truck Unloading Time																						+																											
26	Dump truck width																					+		+																										
	Technological Criteria Group																																																	
27	Haulage distance		+		+		+		+	+				+						+					+			+			+	+	+	+		+	+	+	+			+	+			+	+			
28	Haul road condition				+									+																			+	+			+		+		+	+			+	+	+			

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29	Continuous of mining				+																				+								+																	
30	Compatibility with other equipment to match the production system (compatibility with excavator)						+							+				+		+							+		+	+					+						+							+	
31	Transport berm parameters							+														+																				+								
32	Bench geometry							+	+																															+										
33	Technology change adaptability													+																																				
34	Fill factor													+																					+						+		+		+	+			+	+
35	Cycle time													+													+															+						+		
36	Rock banding capability													+																																				
37	Open pit depth																		+																															
38	Loading time																										+																							
	Geological Criteria Group																																																	
39	Material size				+				+	+	+			+											+							+	+		+	+	+	+	+	+			+							+
40	Moisture (swell factor)				+									+											+							+	+									+				+				
41	The ground condition				+																				+							+	+				+		+		+	+			+	+				
42	Weather conditions				+				+	+															+							+	+		+	+	+		+	+	+	+		+		+				
43	Type and geometry of deposit								+																										+	+		+												
	Economic Criteria Group																																																	
44	Availability				+					+		+		+											+							+	+		+															
45	Capital cost				+	+	+		+	+		+		+	+						+				+		+	+	+		+	+	+	+	+	+	+		+	+									+	+
46	Operating Cost (Material transportation unit cost)				+	+	+		+	+		+	+	+	+						+				+		+		+			+	+	+	+	+	+		+	+					+	+			+	+
47	Depreciation																												+							+	+		+	+					+	+			+	
48	Ownership cost						+																																										+	
49	Warranty																											+								+		+		+					+	+				
50	Risk									+																																								
51	Resale value													+														+						+			+			+		+								
52	Insurance liability													+																																				
53	Manufacture prestige	+																										+																						
	Environmental Criteria Group																																																	

№	Criteria	References																																														
		[59]	[60]	[61]	[44]	[28]	[45]	[46]	[47]	[32]	[30]	[31]	[12]	[38]	[34]	[62]	[63]	[64]	[65]	[66]	[39]	[67]	[43]	[24]	[68]	[69]	[40]	[70]	[41]	[42]	[71]	[72]	[48]	[49]	[25]	[1]	[3]	[15]	[73]	[29]	[74]	[26]	[75]	[76]	[27]	[12]	[77]	[78]	[79]	[80]
54	Environment (dust, noisy, etc.)				+				+	+	+	+	+	+											+							+	+			+	+		+	+						+				
55	Utilization				+				+																+							+	+		+														+	+
56	Air pollution					+	+																						+							+	+		+	+					+	+			+	
57	Nose pollution					+					+																		+									+		+		+			+	+		+	+	
Organizational Criteria Group																																																		
58	Working stability				+								+																				+		+										+					
59	Flexibility				+		+		+	+		+	+	+											+							+	+			+		+		+									+	
60	Support				+																				+								+																	
61	Logistic time (spare parts delivery)						+																					+								+		+							+	+				
62	Back-up service (Support)						+																									+				+		+								+				
63	Labor skill								+																																									
64	Level of technology (robotization, automatization)								+																	+								+									+							
65	Haul trucks usage index																										+																							
66	State of reserve																										+				+																			
67	Number of drivers																										+																							
68	The size of machinery fleet																										+																							

* Compiled by the authors based on the analysis of research in the field of mining.

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The authors identified the following features of the use of dump truck selection criteria in the analyzed studies:

- Variety of criteria. 68 different criteria identified.
- Significant variation in the number of criteria used by different authors. The minimum number of criteria is 2, the maximum is 26.
- Differences in the understanding of the criteria by different authors.
- The predominance of criteria that we previously attributed to the group of economic criteria. 58% of the authors consider only capital and operating expenses.
- 25% of the total number of criteria are unique, that is, they are mentioned in only one study.
- 51% of the total number of criteria used in no more than three studies. We characterized such criteria as rarely used.
- 19% of the total number of criteria is used most frequently, that is, in ten or more studies.
- Some researchers use the criteria to select not only dump trucks, but also with other equipment, for example, when justifying excavator-and-dump truck complex options.
- A different number of levels of the criteria hierarchy – from 1 to 2. In the latter case, the level of criteria and subcriteria is distinguished.
- A variety of ways and systems for grouping criteria are used.
- 57% of the criteria are quantitative, for the remaining criteria qualitative assessments are used.
- We have not identified studies that systematically use the entire set of known criteria for selecting dump trucks.

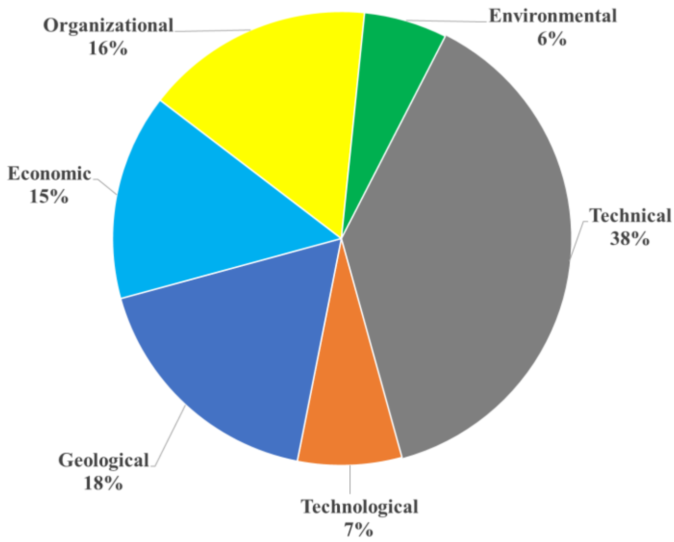

Figure 6. Distribution of the number of criteria in predefined groups.

The variety and large number of criteria for choosing dump trucks motivates us to develop a universal system of criteria.

The sources of data on the criteria, as well as the units of measurement, ranges of values and target values of each criterion are defined in Stage 3 of the methodology.

Secondary grouping of criteria was carried out in accordance with the recommendations of Stage 4 of the methodology. This resulted in 4 groups of criteria. This allowed to eliminate the imbalance of the number of criteria in separate groups, which made further calculations difficult, as well as to reduce the number of criteria under consideration by 36% — from 68 to 43 criteria.

Finally, the criteria were regrouped by competence levels and areas of responsibility of different mining specialists (Stage 5). We assigned 13 criteria to the Strategic level, 18 criteria to the Constructive level, and 15 criteria to the Optimization level. Some criteria were assigned to the areas of responsibility of specialists of several levels.

The system of dump truck selection criteria was formed because of the developed methodology (Table 4). The authors propose to use the developed system of criteria as a universal one because it includes all currently known factors influencing decision-making on the choice of dump truck model.

Table 4. Universal system of criteria for selection of dump trucks

Criteria group, (Notation)	Criteria	Notation	Definition	Unit	Data source*	Value range	Target	Level 1	Level 2	Level 3
Technical, (C1)	Useful life	C1.1	Manufacturer's guaranteed service life of the dump truck	Years or motor hours	A	3-7 years	max	1		
	Grade	C1.2	Maximum possible grade of open pit roads, which can be overcome by the dump truck under consideration in loaded condition	‰	A	60-270‰	max		2	
	Net to Tare Ratio	C1.3	Ratio of dump truck weight to payload capacity	Fractions	A	0.7-0.84	min		2	
	Safety	C1.4	Availability of active and passive safety systems for the dump truck	Score	D		max	1		3
	Comfort, Ergonomics	C1.5	Dump truck driver's workplace comfort	Score	D		max	1		3
	Ease of maintenance	C1.6	Possibility to maintain the dump truck by own repair crews	Score	D		max			3
	Dump truck controllability	C1.7	Speed characteristics, dynamics of acceleration during dump truck driving in loaded and empty conditions	Score	D		max			3
	Minimum turning radius	C1.8	Correlated with the parameters of looping sections of the route in the open pit	meters	A	9-20	min		2	

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Criteria group, (Notation)	Criteria	Notation	Definition	Unit	Data source*	Value range	Target	Level 1	Level 2	Level 3
	Payload capacity	C1.9	Maximum load weight that can be carried by a dump truck	tons	A	25-450	max		2	
	Dump truck tray type	C1.10	Dump track tray configuration and liner design	Score	A		max		2	
	Dump truck width	C1.11	The overall width dimensions of the dump truck, which determine the required haul road width	meters	A	Up to 9.87	min		2	3
Technological, (C2)	Match with excavator and crusher	C2.1	Technological compatibility of dump trucks with related equipment such as excavators and crushers	m^3/m^3	C	3-7	max		2	3
	Haul road width	C2.2	Width of open pit roads	meters	A, B	Up to 45	min		2	
	Payload Factor	C2.3	The ratio of performed transportation work to the maximum possible work performed under the condition of full utilization of the dump truck capacity	Fractions	C	Up to 1	max		2	
	Open pit depth	C2.4	Limit design depth of the pit, in which the dump truck operation is envisaged	meters	B	Up to 800	max	1		2
	Production rate	C2.5	Annual capacity of the open pit for the type of rocks that are planned to be moved by the dump truck	Million tons per year	B	Up to 100 or more	max	1		2

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Criteria group, (Notation)	Criteria	Notation	Definition	Unit	Data source*	Value range	Target	Level 1	Level 2	Level 3
	Haul Road Condition	C2.6	Type of road surface and its condition on open pit roads	Score	D		max		2	3
	Required dump trucks fleet	C2.7	A dump trucks fleet of a certain model to perform the required volume of work	pcs	B	Up to 100 or more	min	1	2	3
Environmental, (C3)	Waste materials produced	C3.1	The amount of waste that is generated during the operation of the dump truck, including waste oil, other fluids, tires, the dump truck itself after decommissioning	Tons per year	C		min	1	2	
	Air pollution	C3.2	Volume of air pollutant emissions	m^3 per year	C		min	1	2	3
	Noisy	C3.3	Noise impact generated by the operation of the dump truck	Decibels	C		min			3
	Type and geometry of deposit	C3.4	The configuration of the mineral deposit, which determines the shape and parameters of the pit	Score	D		max	1	2	
	Climatic zone match	C3.5	Climate of the open pit location zone	Score	D		max			3
Economic and organizational, (C4)	Availability	C4.1	Ratio of number of technically serviceable dump trucks to fleet size	Fractions	A	0.7-1.0	max		2	
	CAPEX	C4.2	Investments in the dump truck fleet	$	C		min	1	2	
	OPEX	C4.3	Operating expenses	$	C		min		2	
	Resale value	C4.4	Residual value of dump truck	$	D		max	1		

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Criteria group, (Notation)	Criteria	Notation	Definition	Unit	Data source*	Value range	Target	Level 1	Level 2	Level 3
	Manufacture reputation	C4.5	Reputation of the dump truck manufacturer in the open pit equipment market	Score	D		max	1		
	Reliability	C4.6	Dump truck operation without unscheduled downtime, breakdowns	Score	D		max			3
	Back-up service (Support)	C4.7	Quality of dump truck service	Score	D		max			3
	Labor skill	C4.8	The company's personnel have the skill to operate a certain dump truck model without additional training	Score	D		max			3
	Technological level (robotization, automation)	C4.9	Availability of automation systems or unmanned operation in a particular dump truck model	Score	D		max	1	2	3

The panel of experts to determine the weighting of the criteria consisted of managers and specialists from various mining companies. Such enterprises were open pit mining iron ore, copper ore, gold ore, construction rocks, as well as raw materials for chemical and metallurgical industries. The composition of the expert group is presented in Table 5.

Table 5. Composition of the expert group.

Level of competence	Expert position	Area of activity (type of mining enterprise)	Number of experts	Notation
Level 1	Director General	Mining of raw materials for the chemical industry	1	DM1
	Director General	Mining of construction rocks	1	DM2
	Director	Mining of raw materials for the metallurgical industry	1	DM3
	Head of Department	Iron Ore Mining	1	DM4

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Level 2	Deputy General Director	Mining of kimberlite	1	DM5
	Chief Geologist	Mining of raw materials for metallurgical industry	1	DM6
	Chief Surveyor	Mining of gold ore	2	DM7, DM8
	Chief Miner	Mining of raw materials for metallurgical industry	1	DM9
	Head of Design and Engineering Department	Copper Ore Mining	1	DM10
	Chief Engineer	Mining of Construction Rocks	1	DM11
Level 3	Mining foreman	Gold Ore Mining	2	DM12, DM13
	Chief mechanic	Iron Ore Mining	1	DM14
	Leading specialist of technical and engineering department	Gold Ore Mining	1	DM15
	Mining Foreman	Mining of raw materials for the chemical industry	2	DM16, DM17

Experts completed questionnaires, the form of which differed for different levels of expert competence. The questionnaires consisted of the following sections: selection of the expert's competence level (Appendix A), instruction (Appendix B), questionnaire to assess the importance of criteria groups (Appendix C). The questionnaires for assessing specific criteria by experts of different levels have a form like Table C1. The difference lies in the set of specific criteria evaluated (Tables 6-8). The names of the group of criteria are present in all questionnaires, while the composition of criteria in the questionnaire depends on the expert's level of competence (Table 4). The combinations of parameters and indicators depending on the level of competence are presented in Tables 6-8.

Table 6. Composition of criteria assessed by experts of Level 1.

Criteria group (Notation)	Criteria (Notation)
Technical (C1)	Useful life (C1.1) Safety (C1.4) Comfort, Ergonomics (C1.5)
Technological (C2)	Open pit depth (C2.4) Production rate (C2.5) Required dump trucks fleet (C2.7)
Environmental (C3)	Waste materials produced (C3.1) Air pollution (C3.2) Type and geometry of deposit (C3.4)
Economic and organizational (C4)	CAPEX (C4.2) Resale value (C4.4) Manufacture reputation (C4.5) Technological level (robotization, automation) (C4.9)

Table 7. Composition of criteria assessed by experts of Level 2.

Criteria group (Notation)	Criteria (Notation)
Technical (C1)	Grade (C1.2) Net to Tare Ratio (C1.3)

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	Minimum turning radius (C1.8)
	Payload capacity (C1.9)
	Dump truck tray type (C1.10)
	Dump truck width (C1.11)
Technological (C2)	Match with excavator and crusher (C2.1) Haul road width (C2.2) Payload Factor (C2.3) Haul Road Condition (C2.6) Required dump trucks fleet (C2.7)
Environmental (C3)	Waste materials produced (C3.1) Air pollution (C3.2) Type and geometry of deposit (C3.4)
Economic and organizational (C4)	Availability (C4.1) CAPEX (C4.2) OPEX (C4.3) Technological level (robotization, automation) (C4.9)

Table 8. Composition of criteria assessed by experts of Level 3.

Criteria group (Notation)	Criteria (Notation)
Technical (C1)	Safety (C1.4) Comfort, Ergonomics (C1.5) Ease of maintenance (C1.6) Dump truck controllability (C1.7) Dump truck width (C1.11)
Technological (C2)	Match with excavator and crusher (C2.1) Haul Road Condition (C2.6) Required dump trucks fleet (C2.7)
Environmental (C3)	Air pollution (C3.2) Noisy (C3.3) Climatic zone match (C3.5)
Economic and organizational (C4)	Reliability (C4.6) Back-up service (Support) (C4.7) Labor skill (C4.8) Technological level (robotization, automation) (C4.9)

4.2. Results of Expert Evaluation of Criteria Groups and Criteria for Selection of Dump Trucks

The results of evaluation of criteria groups for selection of dump trucks by experts of different levels of competence are presented in Tables 9-11.

Table 9. Results of evaluation of the criteria groups by Level 1 experts.

DM1				
Criteria groups (according to rank)	C2	C1	C4	C3
Criteria groups comparisons	1	3	3	6
DM2				
Criteria groups (according to rank)	C2	C4	C1	C3
Criteria groups comparisons	1	3	3	7
DM3				
Criteria groups (according to rank)	C1	C2	C4	C3
Criteria groups comparisons	1	1	2	5
DM4				
Criteria groups (according to rank)	C2	C4	C1	C3

Criteria groups comparisons	1	3	4	5
DM5				
Criteria groups (according to rank)	C4	C2	C1	C3
Criteria groups comparisons	1	3	3	5

Table 10. Results of evaluation of the criteria groups by Level 2 experts.

DM6				
Criteria groups (according to rank)	C3	C1	C2	C4
Criteria groups comparisons	1	1	2	2
DM7				
Criteria groups (according to rank)	C2	C4	C1	C3
Criteria groups comparisons	1	2	2	3
DM8				
Criteria groups (according to rank)	C1	C2	C4	C3
Criteria groups comparisons	1	5	5	7
DM9				
Criteria groups (according to rank)	C2	C1	C4	C3
Criteria groups comparisons	1	3	4	6
DM10				
Criteria groups (according to rank)	C1	C2	C4	C3
Criteria groups comparisons	1	4	5	8
DM11				
Criteria groups (according to rank)	C1	C2	C4	C3
Criteria groups comparisons	1	2	3	6

Table 11. Results of evaluation of the criteria groups by Level 3 experts.

DM12				
Criteria groups (according to rank)	C1	C4	C2	C3
Criteria groups comparisons	1	2	2	3
DM13				
Criteria groups (according to rank)	C1	C2	C4	C3
Criteria groups comparisons	1	3	7	9
DM14				
Criteria groups (according to rank)	C2	C1	C3	C4
Criteria groups comparisons	1	1	4	4
DM15				
Criteria groups (according to rank)	C2	C1	C3	C4
Criteria groups comparisons	1	1	2	2
DM16				
Criteria groups (according to rank)	C2	C1	C3	C4
Criteria groups comparisons	1	1	3	6
DM17				
Criteria groups (according to rank)	C2	C1	C3	C4
Criteria groups comparisons	1	1	4	4

The results of expert evaluation of the selection criteria for dump trucks are presented in Tables 12-14.

Table 12. Results of criteria evaluation by Level 1 experts.

Results of evaluation	Criteria groups (Notation)												
	Technical (C1)			Technological (C2)			Environmental (C3)			Economic and organizational (C4)			
DM1													
Criteria (according to rank)	C1.4	C1.1	C1.5	C2.5	C2.4	C2.7	C3.4	C3.2	C3.1	C4.2	C4.9	C4.4	C4.5
Criteria comparisons	1	2	5	1	2	6	1	4	5	1	2	3	5
DM2													
Criteria (according to rank)	C1.1	C1.4	C1.5	C2.7	C2.5	C2.4	C3.4	C3.1	C3.2	C4.2	C4.4	C4.9	C4.5
Criteria comparisons	1	3	4	1	2	2	1	3	3	1	5	6	8
DM3													
Criteria (according to rank)	C1.1	C1.4	C1.5	C2.5	C2.7	C2.4	C3.2	C3.1	C3.4	C4.2	C4.9	C4.5	C4.4
Criteria comparisons	1	1	4	1	2	2	1	2	5	1	2	4	8
DM4													
Criteria (according to rank)	C1.1	C1.4	C1.5	C2.5	C2.7	C2.4	C3.1	C3.2	C3.4	C4.2	C4.5	C4.9	C4.4
Criteria comparisons	1	3	4	1	2	7	1	4	6	1	3	4	9
DM5													
Criteria (according to rank)	C1.1	C1.4	C1.5	C2.7	C2.5	C2.4	C3.4	C3.2	C3.1	C4.4	C4.5	C4.9	C4.2
Criteria comparisons	1	3	4	1	3	4	1	3	4	1	1	2	2

Table 13. Results of criteria evaluation by Level 2 experts.

Results of evaluation	Criteria groups (Notation)																	
	Technical (C1)						Technological (C2)					Environmental (C3)			Economic and organizational (C4)			
DM6																		
Criteria (according to rank)	C1.9	C1.11	C1.2	C1.8	C1.10	C1.3	C2.1	C2.2	C2.7	C2.3	C2.6	C3.2	C3.1	C3.4	C4.3	C4.2	C4.1	C4.9
Criteria comparisons	1	2	2	2	5	5	1	1	2	3	4	1	1	2	1	1	2	2
DM7																		
Criteria (according to rank)	C1.9	C1.8	C1.11	C1.10	C1.3	C1.2	C2.1	C2.7	C2.2	C2.6	C2.3	C3.2	C3.1	C3.4	C4.1	C4.2	C4.3	C4.9
Criteria comparisons	1	2	2	4	4	5	1	2	3	3	3	1	1	1	1	1	1	2
DM8																		
Criteria (according to rank)	C1.9	C1.11	C1.2	C1.8	C1.10	C1.3	C2.2	C2.1	C2.6	C2.3	C2.7	C3.1	C3.4	C3.2	C4.2	C4.3	C4.1	C4.9
Criteria comparisons	1	2	3	5	6	9	1	2	3	5	7	1	2	3	1	3	4	7
DM9																		
Criteria (according to rank)	C1.9	C1.11	C1.2	C1.10	C1.8	C1.3	C2.1	C2.2	C2.7	C2.3	C2.6	C3.4	C3.2	C3.1	C4.3	C4.1	C4.2	C4.9
Criteria comparisons	1	3	3	5	7	7	1	3	4	6	7	1	5	7	1	3	4	7
DM10																		
Criteria (according to rank)	C1.2	C1.8	C1.9	C1.11	C1.10	C1.3	C2.7	C2.6	C2.2	C2.1	C2.3	C3.4	C3.1	C3.2	C4.1	C4.9	C4.3	C4.2
Criteria comparisons	1	2	3	5	5	7	1	3	5	7	7	1	5	5	1	4	8	8
DM11																		
Criteria (according to rank)	C1.2	C1.11	C1.8	C1.9	C1.10	C1.3	C2.1	C2.5	C2.2	C2.4	C2.3	C3.4	C3.1	C3.2	C4.1	C4.3	C4.2	C4.9
Criteria comparisons	1	2	2	3	4	5	1	2	2	3	3	1	3	7	1	2	2	5

Table 14. Results of criteria evaluation by Level 3 experts.

Results of evaluation	Criteria groups (Notation)														
	Technical (C1)					Technological (C2)			Environmental (C3)			Economic and organizational (C4)			
DM12															
Criteria (according to rank)	C1.4	C1.7	C1.6	C1.5	C1.11	C2.1	C2.7	C2.5	C3.5	C3.3	C3.1	C4.6	C4.8	C4.7	C4.9
Criteria comparisons	1	2	2	4	5	1	1	2	1	3	3	1	1	2	4
DM13															

Criteria (according to rank)	C1.7	C1.4	C1.5	C1.11	C1.5	C2.7	C2.1	C2.5	C3.5	C3.3	C3.1	C4.6	C4.8	C4.9	C4.7
Criteria comparisons	1	2	5	6	6	1	2	3	1	5	8	1	3	6	6
DM14															
Criteria (according to rank)	C1.4	C1.5	C1.7	C1.11	C1.6	C2.1	C2.7	C2.5	C3.5	C3.1	C3.3	C4.6	C4.8	C4.7	C4.9
Criteria comparisons	1	1	1	2	2	1	1	2	1	2	2	1	1	1	3
DM15															
Criteria (according to rank)	C1.4	C1.5	C1.7	C1.11	C1.6	C2.1	C2.7	C2.5	C3.5	C3.1	C3.3	C4.8	C4.6	C4.7	C4.9
Criteria comparisons	1	2	2	4	4	1	1	4	1	3	3	1	1	2	4
DM16															
Criteria (according to rank)	C1.4	C1.6	C1.11	C1.5	C1.7	C2.7	C2.1	C2.5	C3.5	C3.3	C3.1	C4.6	C4.8	C4.7	C4.9
Criteria comparisons	1	2	2	3	5	1	1	3	1	5	5	1	1	4	4
DM17															
Criteria (according to rank)	C1.4	C1.5	C1.7	C1.6	C1.11	C2.7	C2.1	C2.5	C3.5	C3.1	C3.3	C4.8	C4.6	C4.7	C4.9
Criteria comparisons	1	1	1	1	3	1	1	2	1	7	7	1	1	5	6

4.3. Results of Ranking the Criteria Groups and Criteria of the FUCOM Method

The results of calculating the weights of the groups of criteria for selecting dump trucks in accordance with the FUCOM methodology (Section 2.2) are presented in Table 15 and Figure 7. The value of deviation χ for all criteria groups and for all experts is equal to 0.

Table 15. The results of calculating the weights of the criteria groups for selecting dump trucks.

Experts	**Criteria groups**			
	C1	**C2**	**C3**	**C4**
Level 1				
DM1	0.1818	0.5455	0.0909	0.1818
DM2	0.1842	0.5526	0.0789	0.1842
DM3	0.3704	0.3704	0.0741	0.1852
DM4	0.1402	0.5607	0.1121	0.1869
DM5	0.1786	0.1786	0.1071	0.5357
Level 2				
DM6	0.3333	0.1667	0.3333	0.1667
DM7	0.2143	0.4286	0.1429	0.2143
DM8	0.6481	0.1296	0.0926	0.1296
DM9	0.1905	0.5714	0.0952	0.1429
DM10	0.6349	0.1587	0.0794	0.1270
DM11	0.5000	0.2500	0.0833	0.1667
Level 3				
DM12	0.4286	0.2143	0.1429	0.2143
DM13	0.6300	0.2100	0.0700	0.0900
DM14	0.4000	0.4000	0.1000	0.1000
DM15	0.3333	0.3333	0.1667	0.1667
DM16	0.4000	0.4000	0.1333	0.0667
DM17	0.4000	0.4000	0.1000	0.1000

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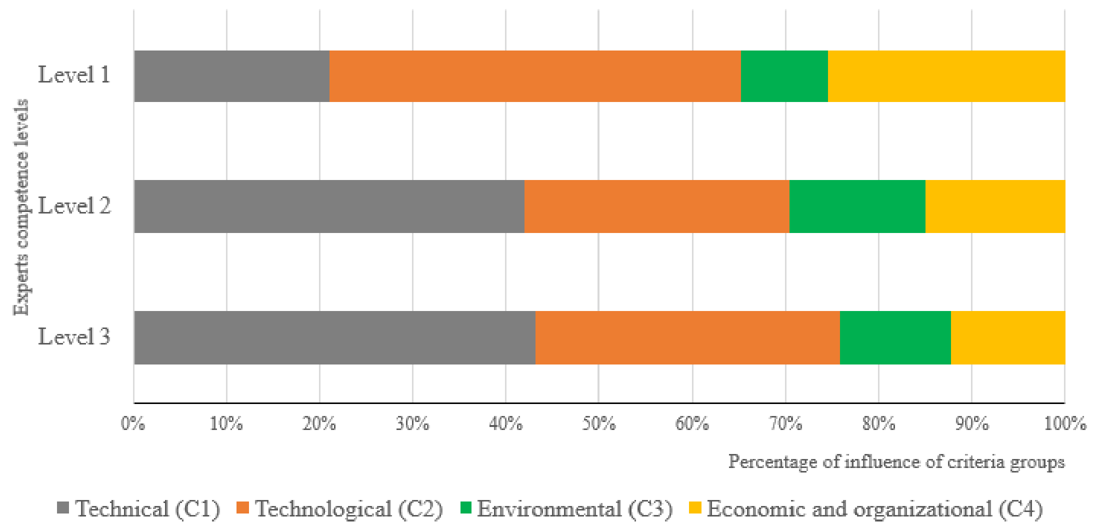

Figure 7. Results of assessment of criteria groups weights by experts of different competence levels.

The analysis of results of assessment of criterion groups weights confirmed the hypothesis about differences of these assessments by experts of different competence levels.

Level 1 experts gave the highest priority to the group of Technological criteria (C2) — the weight coefficient of this group is 0.4416. The Technical (C1) and Economic-Organizational (C4) groups of criteria have almost the same weight — respectively 0.211 and 0.2548. The lowest priority is given to the group of Environmental criteria (C3), with a weight coefficient of 0.0926.

Level 2 and 3 experts give the highest priority to the group of Technical (C1) criteria, the weight coefficients for which are 0.4202 and 0.4320, respectively. This is followed by Technological (C2) – 0.2842 and 0.3263 and Economic-Organizational (C4) – 0.1499 and 0.1229. These experts also put the Environmental (C3) group in last place – 0.1457 and 0.1188.

The group of Environmental (C3) criteria received the least weight according to the assessments of experts of all levels.

This result indicates the insufficient state regulation of environmental problems at the studied mining enterprises. On the other hand, modern research proves the necessity to revise priorities in decision-making for mining enterprises towards environmental aspects [16]. For example, studies [35–37] show the effectiveness of excluding economic criteria at the stage of preliminary assessment of criteria, since economic criteria in most cases are evaluated by experts according to the highest priority.

The results of calculating the weights of the selection criteria for dump trucks are presented in Tables 16-18. The value of deviation χ for all groups of criteria and for all experts, as well as in the case of groups of criteria, is equal to 0.

Table 16. Results of criteria for selection of dump trucks evaluation by Level 1 experts.

Experts	Criteria												
	C1.1	**C1.4**	**C1.5**	**C2.4**	**C2.5**	**C2.7**	**C3.1**	**C3.2**	**C3.4**	**C4.2**	**C4.4**	**C4.5**	**C4.9**
DM1	0.2941	0.5882	0.1176	0.3000	0.6000	0.1000	0.1379	0.1724	0.6897	0.4918	0.1639	0.0984	0.2459
DM2	0.6316	0.2105	0.1579	0.2500	0.2500	0.5000	0.2000	0.2000	0.6000	0.6704	0.1341	0.0838	0.1117
DM3	0.4444	0.4444	0.1111	0.2500	0.5000	0.2500	0.2941	0.5882	0.1176	0.5333	0.0667	0.1333	0.2667

DM4	0.6316	0.2105	0.1579	0.0870	0.6087	0.3043	0.7059	0.1765	0.1176	0.5902	0.0656	0.1967	0.1475
DM5	0.6316	0.2105	0.1579	0.1579	0.2105	0.6316	0.1579	0.2105	0.6316	0.1667	0.3333	0.3333	0.1667

Table 17. Results of criteria for selection of dump trucks evaluation by Level 2 experts.

Experts	Criteria																	
	C1.2	**C1.3**	**C1.8**	**C1.9**	**C1.10**	**C1.11**	**C2.1**	**C2.2**	**C2.3**	**C2.6**	**C2.7**	**C3.1**	**C3.2**	**C3.4**	**C4.1**	**C4.2**	**C4.3**	**C4.9**
DM6	0.1724	0.0690	0.1724	0.3448	0.0690	0.1724	0.3243	0.3243	0.1081	0.0811	0.1622	0.4000	0.4000	0.2000	0.1667	0.3333	0.3333	0.1667
DM7	0.0741	0.0926	0.1852	0.3704	0.0926	0.1852	0.4000	0.1333	0.1333	0.1333	0.2000	0.3333	0.3333	0.3333	0.2857	0.2857	0.2857	0.1429
DM8	0.1442	0.0481	0.0865	0.4327	0.0721	0.2163	0.2298	0.4595	0.0919	0.1532	0.0656	0.5455	0.1818	0.2727	0.1448	0.5793	0.1931	0.0828
DM9	0.1549	0.0664	0.0664	0.4646	0.0929	0.1549	0.5283	0.1761	0.0881	0.0755	0.1321	0.1064	0.1489	0.7447	0.1931	0.1448	0.5793	0.0828
DM10	0.4208	0.0601	0.2104	0.1403	0.0842	0.0842	0.0785	0.1099	0.0785	0.1832	0.5497	0.1429	0.1429	0.7143	0.6667	0.0833	0.0833	0.1667
DM11	0.3593	0.0719	0.1796	0.1198	0.0898	0.1796	0.3750	0.1875	0.1250	0.1250	0.1875	0.2258	0.0968	0.6774	0.4545	0.2273	0.2273	0.0909

Table 18. Results of criteria for selection of dump trucks evaluation by Level 3 experts.

Experts	Criteria														
	C1.4	**C1.5**	**C1.6**	**C1.7**	**C1.11**	**C2.1**	**C2.5**	**C2.7**	**C3.1**	**C3.3**	**C3.5**	**C4.6**	**C4.7**	**C4.8**	**C4.9**
DM12	0.4082	0.1020	0.2041	0.2041	0.0816	0.4000	0.2000	0.4000	0.2000	0.2000	0.6000	0.3636	0.1818	0.3636	0.0909
DM13	0.2459	0.0820	0.0984	0.4918	0.0820	0.2727	0.1818	0.5455	0.0943	0.1509	0.7547	0.6000	0.1000	0.2000	0.1000
DM14	0.2500	0.2500	0.1250	0.2500	0.1250	0.4000	0.2000	0.4000	0.2500	0.2500	0.5000	0.3000	0.3000	0.3000	0.1000
DM15	0.4000	0.2000	0.1000	0.2000	0.1000	0.4444	0.1111	0.4444	0.2000	0.2000	0.6000	0.3636	0.1818	0.3636	0.0909

DM 16	0.3947	0.1316	0.1974	0.0789	0.1974	0.4286	0.1429	0.4286	0.1429	0.1429	0.7143	0.4000	0.1000	0.4000	0.1000
DM 17	0.2308	0.2308	0.2308	0.2308	0.0769	0.4000	0.2000	0.4000	0.1111	0.1111	0.7778	0.4225	0.0845	0.4225	0.0704

The results of the evaluation of the weighting of the selection criteria for dump trucks, performed by the FUCOM method, are presented in Tables 19-21 presented. The results of criteria ranking (Global weight) by expert competence levels are presented in Figures 8-10. The criterion groups and the criteria that received the highest weight values are in bold.

Table 19. Results of evaluation of the weighting of selection criteria for dump trucks by Level 1 experts.

Criteria groups	**Weight**	**Criteria**	**Local weight**	**Global weight**
C1	0,2110	Useful life (C1.1)	**0.5267**	0.1111
		Safety (C1.4)	0.3329	0.0702
		Comfort, Ergonomics (C1.5)	0.1405	0.0296
C2	**0,4416**	Open pit depth (C2.4)	0.2090	0.0923
		Production rate (C2.5)	0.4338	**0.1916**
		Required dump trucks fleet (C2.7)	0.3572	0.1577
C3	0,0926	Waste materials produced (C3.1)	0.2992	0.0277
		Air pollution (C3.2)	0.2695	0.0250
		Type and geometry of deposit (C3.4)	0.4313	0.0400
C4	0,2548	CAPEX (C4.2)	0.4905	0.1250
		Resale value (C4.4)	0.1527	0.0389
		Manufacture reputation (C4.5)	0.1691	0.0431
		Technological level (robotization, automation) (C4.9)	0.1877	0.0478

Table 20. Results of evaluation of the weighting of selection criteria for dump trucks by Level 2 experts.

Criteria groups	**Weight**	**Criteria**	**Local weight**	**Global weight**
C1	**0.4202**	Grade (C1.2)	0.2210	0.0928
		Net to Tare Ratio (C1.3)	0.0680	0.0286
		Minimum turning radius (C1.8)	0.1501	0.0631
		Payload capacity (C1.9)	0.3121	**0.1311**
		Dump truck tray type (C1.10)	0.0834	0.0351
		Dump truck width (C1.11)	0.1654	0.0695
C2	0.2842	Match with excavator and crusher (C2.1)	0.3227	0.0917
		Haul road width (C2.2)	0.2318	0.0659
		Payload Factor (C2.3)	0.1042	0.0296
		Haul Road Condition (C2.6)	0.1252	0.0356
		Required dump trucks fleet (C2.7)	0.2162	0.0614
C3	0.1457	Waste materials produced (C3.1)	0.2923	0.0426
		Air pollution (C3.2)	0.2173	0.0317
		Type and geometry of deposit (C3.4)	**0.4904**	0.0715
C4	0.1499	Availability (C4.1)	0.3186	0.0478

		CAPEX (C4.2)	0.2756	0.0413
		OPEX (C4.3)	0.2837	0.0425
		Technological level (robotization. automation) (C4.9)	0.1221	0.0183

Table 21. Results of evaluation of the weighting of selection criteria for dump trucks by Level 3 experts.

Criteria groups	Weight	Criteria	Local weight	Global weight
C1	**0.4319**	Safety (C1.4)	0.32160	0.13892
		Comfort. Ergonomics (C1.5)	0.16606	0.07174
		Ease of maintenance (C1.6)	0.15926	0.06880
		Dump truck controllability (C1.7)	0.24260	0.10480
		Dump truck width (C1.11)	0.11048	0.04773
C2	0.3262	Match with excavator and crusher (C2.1)	0.39096	0.12756
		Haul Road Condition (C2.6)	0.17263	0.05632
		Required dump trucks fleet (C2.7)	0.43641	**0.14239**
C3	0.1181	Air pollution (C3.2)	0.16638	0.01977
		Noisy (C3.3)	0.17582	0.02089
		Climatic zone match (C3.5)	**0.65780**	0.07815
C4	0.1229	Reliability (C4.6)	0.40830	0.05020
		Back-up service (Support) (C4.7)	0.15802	0.01943
		Labor skill (C4.8)	0.34163	0.04200
		Technological level (robotization. automation) (C4.9)	0.09204	0.01132

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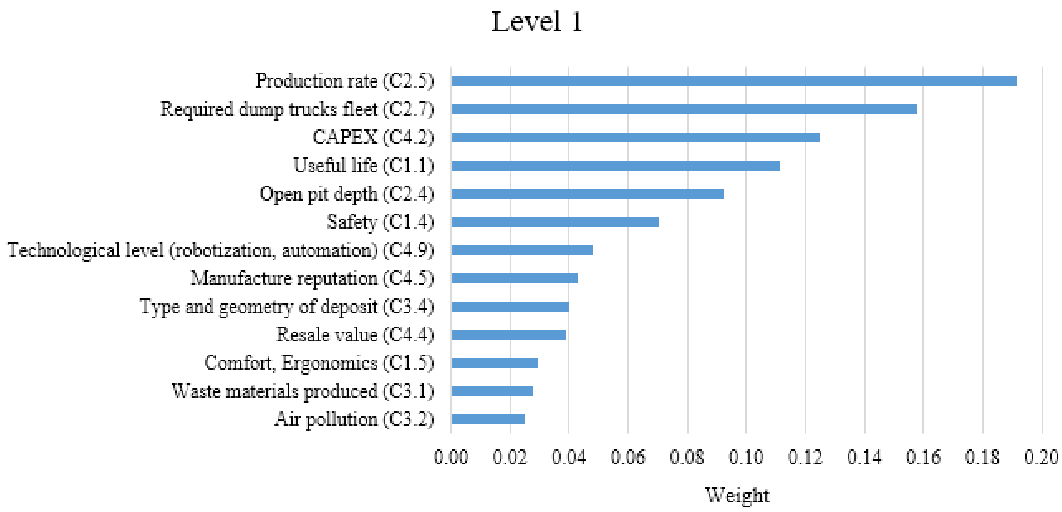

Figure 8. Result of ranking of criteria for selection of dump trucks by Level 1 competence experts.

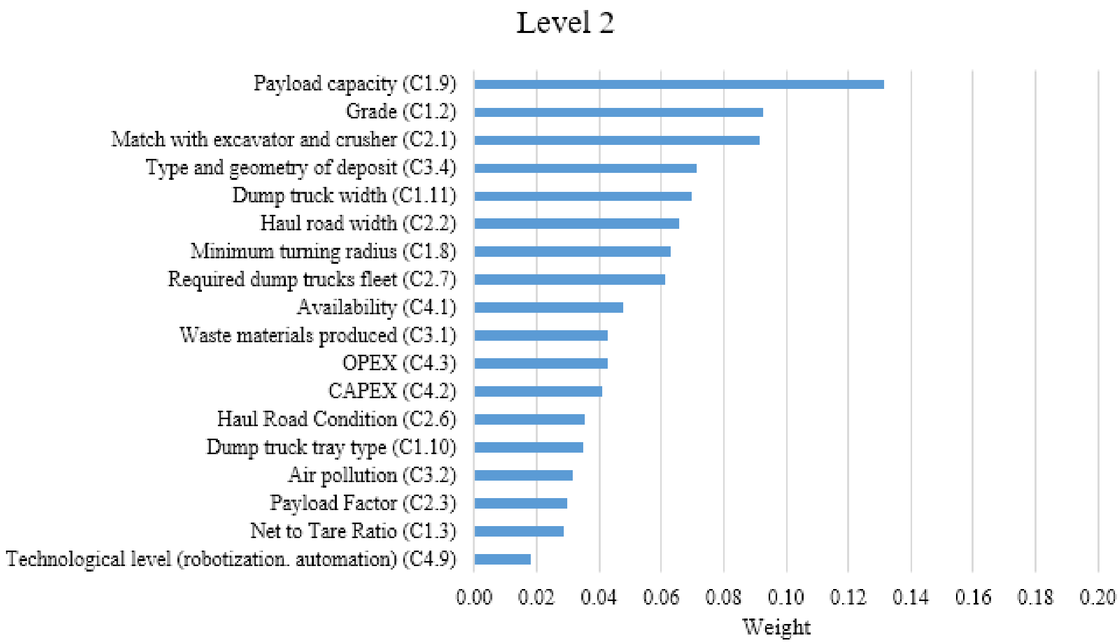

Figure 9. Result of ranking of criteria for selection of dump trucks by Level 2 competence experts.

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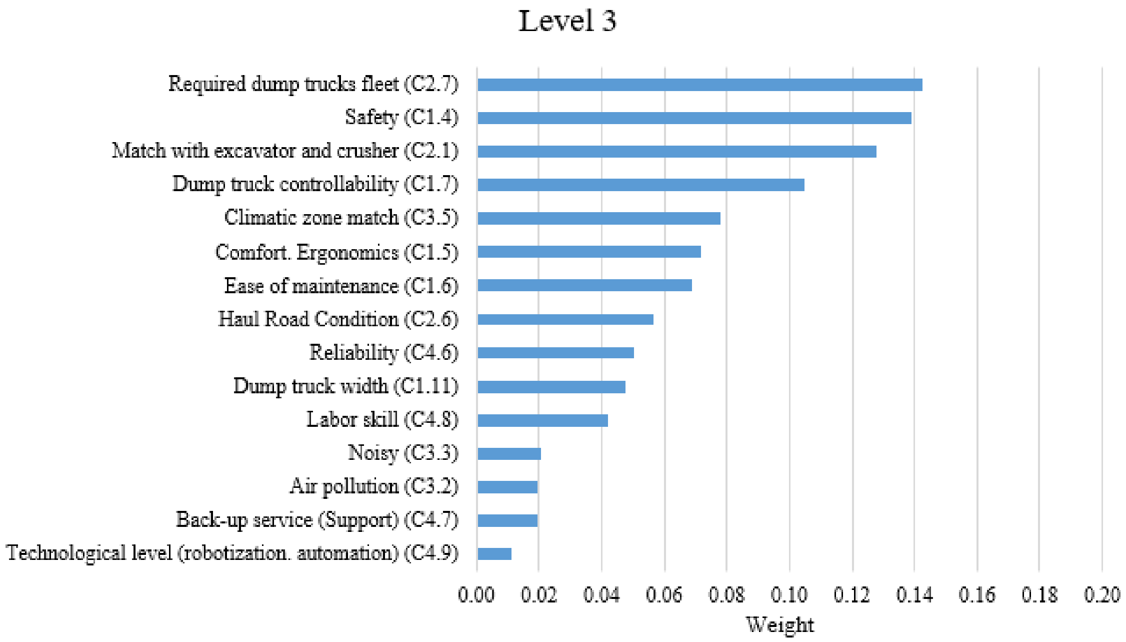

Figure 10. Result of ranking of criteria for selection of dump trucks by Level 3 competence experts.

Estimates of dump truck selection criteria significance differ according to experts of different levels of expertise. The same situation is observed here as in the case of criteria groups.

The authors made several assumptions at the initial stage of the study. These assumptions related to the orientation of experts of a certain level of competence to the criteria corresponding to their field of activity. The hypothesis that Level 1 experts prioritize economic and environmental criteria was if that these experts are oriented towards strategic decisions. Such decisions include, for example, maximizing the financial results of the whole company, as well as strengthening the company's reputation by implementing various environmental and social measures. Emphasis on technological criteria was expected in the Level 2 experts, as these experts are responsible for operational planning. Finally, prioritization of technical criteria was expected in the assessments of Level 3 experts, as they directly operate dump trucks and are interested in their reliability and safety. However, all the above hypotheses were not confirmed. A detailed analysis of the results obtained allowed us to find explanations for the differences between the actual results and the expected ones.

The assessments of criteria groups and local criteria did not coincide among experts of all competence levels. Discussion of the obtained results with experts allowed to establish the reason for such differences. It was found that experts perceive groups of criteria as target criteria and local criteria as constraints to be observed in the process of achieving target criteria.

For example, Level 1 experts prioritized the group of Technological criteria (C2) as target criteria, but the technical criterion “Useful life of dump trucks” (C1.1) was selected by them as a priority local criterion. Level 2 experts chose the group of Technical criteria (C1) as the target criteria, as they are oriented in their activities towards the most efficient operation of machinery. However, the same experts prioritized the local criterion “Type and geometry of deposit” (C3.4) from the Environmental criteria group. This is because the operational decisions of these experts are determined by the actual configuration of the ore body, which may differ significantly from the design configuration. Operational adjustments complicate current and operational planning and are therefore perceived as constraints by this group of experts. Although the Level 3 experts expectedly prioritized their target group of technical criteria (C1), they selected “Climatic zone match” (C3.5) from the Environmental criteria group as the priority local criterion. The main reason for this discrepancy was explained by the fact that the mining enterprises where the interviewed experts work are located in the harsh climatic conditions of the Russian Federation and the Republic of Kazakhstan. Therefore, the influence of climatic conditions, in particular, sharp fluctuations in ambient air temperature is perceived by experts of this level as factors complicating the operation of the mining enterprise, reducing the reliability and safety of dump trucks.

The values of global criteria weights for each group of experts is the result of striving for a balance between target and local criteria — constraints. For example, the technological criterion "Production rate" (C2.5) received the maximum weight from the Level 1 experts because the achievement of the target values of this criterion is the main indicator of the efficiency of experts from this group. We make a similar explanation for the results of other groups of experts. The criterion "Payload capacity" (C1.9) received the maximum global weight in the group of Level 2 experts, and the criterion "Required dump trucks fleet" (C2.7) — in the experts of Level 3.

The findings also explain the non-confirmation of the hypothesis about the priority of certain criteria among experts of certain levels. There are two reasons for this. The first reason is the selection of specific experts. For example, experts who are not owners of mining enterprises or top managers formed the composition of the Level 1 expert group in our case study. Therefore, they selected the technological group of criteria as the target criteria rather than the expected group of economic or environmental criteria. The second reason is the two-tiered nature of our proposed criteria system. The criteria with the highest local weight do not belong to the group of criteria also with the highest weight among experts of all levels. This also indicates differences in the evaluation of target criteria — groups and limiting criteria. We define the criteria with the maximum global weight as compromise criteria, compliance with which allows achieving the target criteria while complying with the limiting local criteria.

Figure 11 shows the results of averaging the weights of the criteria groups in comparison with the assessments of experts of different levels. The average values almost completely coincide with the results of Level 3 experts' assessments. However, Level 1 and Level 2 experts evaluated the groups of technical and technological criteria differently. Level 1 experts gave priority to the group of Technological criteria (C2), while Level 2 experts most highly evaluated the significance of the criteria of the Technical criteria (C1). The obtained result is explained by the peculiarity of work organization at the studied open pits, when direct executors (Level 3) are oriented to the requirements of managers pursuing different, often opposite goals.

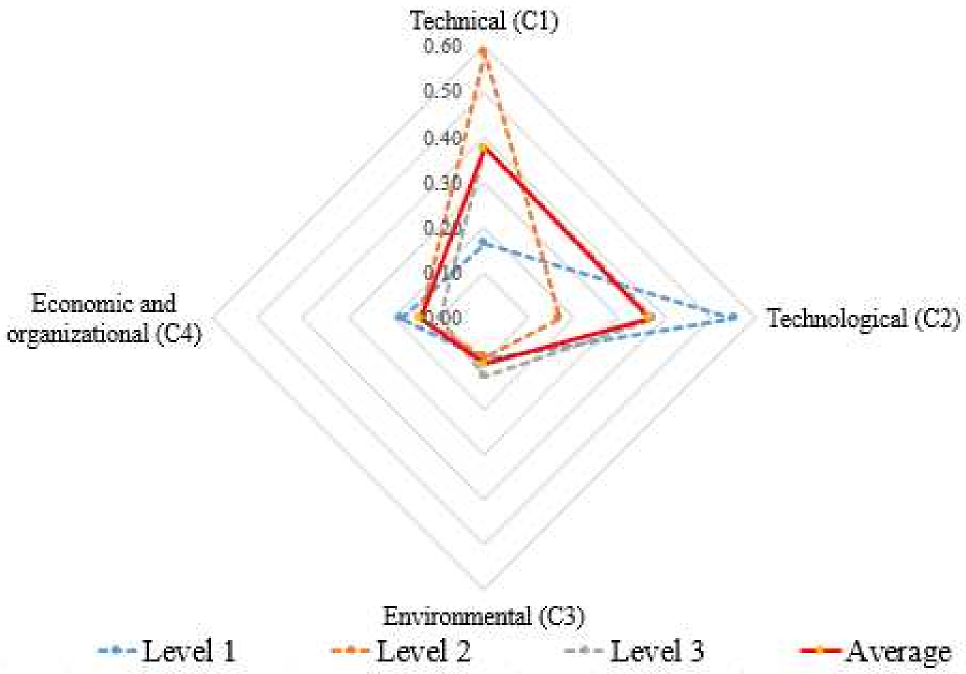

Figure 11. The result of comparing the average weight of the criterion groups with the scores of different experts.

The analysis of the obtained results allowed us to conclude about the productivity of the proposed methodology of forming a system of criteria for selecting dump trucks. The dump truck

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fleet is a critical element of a complex quarry system. The main feature of the methodology is a two-level system of criteria, the weight of which is determined by experts of three different levels of competence. The two levels of the criteria system include the level of target and common criteria for all experts, as well as the level of criteria specific for different experts. The application of the proposed methodology for the conditions of a particular mining enterprise will allow not only to determine the criteria for selecting the dump truck model considering the existing conditions.

5. Conclusions

The problem of selecting a dump truck model is critical, especially for the conditions of deep quarries. This is due to the significant — up to 70% of the total costs of the open pit — costs of transport operation. These costs increase by 20-30% with deepening of the open pit for every 100 meters. In addition, technical and operational characteristics of the selected dump trucks should be coordinated with many parameters of the open pit development process. Inconsistency of these parameters and characteristics is the cause of reduction not only of economic efficiency of the mining enterprise, but also leads to increase in harmful impact on the environment, reduces safety and comfort of personnel work.

The analysis of operating open pits has shown the lack of systematics in solving the problem of selecting the dump truck model. Many important factors and conditions are not considered when deciding. Subjective factors often influence the choice. The lack of systematic in the assessment of influencing factors and conditions of quarries functioning is also present in the analyzed scientific studies. Different authors identify limited groups of factors and conditions that are significant in their opinion. In addition, the sets of such factors and conditions vary from one study to another.

We propose to solve the problem of selecting dump truck models for the conditions of deep open pits using the proposed methodology based on the system analysis of selection criteria and the use of multi-criteria decision-making methods. This approach, in our opinion, can ensure a balanced achievement of both economic, environmental, and social objectives of the functioning of mining enterprises.

A detailed description of the developed methodology is presented in the paper. We have chosen the FUCOM method as a multi-criteria decision-making method. The choice of this method is due to its effectiveness in evaluating a large number of selection criteria compared to other known methods. The presented methodology has two features. First, the system of criteria is two-level. The first level is formed by four groups of criteria: technical, technological, environmental, economic and organizational. The detailed justification for the selection of these groups is contained in the article. Specific selection criteria form the second level. We have created a complete list of all possible selection criteria. This set we have made based on analyzing scientific research, as well as interviews of managers and specialists of careers.

Secondly, we propose to divide specific selection criteria not only by groups, but also by levels of competence of decision-makers. We propose to distinguish three levels of competencies: Level 1, Strategic — the experts of this level have competencies in the field of strategic management of a mining enterprise, Level 2, Design — the experts at this level are the heads and specialists of the design and engineering department, chief engineers, miners, geologists, mine surveyors, heads and specialists of planning and economic departments, heads of labor protection and environmental departments, Level 3, Optimization — such experts include mechanics, power engineers, heads of quarries, transport departments and shift supervisors. We propose to form a set of evaluated specific criteria specific to each level of experts' competence.

We applied the designed methodology to form a system of dump truck selection criteria and to rank the importance of specific criteria. The criteria with the highest weight were: "Production rate" (according to Level 1 experts), "Payload capacity" (Level 2), "Required dump trucks fleet" (Level 3).

The presented system of criteria is, in our opinion, universal, because it is based on a systematic analysis of all currently known criteria for selecting dump trucks. We propose to use this system of criteria as an exemplary one at various mining enterprises. However, we propose to recalculate the

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ranks of criteria using the presented methodology when external conditions and factors change, as well as when expanding the set of private evaluation criteria.

In future studies, the authors will present a methodology for selecting a specific dump truck model using the developed criteria system. We also intend to evaluate all the dump truck models on the market using a case study of dump truck model selection for a deep open pit. Finally, we intend to investigate the dependence of the effectiveness of the management system of an open pit and a mining enterprise on the degree of consistency of opinions of experts of different levels of competence about the importance of one or another group of criteria for selecting a dump truck.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Expert level selection form.

Level	Description	Choosing Level
1	Strategic: company owner; company president; key executives; general, commercial, and technical directors etc.	
2	Design: heads and specialists of the design and engineering department; chief engineers; miners; geologists; mine surveyors; heads and specialists of planning and economic departments; heads of labor protection and environmental departments etc.	
3	Optimization: mechanics; power engineers; head of transport departments; shift supervisors etc.	

Appendix B. Instruction for Experts

Dear Expert, please give your opinion on the importance of selection criteria for dump trucks.

You form your opinion in two stages:

First stage. Give your opinion on the importance of four criteria groups: technical, technological, environmental, economic and organizational. Your opinion is expressed by assigning a certain place to each group of criteria. The first place will go to the most important group of parameters, the second place — less important, the third place — even less important group, and the fourth place — the least important group of parameters of the four. In the "Score" line, enter a score from "1" to "9". A score of "1" indicates absolute superiority of the first ranked criterion group over the second, third, or fourth ranked group. Note that the first ranked group will always have a score of "1". The scores of the other groups should be greater than or equal to "1". Furthermore, check that the score of the lower ranked group is greater than or equal to the score of the higher ranked group.

Second stage. Rank the specific criteria in each group in the same way as in the first stage. A description of each specific criterion is provided to the experts in the form of Table 4.

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Appendix C

Table A2. Questionnaire to assess the importance of criteria groups.

Criteria groups	First place	Second place	Third place	Fourth place
Write the designation of only one group of criteria, C1, C2, C3, or C4*				
Scores from 1 to 9	1			

* C1 — technics, C2 — technology, C3 — environment, C4 — economics and organization.

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