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METHODOLOGY FOR SELECTION OF THE MOST CONVENIENT ORE TRANSPORTATION SYSTEM IN REGARD TO THE ENVIRONMENTAL PROTECTION

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Abstract: *This paper identifies the components necessary to develop a decision analysis framework on issues concerning the environmental protection, to facilitate the selection of a multi-criteria decision analysis process, and thereafter to provide guidance on the implementation of the selected multi-criteria decision analysis method within the larger context of the people, processes, and tools used in decision making. The main subject of research of this paper is the establishment of an optimal system for ore transportation from an open-pit mine to a processing facility considering the aspect of environmental protection, using the multi-criteria decision analysis method Analytic hierarchy processes.*

Key words: *Multi-criteria decision making, Analytic hierarchy processes, optimization, emission estimation techniques.*

1 INTRODUCTION

An important segment of the optimal system for ore transportation through the environment is the establishment of a relation between the rest of the factors influencing the selection of the system and the environmental protection. Therefore, a special attention is paid to the transportation impact quantification and the adjustment of the multi-criteria analysis methods to the requirements of the optimal ore transportation system.

Acceptable methods to be used in the process of selection of the most convenient transportation system in regard to the environment protection are the multi-criteria decision methods. In addition, the used criteria are the degree of impact of particular negative effects on the environment. This creates an opportunity for the environmental protection, in its quantified form, to be considered as one of the criteria for the selection of an optimal ore transportation system along with the rest of the important criteria, such as the specific transportation costs, capital investment, required workforce, energy supply, etc.

In the process of ore transportation type selection, generally, the usual procedure is to look for the solution in multiple variations. In addition, depending on the required accuracy degree, it is a common practice to make decisions on the basis of the following types of analyses:

- technical-economic, and
- multi-criteria.

In the process of multi-criteria decision making, the results of the technical-economic analysis are considered as one of the criteria. The technical-economic analysis defines the feasible variations and establishes the specific ore transportation costs. This procedure trivializes the environmental protection as it only reduces it to direct costs resulting from the investment and work on the environmental protection. Multi-criteria decision analysis involves multiple criteria which, more or less, influence the selection of the most convenient ore transportation variations. The most important criteria to be considered in external ore transportation are as follows:

- specific transportation costs,
- initial investment,
- required workforce,
- energy supply,
- probability of automation,
- system safety and reliability,
- environmental protection and other.

2 MULTI – CRITERIA DECISION MAKING

Multi-criteria decision analysis (MCDA), sometimes called Multi-criteria decision making (MCDM), is a discipline aimed at supporting decision makers who are faced with making numerous and conflicting evaluations. MCDA aims at highlighting these conflicts and deriving a way to come to a compromise in a transparent process.

Decision making may be characterized as a process of selecting a ‘sufficiently good’ alternative to attain a goal or goals, and it involves uncertainity. Thus, one of the most important aspects for a useful decision aid is to provide the ability to handle imprecise and vague information, such as ‘large’ profits, ‘fast’ speed and ‘cheap’ price. A decision model should cover processes for identifying, measuring and combining criteria and alternatives to build a conceptual model for decisions and evaluations in fuzzy environments.

There are a number of examples in the literature on the application of multi-criteria optimization in the process of ore transportation system selection in underground and surface mining. On the basis of this information, and on the basis of the problem analysis, it has been realized that the most suitable multi-criteria method to be applied in this case would be the AHP method (Analytic Hierarchy Processes).

The application of multi-criteria optimization is carried out if several variations for transportation system selection are available. In addition, the multi-criteria optimization produces a ranking of variations ranked in accordance with the criteria upon which the optimization has been done.

3 PROPOSAL SYSTEMS FOR ORE TRANSPORTATION FROM AN OPEN-PIT MINE TO A MINERAL PROCESSING FACILITY

The area of research of this paper is the establishment of an optimal system for ore transportation from an open-pit mine to a minerals processing facility through a well preserved, undamaged environment, taking into account the aspect of environmental protection; four alternatives are to be reviewed. The following alternative technologies for ore transportation are proposed:

- Truck transport (A_1),
- Belt conveyor transport (A_2),
- Pipe conveyor transport (A_3),
- Railway transport (A_4).

The general parameters used in the process of calculating the ore transportation parameters are given in the following table:

Tab. 1 *General parameters of the minerals transportation*

	General parameters	Value	Unit
1	Planned annual capacity for minerals transportation	2.000.000	t/a
2	Mean transportation route length	36	km
3	Mean transportation route inclination	3	‰
4	Ore humidity	14	%
5	Road surface layer silt content	8,2	%
6	Number of working days per year	300	days
7	Number of shifts per day	3	shifts
8	Number of effective working hours per shift	6,5	h
9	Mean wind speed in the transportation area	3,6	m/s
10	Ore specific weight	3,5	t/m^3

3.1 Identification of factors influencing the problem definition and resolution

Ore mining causes a number of negative effects on the environment, particularly in terms of terrain degradation and environmental pollution with various harmful substances. These consequences could be of a larger scale if the excavated masses are larger. Mines could be found in any environment, from national parks to large cities, hence the impact on the environment is different.

Mass minerals production as a consequence of the depleted ore deposits further endangers the environment. The ore transportation from mines to mineral processing facilities, outside the mine boundaries, presents one of the most complicated phases in regard to the environmental protection. Transportation routes from mines to mineral processing facilities pass through various environments, hence it is necessary to appropriately evaluate the minerals transportation impact on each of these environments.

A mine could have several production plants (underground or open pits) and the excavated material needs to be transported to the mineral processing facilities (flotation plants, screening plants, coal fired plants, etc.) which could be located significantly away from the mine itself. Various transportation means could be used for transporting the excavated material, and all of them have different impact on the environment. It is necessary therefore that this impact is quantified in order to compare it to the other parameters.

The selection of a transportation system for ore transportation from any mine to a distant mineral processing facility, concerning the environmental protection, must meet the following criteria:

- Terrain degradation as a consequence of transportation route construction should be reduced to a minimum provided that the achievement of mine annual capacity would not be affected;
- PM_{10} emissions resulting from the ore loading/unloading processes and vehicle movement (ore movement) should be reduced to a minimum;
- Exhaust gasses emissions resulting from the transportation system operation should be reduced to a minimum;
- The transportation system should produce low noise and vibrations during its operation;
- The risk of material spillage in the environment where the transportation routes passes should be reduced to a minimum;
- The risk of oil and lubricants effluence and watercourses pollution should also be reduced to a minimum.

The decision on the ore transportation type selection could be made after a detailed analysis of all these factors. The proper definition of each of the aforementioned factors and the selection of the appropriate ore transportation type provide for a minimum pollution of the environment. On the basis of such an analysis, a calculation of the parameters of each of the proposed transportation systems has been made and an evaluation of the negative effects that each of those systems causes to the environment has been done.

This procedure involves finding a solution that maximizes the environmental protection during ore transportation from the mine to the mineral processing facility, i.e. the environmental degradation and pollution is reduced to a minimum. The problem solution, i.e. the selection of the most convenient type of ore transportation, concerning the environmental protection, could be reached using the multi-criteria decision analysis.

3.2 Model definition

In order to do the model definition, it is necessary to carry out the following procedure:

- do a problem analysis;
- establish the alternatives (variations);
- establish the final selection of criteria and define their weight;
- do the transformation of attributes (criteria) quality.

3.3 Problem analysis and determining the variations

The general problem case can be defined in the following way:

A specific quantity of ore needs to be transported from an open-pit mine to a mineral processing facility through a well preserved and undamaged environment. The ore general parameters and characteristics, and the transportation conditions are presented in Table 1. A suitable ore transportation plan should be determined on the basis of previously determined criteria upon which the evaluation of impact is carried out so that the transportation impact on the environment is reduced to a minimum.

In this specific example, and in accordance with the contemporary experience in ore transportation in the mining industry, four alternative solutions for ore transportation have been established, Table 2:

Tab. 2 *Alternative solutions for the type of transportation*

	Alternative	Mark
1	Truck transportation	A_1
2	Belt conveyor transportation	A_2
3	Pipe conveyor transportation	A_3
4	Train transportation	A_4

3.4 Criteria selection and identification

After the problem identification and analysis have been done, the criteria with the highest impact on the problem solution are selected and identified. A detailed description of each criterion is presented in Table 3.

Tab. 3 *Criteria description*

	Criterion	Mark	Description
1	Terrain degradation	K_1	The width of the degraded area used for the transportation route construction, given in meters
2	Noise and vibrations	K_2	An estimation of the degree of noise and vibrations produced as a result of the operation of transportation systems along the transportation route
3	Dust emission	K_3	Quantity of PM_{10} emitted in the atmosphere as a result of the movement of transportation systems along the route and the loading/unloading of material, given in tons per year
4	Exhaust gasses emission	K_4	Quantity of exhaust gasses emitted in the atmosphere as a result of the internal combustion engines operation in the transportation systems, given in kilograms per year
5	Material spillage	K_5	An evaluation of the risk (probability) of ore spillage during loading/unloading/transportation
6	Oil and lubricants effluence	K_6	An evaluation of risk (probability) of oil and lubricants effluence and potential watercourses pollution

Each of these criteria has its own impact (weight) on the alternative solutions. For this specific model, an analysis has been done on the negative effects that each type of transportation causes to the environment; also, an analysis of the transportation system parameters, and an evaluation of the negative effects that each transportation system causes to the environment have been carried out based on the contemporary experience for the given model.

Each of the criteria has its own nature, i.e. goal, given in Table 4:

Tab. 4 *Evaluation factors and criteria goals*

Mark	**First level criteria**	**Evaluation factor**	**min/max**
K_1	Terrain degradation	m	min
K_2	Noise and vibrations	Qualitative evaluation	min
K_3	Dust emission	t/year	min
K_4	Exhaust gasses emission	kg/year	min
K_5	Material spillage	Qualitative evaluation	min
K_6	Oil and lubricants effluence	Qualitative evaluation	min

3.5 Decision matrix

After the quantification calculations have been made, the decision matrix gets the following values:

Tab. 5 *Decision matrix*

	K_1	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**
	min	**min**	**min**	**min**	**min**	**min**
A_1	12,14	Extremely high	1753	3,23	High	High
A_2	5,90	Low	1,54	0	Average	Low
A_3	5,45	Low	0,28	0	Extremely low	Low
A_4	4,00	High	3,92	0,77	Average	Average

After the transformation of qualitative into quantitative values has been done, the decision matrix gets the following values:

Tab. 6 *Quantitative Decision matrix*

	K_1	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**
	min	**min**	**min**	**min**	**min**	**min**
A_1	12,14	1	1753	3,23	3	3
A_2	5,90	7	1,54	0	5	7
A_3	5,45	7	0,28	0	9	7
A_4	4,00	3	3,92	0,77	5	5

4 CONSISTENCY

The AHP method belongs to the group of popular methods for its possibility of identification and analysis of the consistency of decision maker in the process of comparison of elements in the hierarchy. Considering that the alternative comparison is based on a subjective estimation by the decision maker, it is necessary that it is constantly monitored in order to secure the required accuracy. The AHP method ensures that the evaluation consistency is monitored constantly in the alternative pairwise comparison procedure. The consistency index C.I. = $(\lambda_{max} - n)/(n-1)$, calculates the consistency ratio C.R. = C.I./R.I, where R.I. is the random consistency index (n size matrix consistency index of randomly generated pairwise comparison, for which table 7 is used (with calculated values):

Tab. 7 *Random consistency index values R.I. (Saaty, 1980)*

n	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

λ_{max} is the matrix Eigen value, whereas n is the matrix size. Thereto, it is true that $\lambda \geq n$, and the difference $\lambda_{max} - n$ is used to measure the evaluation consistency. In case of inconsistency, if λ_{max} is closer to n, the evaluation is more consistent. If C.R.$\leq$ 0.10, the calculation of relative criteria importance (alternative priority) is considered acceptable. In the opposite case, the decision maker has to analyze the reasons for unacceptably high evaluation inconsistency.

5 PHASES OF AHP

Phase 1: Problem structuring

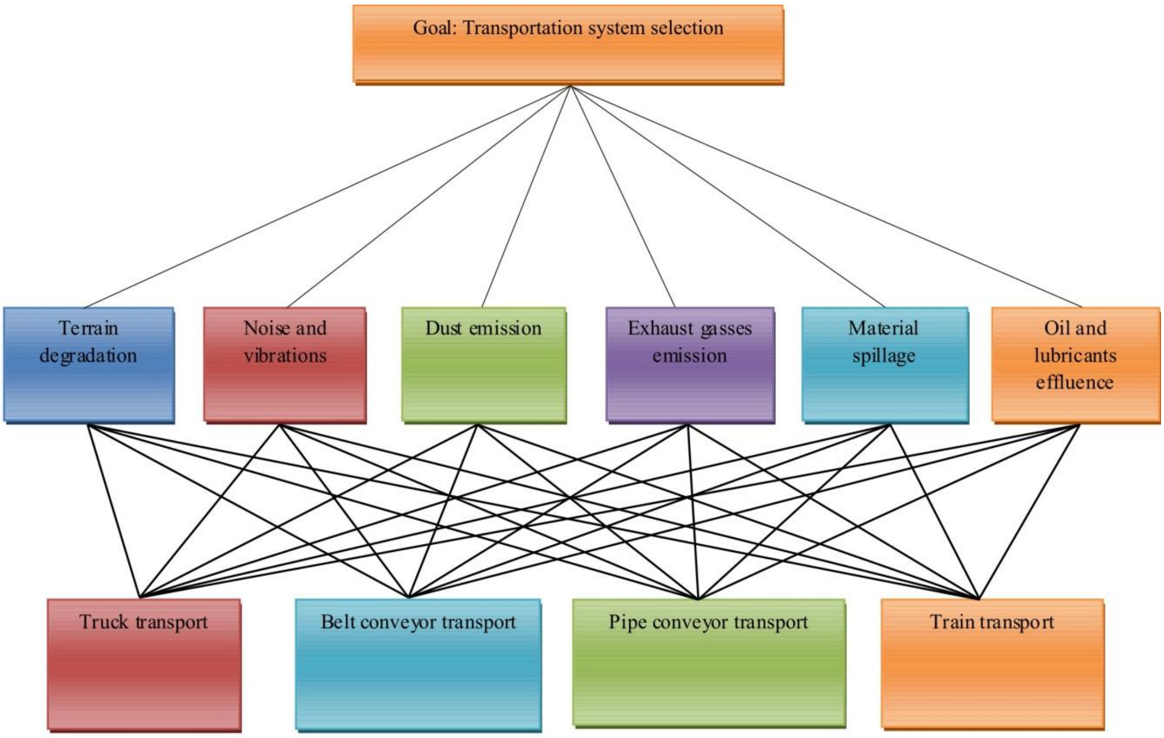

Fig.1 *Hierarchy structure of the transportation system selection problem*

Phase 2: Data collection

First, a comparison of the significance of the individual attributes (criteria) should be carried out in accordance with the scale defined in Table 8 (Saaty 9-point scale).

Tab.8 *Saaty 9-point scale*

Scale	Ranking	Explanation
1	Equally important	Both criteria or alternatives contribute to the objective equally
3	Moderately important	Based on experience and estimation, moderate preference is given to one criteria or alternative over the other
5	Strictly more important	Based on experience and estimation, strict preference is given to one criteria or alternative over the other
7	Very strict, proven importance	One criteria or alternative is strictly preferred over the other; its dominance has been proven in practice
9	Extreme importance	The evidence based on which one criteria or alternative is preferred over the other has been confirmed to the highest confidence
2, 4, 6, 8	Mid-values	

Phase 3: Relative weight evaluation

In order to solve the given model, an approximate procedure for obtaining the eigenvector is used. This procedure involves the following steps:

Step 1: Pairwise comparison in the matrix and summarizing the elements in each column;

Step 2: Dividing the elements of each column by the sum of values of that column obtained in the previous step. In that way, the normalized relative weight of each of the elements is obtained. The sum of each column equals to 1.

Step 3: Summarizing the elements in each row and determining the average of each row. The column containing these averages is actually the normalized eigenvector, also called the priority vector. Given that the vector is normalized, the sum of all elements in the priority vector equals to 1. The priority vector represents the relative weights of the elements compared.

Tab. 9 *First level attributes comparison (decision criteria)*

	K_1	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**	**Weight**
K_1	0,2264	0,2609	0,1974	0,2727	0,2609	0,2353	0,3744
K_2	0,0755	0,0870	0,0987	0,0682	0,0870	0,1176	0,2423
K_3	0,4528	0,3478	0,3947	0,4091	0,3478	0,2941	0,1509
K_4	0,1132	0,1739	0,1316	0,1364	0,1739	0,1765	0,0890
K_5	0,0755	0,0870	0,0987	0,0682	0,0870	0,1176	0,0890
K_6	0,0566	0,0435	0,0789	0,0455	0,0435	0,0588	0,0545

λ_{max} =6,0987; C.I. = 0,01974; C.R.= 0,01579

Tab. 10 *Matrix of alternative relative importance compared to K_1 attribute (Terrain degradation)*

	A_1	**A_2**	**A_3**	**A_4**	**Weight**
A_1	0,1250	0,1111	0,1111	0,1428	0,4231
A_2	0,2500	0,2222	0,2222	0,2143	0,2272
A_3	0,2500	0,2222	0,2222	0,2143	0,2272
A_4	0,3750	0,4444	0,4444	0,4286	0,1225

λ_{max} = 4,012; C.I. = 0,004; C.R.= 0,0045

Tab. 11 *Matrix of alternative relative importance compared to K_2 attribute (Noise and vibrations)*

	A₁	**A₂**	**A₃**	**A₄**	**Weight**
A_1	0,0556	0,0610	0,0610	0,0294	0,4209
A_2	0,3889	0,4268	0,4268	0,4412	0,4209
A_3	0,3889	0,4268	0,4268	0,4412	0,1064
A_4	0,1667	0,0854	0,0854	0,0882	0,0517

λ_{max} = 4,1096; C.I. = 0,0365; C.R.= 0,041

Tab. 12 *Matrix of alternative relative importance compared to K_3 attribute (Dust emission)*

	A_1	**A_2**	**A_3**	**A_4**	**Weight**
A_1	0,0400	0,0345	0,0571	0,0233	0,4786
A_2	0,3200	0,2759	0,2571	0,3256	0,2946
A_3	0,3600	0,5517	0,5143	0,4884	0,1880
A_4	0,2800	0,1379	0,1714	0,1628	0,0387

λ_{max} = 4,1218; C.I. = 0,0406; C.R.= 0,0456

Tab. 13 *Matrix of alternative relative importance compared to K_4 attribute (Exhaust gasses emission)*

	A_1	**A_2**	**A_3**	**A_4**	**Weight**
A_1	0,0476	0,0541	0,0541	0,0323	0,3693
A_2	0,3333	0,3784	0,3784	0,3871	0,3693
A_3	0,3333	0,3784	0,3784	0,3871	0,2144
A_4	0,2857	0,1892	0,1892	0,1935	0,0470

λ_{max} = 4,0469; C.I. = 0,0156; C.R.= 0,0176

Tab.14 *Matrix of alternative relative importance compared to K_5 attribute (Material spillage)*

	A_1	**A_2**	**A_3**	**A_4**	**Weight**
A_1	0,0714	0,0455	0,0926	0,0455	0,6279
A_2	0,2143	0,1364	0,1296	0,1364	0,1542
A_3	0,5000	0,6818	0,6481	0,6818	0,1542
A_4	0,2143	0,1364	0,1296	0,1364	0,0637

λ_{max} = 4,1222; C.I. = 0,0407; C.R.= 0,0458

Tab. 15 *Matrix of alternative relative importance compared to K_6 attribute (Oil and lubricants effluence)*

	A_1	**A_2**	**A_3**	**A_4**	**Weight**
A_1	0,0714	0,0789	0,0789	0,0455	0,3889
A_2	0,3571	0,3947	0,3947	0,4091	0,3889
A_3	0,3571	0,3947	0,3947	0,4091	0,1534
A_4	0,2143	0,1316	0,1316	0,1364	0,0687

λ_{max} = 4,0575; C.I. = 0,0192; C.R.= 0,0216

Phase 4: Determining the problem solution

The overall problem synthesis follows at the end of procedure. The overall problem synthesis is calculated so that each alternative is multiplied by its own weight within the reviewed criterion. The same procedure is applied to all criteria in a row, and the results obtained are summarized.

The results are presented in Table 16.

Tab. 16 *Alternatives ranking*

Alternative	**Ranking**
A_3	**0,4046**
A_2	0,2935
A_4	0,2369
A_1	0,0653

On the basis of the results obtained given in the previous alternatives ranking table, it is obvious that the most convenient type of ore transportation is the **A_3 alternative**, i.e. **the pipe conveyor transportation model**.

6 CONCLUSIONS

The negative impact of ore transportation through the environment requires that everyone involved in this field of work fully focuses on this problem. In order to achieve that, it is necessary to know all the possible consequences caused by the transportation system operation in the environment. The assessment of possible damages to the land, water, and air should precede each review of the transportation through the environment. The harmful consequences are not the same for each environment, and a classification into separate categories is done accordingly. The environment categorization is done in multiple levels, i.e. further classification is possible within an established category in order to carry out more specific damage quantification. Conventional transportation technologies (railway transport, truck transport, belt conveyor transport, etc.) have to meet the requirements in terms of environmental protection. Noticing the shortcomings of the standard types of transport, new solutions and new transportation technologies could be introduced, such as the pipe conveyor transportation.

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