MULTICRITERIA OPTIMIZATION OF EARTHWORK PROCESSES USING THE METHOD OF LEAST SQUARES

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ABSTRACT

The selection of mechanization in the earthwork processes has become a very difficult these days because of availability of variety models of mechanization. To overcome this problem, the multicriteria optimization has become the most popular methods to make the final decision. In this paper, the method of least squares is presented to compare some alternatives of excavators which are commonly used in the fields of construction and engineering. Application of this method is presented with a case study to demonstrate an approach to make a step wise decision from the point of the key criteria of optimizing.

Key words: *earthwork, excavator, method of least squares*

1 INTRODUCTION

The most important task in the area of optimizing the earthwork processes is to determine the method which can the most accurate calculate the performance of construction machinery and the amount of the actual cost of the machines and their combination under certain specific conditions. Presently, the majority of studies published in the literature focus on the optimization of equipment selection are based on diverse complex factors. In the area of earthwork processes, multiplicity of parameters and alternatives may possibly lead to a number of complexities hence, because the selection of accurate equipment needs enough experience as well as taking into account all parameters in connection with each other. In this regard, on could point to application of multi decision making method.

Machine selection method and evaluation problem has been studied extensively. In contemporary equipment selection process for earthwork, the best alternative of machines is evaluated against multiple criteria rather than considering a single factor. Shapira and Goldenberg developed a model which is based on an analytical hierarchy process which was developed by Thomas Saaty. The developed model is capable of providing users with results to compare with different alternatives based on several criterions for selection of equipment based on highest score. Its hierarchy was structured by dividing the problem into four criteria and eighteen sub-criteria, which were tackled in accordance to three perspectives: cost evaluation, benefit evaluation and total evaluation [Shapira and Goldenberg, 2005].

Bascetin have used Analytical Hierarchy Process approach for the equipment selection in final decision in the area of mining operations. The criteria for equipment selection are clearly identified what enables to decision makers to examines strength and weakness of loading-hauling systems by comparing them with the respect to appropriate criteria [Bascetin, 2003].

Typically the literature has advocated the use of dominant right eigenvector and associated consistency ratio for estimating multi decision making problems. Crawford gives reasons why the geometric mean (also known as the logarithmic least squares method) may be preferable as an estimator of the unknown underlying scale. He also develops an index of consistency and related rules to judge the consistency of a matrix when we using the geometric mean as an estimator [Crawford, 1987].

In this paper, the multicriteria model for evaluation of the chosen variants of excavator and trucks is presented. The chosen variants are submitted by the definitive list of variations which can be used in the chosen excavation process. For comparison of these variants, the logarithmic method of least squares is presented.

2 THE MULTICRITERIA OPTIMIZATION METHODS

The multicriteria decision making proved as an effective methodology thanks to its ability to combine various criteria in order to select the best alternative. The model of multicriteria optimization is based on:

- definitive set of possible alternatives (choice set),
- definitive number of criteria (when the decision maker is making his choice among the alternatives within choice set, he evaluates the alternatives in line with attributes of alternatives. These evaluation lines we can called criteria),
- weights, which express the importance of the criteria and are chosen by the experts or the decision maker [Vavríková, 2011].

The process of multicriteria decision making is following by the six steps:

- recognize and define the problem,
- evaluate the set of possible alternatives,
- determinate the key criteria of optimizing,
- determinate the weights for chosen criteria according to the selected method,
- normalize the values for chosen variants for making the final decision,
- purchase the final decision and evaluate the results.

At the beginning, it is necessary to define the problem, select the key criteria of optimizing and propose variants of machines and its group which can fulfill the defined excavation problem and are useful for final building product. In this paper, a method of multi-criteria decision making in the field of mechanized earthwork process was implemented for the selection of excavator and trucks from the chosen criteria of optimizing - the overall duration, the rental cost of machines per hour, fuel consumption and emissions. The determination of weights of the criteria is a central role in the entire process multi-criteria evaluation of choices that can affect the entire outcome of the evaluation. To determine the weights of criteria there are a great number of different multicriteria methods, from simpler to more difficult techniques and this issue is addressed in more and more authors. Most methods fall within following groups:

- Weighting methods: The entropy method, Analytical Hierarchy Process, Direct evaluation methods, Eigenvalue methods;
- Ordinal methods: these methods like The Condorcet method, The Borda method etc. are commonly used in voting systems;
- Outranking methods: Electre, Promethee [Pomero et al., 2000].

In this paper, the method of least squares is used for determination of preferences and evaluation of weights for selected criteria. Weights reflect the different importance of single inputs which are processed.

3 THE LOGARITHMIC LEAST SQUARES METHOD

The Method of Least Squares is one of the oldest techniques in the mathematics requiring just some calculus to determine the weights for selected criteria. Method of least squares method is an individual award criteria, which is based on the preferences described by a decision matrix marked as “S”. The decision maker can give a numerical value, such as x_{ij}, representing the performance of alternative *i* on criterion *j*. If in a multicriteria problem, there are m alternative options and each need to be assessed on n criteria, then the decision matrix for the problem has m rows and n columns or m x n elements, as is shown by the equation 1:

$$S = \begin{pmatrix} 1 & s_{12} & s_{13} & s_{14} \\ 1/s_{12} & 1 & s_{23} & s_{24} \\ 1/s_{13} & 1/s_{23} & 1 & s_{34} \\ 1/s_{14} & 1/s_{24} & 1/s_{34} & 1 \end{pmatrix}. \quad (1)$$

If the criterion at line significantly as a criterion in the column entered in the appropriate field size value preference criteria in line to the criterion of the column by the chosen intensification evaluation. If it is more important criterion in line, entered in the appropriate field inverse of the display preferences. That is, the matrix S we only need to fill out using a pairwise comparison of the upper triangle, since the symmetrical positions will be located and the inverted value of the diagonal of the same one, which represents the significance of the two same criteria. By application of the method of least squares we try to minimize the sum of the squares of the difference, as is expressed by the equation 2:

$$F = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(s_{ij} = \frac{v_i}{v_j}\right)^2 \rightarrow MINIMUM. \quad (2)$$

The equation 2 has to fulfill following condition:

$$\sum_{i=1}^{n} v_i = 1, \ \ v_i \geq 0. \quad (3)$$

Solution of this task is then normalized geometric mean of the rows given by the matrix S which can be expressed by equation 4:

$$v_i = \frac{\left[\prod_{j=1}^{n} s_{ij}\right]^{\frac{1}{n}}}{\sum_{i=1}^{n}\left[\prod_{j=1}^{n} s_{ij}\right]^{\frac{1}{n}}}, \ \text{i=1,2,...n.} \quad (4)$$

The least square method is quite not difficult method and with using of this method we can minimize errors, which committed by estimating the weights of individual criteria. The least square method does not require the consistency analysis and its numerical implementation is not extraordinarily difficult, the method is used preferably in many cases, not only in the earthwork processes [Ocelíková, 2004].

4 THE CASE STUDY

The mentioned method of the least squares was for a case study applied into the selection of machine group for excavation and the removal of the earth at the given distance from the above mentioned criteria. With regard to the great number of the model variables and the extent of the work, only the application of multicriteria method is described. In this example we take real data to rank six variants of machines according to four criteria (the overall duration of work, the rental cost of machines per hour, fuel consumption and emissions). The basic input data:

- A given type of the building works = earthwork processes, excavation,
- soil type and class = sandy soil, the second class of cohesion,
- the required work capacity = 8050m^3,
- required time of duration of works T = 7200 min. (15 shifts).

The input universe of system is being created by the depth shovel excavator Caterpillar 324E (CAT324E) and 3 types of folding transport means:

- D1 – transport mean TATRA T158 8x8,
- D2 – transport mean TATRA T158 6x6,
- D3 – transport mean TATRA T815 S3 6x6.

According to the required work capacity and time of duration, the minimum amount of transport means was defined and the queuing theory is being applied. In this contribution are shown the final variants which are able to complete the task in time set by user. The following Table 1 illustrated the values of key criteria of optimizing for selected variants of machines.

VARIANTS OF MACHINES	DURATION [min]	THE RENTAL COST OF MACHINES [€/m^3]	FUEL CONSUMPTION [l]	EMISSIONS [kg]
CAT 324E + 3xD1	5884,640682	2,107968976	11031,43731	28681,73701
CAT 324E + 4xD1	4833,260151	2,156468881	13464,50594	35007,71544
CAT 324E + 4xD2	6354,07048	2,965859246	14678,52932	38164,17622
CAT 324E + 5xD2	5341,866328	2,978982846	17108,3055	44481,5943
CAT 324E + 5xD3	6943,006869	2,645050391	20670,67839	53743,7638
CAT 324E + 6xD3	5948,869981	2,633091014	23101,29371	60063,36365

Tab. 1. The values of key criteria of optimizing for selected variants of machines

In assessing the selection of acceptable variant of machines group it is important to provide the weights for each criterion. To avoid an intuitive decision making, based on the proposed methodology we used to determine weights of criteria the method of least squares. The first step is pairwise comparison of selected criteria, when the decision maker evaluates the alternatives in the line with attributes of the alternatives (on a scale 1-9 according to Saaty's method). The preferences are described by the decision matrix according to the preferences of author for this case study.

$$S = \begin{pmatrix} 1 & 6 & 8 & 9 \\ 1/6 & 1 & 4 & 7 \\ 1/8 & 1/4 & 1 & 1 \\ 1/9 & 1/7 & 1/1 & 1 \end{pmatrix}. \qquad (5)$$

According to the method of least squares and equation 4, the weight of individual criteria chosen look for example as follows:

- weight for the total duration of works: 0,638,
- weight for the costs per unit of output: 0,206,
- weight for the fuel consumption: 0,059,
- weight for overall CO_2 emissions: 0,049.

If we set weights for each criterion, we can evaluate the selected application example to evaluate and make the final decision. To be able to compare the selected variants of machines summarizing Table 1, we have to normalize the values. Optimal machines group (excavator and different number of trucks) is determined according to the weight of the individual parameters. Scoreboard we obtained by aggregating normalized optimizing parameter multiplied by the weight of individual criteria. The final optimal variant of machines will be the one which has the maximum number. The results for selected variants with application of the method of least square are shown in Table 2.

VARIANTS OF MACHINES	THE FINAL SCOREBOARD	RANKING
CAT 324E + 3xD1	0,6584896	**3.**
CAT 324E + 4xD1	0,9300715	**1.**
CAT 324E + 4xD2	0,4430724	**5.**
CAT 324E + 5xD2	0,7067786	**2.**
CAT 324E + 5xD3	0,2773789	**6.**
CAT 324E + 6xD3	0,5381421	**4.**

Tab. 2 The final rankings for selected variants with application of the method of least square

The final machine group, which reflects selected preferences and weight of each criterion is composed of the excavators CATERPILLAR 324E and four transport means TATRA T158 8x8. The selected variant of machine group composed of Cat 324E and four transport means TATRA T158 8x8 would be able to implement the required volume of work at the time of 4,833.26 minutes, which is a work transfer t = 2366.74 minutes before the required deadline, representing almost 5 days. The total costs for this variant would be accounted for the required volume 17 360 €. In addition to these costs, still need to count the cost of diesel, which would be able to save a lot of money supplier based on the rapid implementation of the works. The current average price of diesel is on average € 1.012 / liter. If we implement the works covering a total of 7,200 minutes, diesel consumption for that assembly would represent 20 060 liters. In terms of environmental protection and the total exhaust emissions into the atmosphere by implementing those variant we produce less by 32.87% of total emissions of CO_2. The amount of emissions produced by the combustion engine is dependent on the performance of the machine itself and the fuel consumption because of decreasing fuel consumption also reduces the amount of emissions produced.

CONCLUSIONS

The multi-criteria optimization and its application proved as an effective methodology thanks to its ability to combine various criteria in order to select the best alternative in terms of our key criteria of optimality. The importance of the criteria is expressed by weights, which are chosen by the experts or the decision makers and can be normalized real numbers. In this paper, the Method of least squares is presented to find final alternative of excavator and trucks. The key mathematical formulas are presented and the proposed model can be used like a tool for comparison of some type of machines. On the basis of the presented case study, we can see that the process of finding the optimal variant of machine assembly is mathematically challenging and over time is a few hours of time to be building and technological designers spend about it, in order to find the optimal solution.

Literature

[1] SAPHIRA, A., GOLDENBERG, M. AHP based equipment selection model for construction projects. In: *Journal of Construction Engineering and Management*, Volume 131, no. 12, 2005, pp. 1263-1273.

[2] BASCETIN, A.: A Decision Support System for Optimal Equipment Selection in Open Pit Mining: Analytical Hierarchy Process, Istanbul University, In: *Journal of Geoscience*, vol.16, 2003, pp.1-11.

[3] CRAWFORD, G., B. The geometric mean procedure for estimating the scale of a judgement matrix, In: *Journal of Mathematical Modelling*, Volume 9, Issue 3, 1987, pp. 327-334, ISSN 0270-0255.

[4] OCELÍKOVÁ, E. Multikriteriálne rozhodovanie, Košice: Elfa, 2004, s. 87, ISBN 80-89066-28-3.

[5] VAVRÍKOVÁ, L. Transitive preference structures and multicriteria decision making - Dizertačná práca. Bratislava: SvF STU, 2011.

[6] POMEROL, CH., ROMERO, S. Multicriterion Decision in Management: Principles and Practice, Kluwer Academic Publishers, Boston, 2000.