NEW APPROACH TO EQUIPMENT QUALITY EVALUATION METHOD WITH DISTINCT FUNCTIONS

by

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The paper presents new approach for improving method for quality evaluation and selection of equipment (devices and machinery) by applying distinct functions. Quality evaluation and selection of devices and machinery is a multi-criteria problem which involves the consideration of numerous parameters of various origins. Original selection method with distinct functions is based on technical parameters with arbitrary evaluation of each parameter importance (weighting). Improvement of this method, presented in this paper, addresses the issue of weighting of parameters by using Delphi method. Finally, two case studies are provided, which included quality evaluation of standard boilers for heating and evaluation of load-haul-dump machines, to demonstrate applicability of this approach. Analytical hierarchical process is used as a control method.

Key words: *quality evaluation, selection, Distinct functions, Delphi method, analytical hierarchical process*

Introduction

Quality evaluation of equipment (devices and machines) is a multi-attribute decision-making problem which is important issue for an effective production system, which can be used in selection process. Most common approach is to evaluate several alternatives which should be ranked according to various qualitative or quantitative criteria. During evaluation of machinery for given working conditions numerous factors, such as technical, economical, ergonomic, *etc.*, should be taken into consideration. Purpose of this task is to acquire the best possible alternative for given restrictions. However, the importance of technical characteristics in evaluation or selection process is emphasised by many researchers but it was not deeply investigated.

Recent researches of several authors are suggesting application of operational research methods such as analytical hierarchical process (AHP), analytical network process, and preference ranking organization method for enrichment evaluations (PROMETHEE) [1-5]. Also, some authors investigated possibility of application of Fuzzy sets [6, 7] or more general approach to machinery selection [8].

It should be mentioned that particular issue in solving the problem of ranking of various alternatives is assigning the importance or *weight* to each criterion. Some recent re-

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searchers are using simple assessment grades [7], while the other are incorporating Fuzzy theory to convert linguistic variables-descriptions into weight parameters of each criterion, such as Fuzzy simple additive weighting [9], or combination of Fuzzy theory and multi-attribute decision making tools [10, 11].

On the other hand, weighting for AHP and PROMETHEE methods is based on comparison of pairs of criteria, resulting in general ranking of criteria, as described for PROMETHEE example in [5]. Main disadvantage of this approach is unstructured weighting procedure, which is by definition subjective process, and it can generate unrealistic results. For solving this issue, it is proposed to use Delphi method for the purpose of criteria weighting. Example of using the Delphi method for the purpose of selecting the most influential criteria by a few professional experts or decision makers is presented in [12].

This paper describes improvement of the method for quality comparative evaluation of devices or machinery based on their technical characteristics [13], with Delphi method. Reason for application of Delphi method was to reduce the subjectivity in the evaluation process, through structuring of weighting factors determination, which has impact on ranking of the machines.

Description of the new approach of quality evaluation method

Method for quality evaluation of devices and machinery was initially developed at the Faculty of Mining and Geology, University of Belgrade, Belgrade [14], subsequently is improved [15], and made available for use at computers [16].

Final method which includes Distinct functions was developed in 2003 [13]. The latest method proposes the methodology for ranking of m alternatives, according to their n technical characteristics (parameters). Technical characteristics can be presented in the form of matrix [A] with type (format) $m \times n$:

$$[\mathrm{A}] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & . & \dots & . \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

where a_{ij} ($i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$) is the value of j^{th} characteristic for i^{th} machine. The matrix [A]will be called the matrix of technical characteristics.

The nature of the technical characteristic is that the biggest or the smallest value of a single characteristic is at the same time the best. This means that it is always possible to arrange characteristics (by calculating reciprocal values of some characteristics) in such way that, for example, the biggest value is at the same time the best. For this reason, let us find maximum value in every column of [A], *i. e.*:

$$b_j = \max \{a_{1j}, a_{2j}, \dots, a_{mj}\} \qquad j = 1, 2, \dots, m$$

and then let us find the ratio:

$$q_{ij} = \frac{b_j}{a_{ij}} \qquad j = 1, 2, \dots, n; i = 1, 2, \dots,)$$

and form the matrix [Q]:

$$[\mathrm{Q}] = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & q_{22} & \cdots & q_{2n} \\ \cdot & \cdot & \cdots & \cdot \\ q_{m1} & q_{m2} & \cdots & q_{mn} \end{bmatrix}$$

which will be called the matrix of technical characteristics (parameters) comparative values. From the way of selecting b_j and calculating ratio q_{ij} it follows that $q_{ij} \geq 1$ for every $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$, and that in every column of [Q] number 1 appears at least once in the place of the highest value of the corresponding parameter in the [A].

Parameter of machine quality, p_i, is calculated in following way:

$$p_i = \sqrt{\sum_{j=1}^{n} \omega_j (q_{ij} - 1)^2} \quad i = 1, 2, \ldots, m. \tag{1}$$

Conclusion about machine quality is drawn from the following criteria: the smaller p_i, the better is alternative (device or machine). In fact, eq. (1) is measuring the *distance* of every parameter ($i = 1, 2, \ldots, m$) for each alternative (device or machine) from the one *perfect* alternative which has all the best parameters. Therefore, ranking can be established, where the best alternative has the smallest parameter, p_i, meaning that the best alternative is one closest to the *perfect* alternative.

Equation (1) includes factor ω_j ($j = 1, 2, \ldots, n$) which represents the weight of the j^{th} technical characteristic to the quality of the machine. Factors, ω_j ($j = 1, 2, \ldots, n$) are in range from 0-1, but sum of all factors is equal 1. It is suggested that value of ω_j should be determined according to the experience.

This paper addresses the issue of determination of weight factor, ω, by using Delphi method.

The Delphi method is a proven and popular tool in information systems research for identifying and prioritizing issues for managerial decision-making [17]. Main principle of the Delphi method is that decision or forecast from a structured group of individuals is more accurate than those from unstructured group [18]. First applications of the Delphi method were in the field of science and technology forecasting. The objective of the method was to combine expert opinions on probability and expected development of the particular technology, in a single indicator.

Therefore, Delphi method is a structured communication method, originally developed as a systematic, interactive forecasting method which relies on a structured group of experts [19, 20]. The experts are providing answers to given questions in two or more rounds. After each round, a facilitator provides an anonymous summary of the experts' answers from the previous round. Thus, experts are encouraged to revise their earlier answers in light of the replies of other members of their panel. This process is narrowing the range of the answers and the group will converge towards the *correct* answer. Finally, the process is finalized after a pre-defined stop criterion and the median scores of the final round determine the results.

For the purpose of determination of weight (ω) for each characteristic of machine it is suggested to organize panel of experts' survey with at least two rounds. First round would include marking-scoring of each characteristic of the machine, while the second round would enable experts to revise their initial scoring with knowledge of replies of other experts. Additional rounds can be organized, depending on the complexity of the machine, *i. e*. required accuracy. Although Delphi method can be considered as a subjective method, structured approach with panel of experts refining their opinions will surely provide more accurate characteristic's weights to be used for calculation of machine quality, eq. (1).

Control method – analytic hierarchy process

Case studies – examples given in following chapters uses AHP, as a control method. This method, developed by Saaty [21], is a structured technique for organizing and analysing complex decisions. Also, this method is widely applied through-out numerous industries for solving multi-criteria decision-making problems. Therefore, only basic description is given in the paper.

The AHP is based on opinion of experts for the purpose to decompose a problem into hierarchies [22]. Therefore, it can be said that this method is a subjective one. Complexity of problem is simulated by the numerous levels in the hierarchy, combining the developed model of the problem to be solved. Such hierarchy is then used to derive scaled measures for decision alternatives and the relative value that alternatives have against organizational goals and project risks. General example of hierarchy of AHP is shown in fig. 1. The AHP uses matrix algebra for calculation of parameters in order to obtain optimal solution. The AHP is a well proved method in numerous industries.

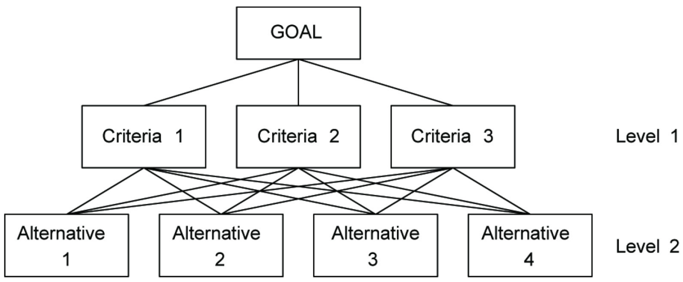

Figure 1. Scheme of hierarchy levels of AHP

The AHP derives ratio scales from paired comparisons of factors and choice options, which are marked according to so-called Saaty scale [21], which is given in the following table.

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other
5	Much more important	Experience and judgement strongly favour one over the other
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed

Case study – Example 1

Eight standard boilers used for house heating [23] are selected to present the improved machinery quality evaluation method with distinct functions. These machines will be evaluated according to their five characteristics, tab. 1.

Table 1. Standard boilers for heating and characteristics (matrix A)

Country of origin	Maximal heat load [kW]	Operating power range [kW]	Efficiency at max. heat load [%]	Efficiency at min. heat load [%]	NO_x emission [$mgkW^{-1}h^{-1}$]
Hungary	20.00	14.00	88.08	83.74	188.25
Germany, a	27.60	19.40	89.08	84.17	105.37
Serbia, a	26.00	13.20	90.50	84.11	111.93
Germany, b	26.10	16.00	90.63	84.12	100.94
France/Italy	26.05	16.50	90.35	84.11	148.04
Slovakia, a	12.50	8.20	91.88	83.18	145.83
Slovakia, b	30.50	17.50	89.62	84.31	105.64
Serbia, b	26.92	9.31	91.46	84.17	148.78

Highest value of each characteristic is the best one, except for the emission of NO_x, which is taken into consideration by calculating reciprocal values in last column. Comparative values of technical characteristics for boilers are given in tab. 2 (matrix [Q]). It should be noted that number 1 appears at least once in each column, at place of the best parameter. Also, the biggest comparative value in each column is at the place of the worst parameter. Best boiler would be the one with all comparative values closest to the number 1, and this is calculated with eq. (1).

Table 2. Matrix [Q] – Comparative values of boilers

1.52500	1.38571	1.04314	1.00681	1.86499
1,10507	1,00000	1.03143	1.00166	1.04390
1.17308	1.46970	1.01525	1.00238	1.10889
1.16858	1.21250	1.01379	1.00226	1.00000
1.17083	1.17576	1.01693	1.00238	1.46663
2.44000	2.36585	1.00000	1.01358	1.44474
1.00000	1.10857	1.02522	1.00000	1.04658
1.13299	2.08378	1.00459	1.00166	1.47396

Delphi method was introduced in the next step, including establishment of panel of five experts, which was asked to rank characteristics of boilers according to their importance. After two rounds of facilitation values of weights for each characteristic was established, tab. 3.

Table 3. Values of weight factors (ω) for boilers calculated by Delphi method

Maximal heat load [kW]	Operating power range [kW]	Efficiency at max. heat load [%]	Efficiency at min. heat load [%]	NO_x emission [$mgkW^{-1}h^{-1}$]
0.26	0.25	0.20	0.13	0.16

Diagonal pairwise comparison matrix for AHP is presented in tab 4.

Table 4. Pairwise comparisons matrix of boilers

	Maximal heat load [kW]	Operating power range [kW]	Efficiency at max. heat load [%]	Efficiency at min. heat load [%]	NO_x emission [$mgkW^{-1}h^{-1}$]
Maximal heat load [kW]	1	2	2	2	5
Operating power range [kW]	1/2	1	2	2	5
Efficiency at max. heat load [%]	1/2	1/2	1	5	5
Efficiency at min. heat load [%]	1/2	1/2	1/5	1	3
NO_x emission [$mgkW^{-1}h^{-1}$]	1/5	1/5	1/5	1/3	1

It should be noted that parameters related to AHP method are: λ_{max} = 5.3778, CI = 0.0945, and CR = 0.0843.

Results of machine quality calculation according to eq. (1) are given in tab. 5. Calculations was also performed in same manner for case with equal weight parameters (ω = 1/5) and with AHP, for purpose to demonstrate the difference.

Table 5. Rankings of the boilers

	GER, a	SVK, b	GER, b	FR/IT	SER, a	HUN	SER, b	SVK, a
Distinct functions with Delphi method	Rank: 1 p_i = 0.058	Rank: 2 p_i = 0.059	Rank: 3 p_i = 0.137	Rank: 4 p_i = 0.224	Rank: 5 p_i = 0.255	Rank: 6 p_i = 0.478	Rank: 7 p_i = 0.578	Rank: 8 p_i = 1.018
Distinct functions with equal weight parameters	Rank: 1 p_i = 0.053	Rank: 2 p_i = 0.054	Rank: 3 p_i = 0.121	Rank: 5 p_i = 0.236	Rank: 4 p_i = 0.229	Rank: 6 p_i = 0.485	Rank: 7 p_i = 0.532	Rank: 8 p_i = 0.909
AHP ranking	Rank: 1	Rank: 2	Rank: 3	Rank: 4	Rank: 5	Rank: 8	Rank: 6	Rank: 7

Distinct functions evaluation method provided almost same ranking. The only difference is switched position of fourth and fifth boiler, *i. e.* FR/IT boiler advanced one rank in case with Delphi method. The AHP method provided same ranking for best five boilers, while 6th, 7th, and 8th boilers switched ranks. Similar results with comparison of various ranking methods can be found in research [3].

Case study – Example 2

A second example is provided, for the purpose of further suitability and reliability confirmation of Distinct functions with Delphi method. In this example we ranked five machines (underground loaders), which are evaluated according to their nine characteristics, tab. 6.

The best characteristic in column four, five, seven, eight, and nine is the smallest value, while the best characteristic in remaining columns is the highest value. This was taken

Table 6. Underground loaders and characteristics (matrix [A])

Machine	Bucket volume [m^3]	Engine power [kW]	Payload [kg]	Machine mass [t]	Loading cycle [s]	Velocity max. [kmh^{-1}]	Radius turning outside [mm]	Radius turning inside [mm]	Bucket width [mm]
Atlas Copco ST 3.5	3.4	136	6000	17.10	12.6	21.0	5446	2620	1956
Sandvik Tamrock Toro 006	3.0	142	6700	17.20	12.9	26.0	5600	3030	2100
GHH Fahrzeuge LF/6	3.0	136	6000	19.50	12.5	23.0	6022	3247	2040
Caterpillar R1300	3.4	123	6800	20.95	9.3	24.0	5741	2825	2400
Wuhan KHD-3	3.0	112	6500	17.20	13.5	23.0	6060	3274	2110

into consideration by calculating reciprocal values in columns four, five, seven, eight, and nine. Comparative values of machines technical characteristics are given in tab. 7 (matrix Q). Same as in previous example, number 1 appears at least once in each column, at place of the best parameter. Also, the biggest comparative value in each column is at the place of the worst parameter. Best load-haul-dump (LHD) machine would be the one with smallest comparative p_i calculated with eq. (1).

Table 7. Matrix [Q] – Comparative values of LHD

1.00000	1.04412	1.13333	1.00000	1.35488	1.23810	1.00000	1.00000	1.00000
1.13333	1.00000	1.01493	1.00586	1.38714	1.00000	1.02816	1.15655	1.07352
1.13333	1.04412	1.13333	1.14036	1.34413	1.13043	1.10564	1.23938	1.04285
1.00000	1.15447	1.00000	1.22516	1.00000	1.08333	1.05405	1.07830	1.22688
1.13333	1.26786	1.04615	1.00586	1.45173	1.13043	1.11262	1.24969	1.07863

As in previous example, five experts provided ranking of characteristics for loaders in two rounds of facilitation, according to Delphi method. Weights are given in tab. 8.

Table 8. Values of weight factors for loaders calculated by Delphi method

Bucket volume [m^3]	Engine power [kW]	Payload [kg]	Machine mass [t]	Loading cycle [s]	Velocity max. [kmh^{-1}]	Radius turning outside [mm]	Radius turning inside [mm]	Bucket width [mm]
0.1232	0.1311	0.1367	0.0990	0.1697	0.1003	0.0879	0.0677	0.0844

Initial step in AHP is making of diagonal pairwise comparison matrix (tab. 9). Values in this matrix are representing pair comparisons of all criteria-characteristics.

It should be noted that parameters related to AHP method are: λ_{max} = 10.09, CI = 0.1366, and CR = 0.0942.

Table 9. Pairwise comparisons matrix of LHD machines

	Bucket volume [m^3]	Engine power [kW]	Payload [kg]	Machine mass [t]	Loading cycle [s]	Velocity max. [kmh^{-1}]	Radius turning outside [mm]	Radius turning inside [mm]	Bucket width [mm]
Bucket volume [m^3]	1	5	1	5	3	5	4	3	3
Engine power [kW]	1/5	1	1	1	1/5	1	1	1	1
Payload [kg]	1	1	1	1/3	1	1/3	1	1	1
Machine mass [t]	1/5	1	3	1	1/3	1/3	1	1	1
Loading cycle [s]	1/3	5	1	3	1	1	4	4	5
Velocity max. [kmh^{-1}])	1/5	1	3	3	1	1	4	4	4
Radius turning outside [mm]	1/4	1	1	1	1/4	1/4	1	2	1
Radius turning inside [mm]	1/3	1	1	1	1/4	1/4	1/2	1	1
Bucket width [mm]	1/3	1	1	1	1/5	1/4	1	1	1

Results of machine quality calculation according to eq. (1) are given in tab. 10. Similar calculations were also performed and results are provided in same table, for case with equal weight parameters, $\omega = 1/9$, for purpose to demonstrate the difference. Table 10 also provides ranking of loaders according to AHP method.

Table 10. Rankings of the machines

Method	Caterpillar R1300	Atlas Copco ST 3.5	Sandvik Tamrock Toro 006	GHH Fahrzeuge LF/6	Wuhan KHD-3
Distinct functions with Delphi method	Rank: 1 $p_i = 0.11773$	Rank: 2 $p_i = 0.17246$	Rank: 3 $p_i = 0.17275$	Rank: 4 $p_i = 0.18342$	Rank: 5 $p_i = 0.23256$
Distinct functions with equal weight parameters	Rank: 1 $p_i = 0.12562$	Rank: 3 $p_i = 0.14994$	Rank: 2 $p_i = 0.14855$	Rank: 4 $p_i = 0.17092$	Rank: 5 $p_i = 0.20921$
AHP ranking	Rank: 1	Rank: 2	Rank: 3	Rank: 4	Rank: 5

It can be seen that in case of LHD machines all three evaluation methods are suggesting same machine as the best. However, it is obvious that weight parameters are having importance. Second ranked machine, according to Distinct functions ranking with equal weight parameters, switched rank with third machine in case of Distinct functions with Delphi method. Also, it is obvious that evaluation with Delphi method have wider range of p_i parameter, which is direct result of allocating the weight with Delphi method to specific characteristics of the machine. It should be noted that ranking of machines obtained with Distinct functions with Delphi method completely corresponds with ranking obtained with AHP method.

Conclusions

Distinct functions with Delphi method can be used for comparative evaluation of quality to arbitrary number of machines according to their technical characteristics. Introduction of Delphi technique into this approach should minimize subjectivity through panel of experts, which are providing their opinions in at least two rounds. Case studies indicated the importance of allocating weight parameters to specific characteristics, which resulted in different ranking of alternatives-machines. Finally, presented method for quality evaluation of machines was validated by very similar ranking obtained by AHP method. Therefore, application of Distinct functions with Delphi method for quality evaluation of equipment, as presented in this paper, is justifiable and suitable for ranking of arbitrary number of alternatives-machines according to their technical characteristics.

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