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Use of Multi-Criteria Decision Aid Methods for Selection of the Best Alternative for the Highway Tunnel Doors

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Abstract

The paper describes the application of the multicriteria optimization in selecting the best alternative when choosing a tunnel security door. The paper presents an overview of the requirements of internationally recognized and other important standards and recommendations aimed at increasing the level of safety in tunnels, as well as an example of the multicriteria analysis for the selection of doors. The applied alternatives multicriteria ranking methods are VIKOR, PVIKOR and PROMETHEE, whose results are compared in order to propose and adopt a final solution. Paper also assesses the possibilities and profitability of production of such doors in BiH. The application of these methods shows that multicriteria optimization can significantly facilitate and accelerate the decision-making process.
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Keywords: multicriteria optimization; security in tunnels; Vikor method; Promethee method; Multicriteria decision aid

1. Introduction

1.1. Fire safety

Fire safety and safety in general are becoming increasingly important. Modern society is characterized by a complex production and communication systems, development of new materials, machinery and equipment, keeping valuable assets, and increased scope of handling, storage and transport of hazardous substances. Larger and more complex structures, machines and equipment, as well as new materials, can lead to major fires; it is difficult to

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predict and assess all future risks, the attention of the media is attracted to events with casualties and / or major damage.

During the last decades several devastating fires in European tunnels, with a large number of casualties, attracted attention of both the public and the scientists. Below Table 1 lists examples of tunnel fires occurred, with the number of killed and injured people.

Table 1. Fires in tunnels on auto routes with 5 or more injured people [1].

Year	Tunnel	Lenght	Tubes	Casualties	Injured
1978	Velsen (Netherland)	770 m	2	5	5
1979	Nihonzaka (Japan)	2 km	2	7	2
1980	Sakai (Japan)	460 m	2	5	5
1982	Caldecott (USA)	1,1 km	3	7	2
1983	Pecorile (Italy)	660 m	2	9	22
1996	Isola delle Femmine (Italy)	148 m	2	5	20
1999	Mont- Blanc (France-Italy)	11,6 km	1	39	0
1999	Tauern (Austria)	6,4 km	1	12	40
2001	Gledinalm (Austria)	8,3 km	1	5	4
2001	St. Gotthard (Switzerland)	16,9 km	1	11	0
2006	Viamala Tunnel (Switzerland)	750 m	1	9	6
1978	Velsen (Netherland)	770 m	2	5	5

The importance of fire protection is particularly noticeable in tunnels heavily loaded with traffic. Fires and accidents in the tunnels in general cause direct costs for damages and temporary closing, but also threaten human communities and markets that are connected to the tunnels. Tunnel fires cut off companies from their customers and suppliers, workers from their jobs, the alternative transport routes usually lead to roads congestion, loss of time and money, increased pollution, dissatisfaction with the local population and the increased risk of accidents. Increasing safety for tunnels, or reducing the risk of fire and other accidents, are providing both direct and indirect benefits. Direct benefits include avoiding injuries and fatalities, avoiding losses in production due to injury, avoiding cost of the reconstruction, avoiding the cost of emergency services and medical costs, avoidance of increased travel time caused by the use of alternative routes during the period of reduced functionality of the tunnel (eg. closing one lane, or the whole tunnel), no revenue reduction due to the closure of the tunnel, avoiding significant economic disruptions that may occur due to the closure of the tunnel, reduction in insurance premiums and many other. Indirect effects can also have significant social and economic impact, like e.g. the public perception of reduced risk that may increase traffic through tunnels and stimulate economic activity, reduced emissions of CO_2 and other pollutants, reduced fuel consumption and other. When it comes to safety in tunnels, at first place it is necessary to avoid incidents that could pose a threat to human life, the environment and the tunnel infrastructure. But at the same time, if the incidents would still happen, it is of upmost importance to ensure the best conditions for achieving security for the tunnel users who find themselves affected by the incident (fire, accident, etc..).

When an incident occurs, the first ten to fifteen minutes are crucial for tunnel users to come to a safe place. To make this possible it is necessary to provide safe paths to escape. In this sense the doors in the tunnels, connecting the two lanes in the tunnel, have a dual role - at first they are a barrier to smoke or toxic gases and fire, and secondly it has to allow the escape for tunnel users and quick entrance for emergency rescues. Special requirements for such tunnel doors far exceed the ordinary demands. Standardization of the tunnel door will help users to react quickly and appropriately in emergency situations and thus contribute to limiting the extent of the damage. This paper present multicriteria decision aid use for selection of the doors in the tunnels based on different criteria that the door must satisfy, where there was very limited research in this specific area done in the past.

1.2. Multicriteria decision aid

The multicriteria optimization is a part of the multicriteria decision making process. The basic steps in this optimization are:

Step1: Defining the goals and methods to achieve the goals,
Step 2: Formalizing the problem, determining and valuation of criteria,
Step 3: Selection and use of appropriate multicriteria optimization method, and
Step 4: Making the final decision or re-evaluation, repeating the procedure from the second step.

Numerous different methods are developed to solve this type of problem, like methods for determining non-inferior solutions, methods with pre-expressed preferences, interactive methods where preferences are gradually determined, stochastic methods, compromise programming, etc. [2, 3]. Solution is not unique and it directly depends on the method selected. Since the n-dimensional space is not fully ordered, most of these methods generally tend to order the space completely or partially. Methods used specifically in water sector are described in [4, 5, 6].

The entire process of defining problems, determining alternatives and valuation criteria, contour constraints, optimization and making the final choice is called multicriteria decision making. The term "decision" more accurately determines the whole process, since only by decision one can select a solution (or set of solutions).

Various multicriteria decision making (MCDM) methods have been applied in similar problems and selection of an appropriate MCDM method is an MCDM problem itself. E.g. Analytic Hierarchy Process (AHP, described in [7]), used successfully for alternative energy source selection and energy resource allocation, ELECTRE method, applied e.g. for choosing the most suitable heating system for buildings or community energy modernization and development planning, PROMETHEE used for ranking alternative cooking options in India, or VIKOR largely used in water sector, are among the most commonly used MCDM methods. It is necessary first to clearly define the problem, then to identify realistic alternatives, actors involved in the decision making, select the evaluation criteria, and evaluate each alternative according to the set of criteria. After all that being done an MCDM method is selected to aggregate the performance of each alternative, with or without weighting of the selection criteria [8].

Authors of this study decided for VIKOR method (including its extended version PVIKOR), as one of the compromise optimization methods, compared with results achieved by PROMETHEE method.

1.2.1. VIKOR method

The VIKOR ("VIšekriterijumsko KOmpromisno Rangiranje" - multicriteria optimization and compromise ranking) method was first proposed by Zeleny and later advanced and advocated by Opricovic [2]. The method aims at solving the multicriteria decision making problems having conflicting and non-commensurable attributes (e.g. simultaneously minimizing implementation costs and maximizing effects). The method assumes that as compromise, decision maker would accept a solution that is the closest to the so-called ideal solution. It results with ranking a finite set of alternatives with conflicting criteria, where decision maker may select and propose the compromise solution (one or more). The compromise solution is then always a feasible solution, which is the closest to the ideal solution, and a compromise here means an agreement established by mutual concessions made between the alternatives [9].

Measure of distance to ideal solution is based on the Lp-metric D, as follows:

$$D(A_j) = \sqrt[p]{\sum_{i=1}^{N} c_i \left(\frac{{f_i}^{+} - f_{ij}}{{f_i}^{+} - {f_i}^{-}}\right)^p} \tag{1}$$

where:

$$f_i^{+} = max\, f_{ij} \quad (i=1, 2, \ldots, n)$$
$$f_i^{-} = min\, f_{ij} \quad (i=1, 2, \ldots, n) \tag{2}$$

while f_{ij} are values of j^{th} criteria of i^{th} alternative and c_i are criteria weights, where request is to maximize all individual criteria.

VIKOR uses as basis two forms of the Lp-metric, for p=1 and p=∞:

$$S_j = \sum_{i=1}^{N} c_i \left|\frac{{f_i}^{+} - f_{ij}}{{f_i}^{+} - {f_i}^{-}}\right| \tag{3}$$

and

$$R_j = \max_i \left(c_i \left| \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \right| \right) \quad (4)$$

and then forms another two-dimensional space RS of alternatives, with L_1-metric Q defined as follows:

$$Q(A_j) = Q_j = \nu\, QS_j + (1-\nu)\, QR_j = QR_j + \nu\, (QS_j - QR_j) \quad (5)$$

where

$$QR_j = (R_j - R^+) / (R^- - R^+) \quad \text{and} \quad QSj = (S_j - S^+) / (S^- - S^+) \quad (6)$$

and

$$S^+ = \min S_j\,,\ S^- = \max S_j\,,\ R^+ = \min R_j \ \text{and}\ R^- = \max R_j \quad (7)$$

Coefficient ν is called "strategy coefficient", and it always belongs to interval [0,1], where values higher then 0.5 are giving more focus to satisfying most of the criteria, while values lower then 0.5 are setting higher priority to minimizing individual differences from ideal solution (alternative).

An additional criterion is set for deciding if the first ranked alternative for ν=0.5 is to be recommended (if it is stabile as first) - it needs also to meet the following conditions:

- To have solid advantage over the second-ranked alternative, which is correct if for ν=0.5 is valid $Q(A_j)-Q(A_i) \geq DQ$, where DQ = min (0.25, 1/(M-1)), and M is number of alternatives (8)
- Has stabile position with changes of "strategy coefficient" ν, meaning that at least one of the following is correct:

  – the same alternative is first ranked with ν=1,
  – the same alternative is first ranked with ν=0, or
  – the same alternative is first ranked with ν=0.25 and with ν=0.75.

If the first ranked alternative does comply with both these conditions, then it is not fairly better than the second one and thus both are considered as compromise solutions. If it does not comply only with the first condition, compromise solutions include all those ranked from the first which are also not meeting the first condition. If the first ranked alternative does not comply only with the second condition, then it is excluded and only second one is the compromise to be proposed [3].

Quite similar is PVIKOR method that besides Sj and Rj described with (3) and (4) introduces also P_j with

$$P(A_j) = \sqrt[p]{\sum_{i=1}^{N} c_i \left| \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \right|^p} \quad (9)$$

so as:

$$P^+ = \min P_j\,,\ P^- = \max P_j$$

and:

$$QP_j = (P_j - P^+) / (P^- - P^+)$$

with new L_1-metric Q defined as follows:

$$Q(A_j) = Q_j = \nu\, QS_j + \mu\, QR_j + (1-\nu-\mu)\, QP_j$$

VIKOR has been very successfully used as MCDM tool - some examples proving that fact refer to selection of industrial robots [10], applicability for seismic upgrading building structures [11] or selection of materials under aggressive environments [12].

1.2.2. PROMETHEE method

The method PROMETHEE (Preference Ranking Organization Methods for Enrichment Evaluation) requires certain pre-defined preference of the Decision Maker. Preferential relations are introduced for each criteria separately, as presented below:

$$P_k\left(A_i, A_j\right) = \begin{cases} 0, & za\ f_k(A_i) \leq f_k(A_j) \\ P_k\left(d_{ij}^k = f_k(A_i) - f_k(A_j)\right), & za\ f_k(A_i) > f_k(A_j) \end{cases} \quad (10)$$

Function Pk(fk(Ai) - fk(Aj)) has values from the interval [0,1], some of the examples are presented below:

$$P_k\left(A_i, A_j\right) = \begin{cases} 0, & \text{for } d_{ij}^k \leq 0 \\ 1, & \text{for } d_{ij}^k > 1 \end{cases} \quad \text{(simple criteria)} \quad (11)$$

$$P_k\left(A_i, A_j\right) = \begin{cases} 0, & \text{for } d_{ij}^k \leq q_k \\ 1, & \text{for } d_{ij}^k > q_k \end{cases} \quad \text{(quasi criteria)} \quad (12)$$

$$P_k\left(A_i, A_j\right) = \begin{cases} 0, & \text{for } d_{ij}^k \leq 0 \\ \frac{d_{ij}^k}{p_k}, & \text{for } 0 \leq d_{ij}^k \leq p_k \\ 1, & \text{for } d_{ij}^k > p_k \end{cases} \quad \text{(linear criteria)} \quad (13)$$

where the boundary values p_k or q_k are defined in advance for each of the criteria. Normalized criteria weights c_k are also preselected for each of the criteria functions f_k, where

$$\sum_{i=1}^{n} c_i = 1 \quad (14)$$

Overall preferential index $P(A_i, A_j)$ of alternative Ai to alternative Aj is calculated as

$$P\left(A_i, A_j\right) = \sum_{k=1}^{n} c_k P_k\left(A_i, A_j\right) \quad (15)$$

after which positive and negative preference of alternative Ai is calculated with

$$P^+(A_i) = \sum_{j=1}^{J} P\left(A_i, A_j\right) \quad (16)$$

and:

$$P^-(A_i) = \sum_{j=1}^{J} P\left(A_j, A_i\right) \quad (17)$$

Final measure for alternative A_i is evaluated with

$$P(A_i) = P^+(A_i) - P^-(A_i) \quad (18)$$

PROMETHEE is another very successfully used MCDM tool, examples include mining method selection [13], facility location selection [14] defining new exploration strategies for rescue robots [15].

2. Multicriteria ranking of the tunnel doors

2.1. Criteria selection

Based on the existing recommendations, regulations, research and market assessment, the authors decided for the following list of criteria, limited also by available and accessible information on the doors and their use:

Door width - this criteria relates to the request that all persons affected by the incident in the tunnel need to be successfully evacuated. Recommendations for fire safety [16] write that the door width depends on the number of persons that will use it, and it has to be at least 750 mm for 60 persons, 850 mm for 110 persons, 950 mm for 160 persons, 1050 mm for 220 persons, and 1050 mm + 5 mm extra for each additional person for more than 220 persons.

Pressure resistance - door need to be constructed to resist pressures in road tunnels that vary ±1 kPa to ±3 kPa. Air pressure to the door can reach even several hundreds of Pascal for the traffic load, ventilation, natural pressure differences in rising tunnels or explosions. In case of fire in the tunnel pressure in incident tunnel tube is higher, and than the other tube is put under higher pressure in order to prevent smoke intrusion.

Door closure speed - door closing speed can vary from 50 to 300 mm/s. It is achieved by using a shutter gate whose function is self-closing open door. After the user enters the transverse passage, closing speed should be as fast as possible in order to avoid the entry of smoke, dust and heat. The door must be closed in a maximum of 10 seconds.

Force needed to close and open the door - force required to manually open the door can vary from 80 to 200 N. Recommend values of 100-120 N relate the worst ventilation conditions. This force should be as small as possible for users to more easily open and fled to safety. The force required to close the door (if the automatic closure does not work) may range from 15 to 100 N

Time needed to replace spare parts - assuming the minimum time for the purchase of spare parts or their existence in the stock, it is desirable that the time of replacement or repair of individual components (e.g. electric appliances) would be as short as possible..

Lifetime (duration) - minimum operating life (depreciation period) for door is 25 years. Average lifetime for the technical equipment in the tunnels (according to PIARC - World Road Association) is presented in the below figure [1].

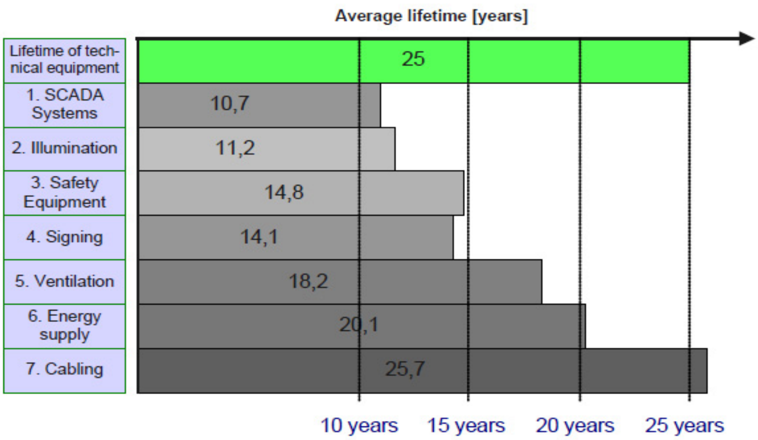

Fig. 1. Average duration of technical equipment in the tunnels [1].

Cost - for the ranking purposes this criteria will be considered as linearly independent from the lifetime.

Several additional criteria are assessed, but decided not be included for the multicriteria ranking since their actual values are similar or same for all the alternatives. These include:

Fire resistance - the materials used for the structure and equipment in tunnels should not burn or produce large amounts of toxic smoke in case of fire. Moreover, the tunnel structure may not be distorted at least until the evacuation and fire fighting is over. Fire resistance is the time that elapses between the start of the fire and the time when the structure does not provide its function any more, either because of deformation or of collapse. During the interviews, relevant experts pointed out that the selection of door with longer period of fire resistance (e.g. 120 min.) is not the tunnel wall structure can not resist the same period. Therefore, the required fire resistance for all manufacturers is equal, and it is 90 minutes.

Door height - recommended is 2000 mm.

Air flow - door must not lea smoke, maximum permeability is 0,15 m3/s.

Door opening direction - the door should open in the direction of escape. Preferably, the handle used to open the door should be intended to open with both hands.

Material - doors should be made of stainless steel.

Guarantee - minimal guarantee should be 2 years.

Selected criteria are assigned, based on interviews with the competent highway managers, with related normalized weighting coefficients describing their relative importance (and with indication if the criteria should be maximized or minimized). Criteria weights are presumed to be sufficiently precisely identifiable (if that is not the case and only fuzzy measure is available to capture relative importance of the criteria, the Golden Rule aggregation is proposed in [17]). Criteria weights used are as follows:

Table 2. Relative criteria weights.

Criteria		Max or Min	Weight
Door width	Criteria 1	Max	0,08824
Pressure resistance	Criteria 2	Max	0,11765
Door closure speed	Criteria 3	Min	0,14706
Force needed to manually open the door	Criteria 4	Min	0,13235
Force needed to manually close the door	Criteria 5	Min	0,13235
Time needed to replace spare parts	Criteria 6	Min	0,14706
Lifetime (duration)	Criteria 7	Max	0,13235
Cost	Criteria 8	Min	0,10294

2.2. Alternatives evaluated and criteria values

During the research period three tunnel doors' producers, out of 10 contacted, have provided needed information and input data for the offered doors (one from UK and two from Germany), and they will be addressed as alternatives A_1, A_2 and A_3. Missing data were practically evaluated or valuated through interviews with relevant experts. Criteria values for each of the three alternatives are presented in the below table.

Table 3. Alternatives' criteria values.

Criteria	Criteria	Unit	A_1	A_2	A_3
Door width	Criteria 1	mm	1050	1010	1000
Pressure resistance	Criteria 2	kPa	2.5	2	3
Door closure speed	Criteria 3	mm/s	50	80	100
Force needed to manually open the door	Criteria 4	N	200	150	100
Force needed to manually close the door	Criteria 5	N	40	20	15
Time needed to replace spare parts	Criteria 6	Hours	4	4.5	5
Lifetime (duration)	Criteria 7	Years	25	25	5.5
Cost	Criteria 8	Euro	5180	5500	4860

2.3. Multicriteria ranking of alternatives

VIKOR method - After replacing all criteria f_i to be minimized with $-f_i$ (to be maximized), the normalized values with related weights are as follows:

Table 4. Alternatives' criteria normalized values and weights.

Criteria	Weights	A_1	A_2	A_3
Criteria 1	0.08824	0.000	0.071	0.088
Criteria 2	0.11765	0.059	0.118	0.000
Criteria 3	0.14706	0.000	0.088	0.147
Criteria 4	0.13235	0.132	0.066	0.000
Criteria 5	0.13235	0.132	0.026	0.000
Criteria 6	0.14706	0.000	0.074	0.147
Criteria 7	0.13235	0.000	0.000	0.132
Criteria 8	0.10294	0.051	0.103	0.000

These values are used to evaluate Sj, RJ and finally Qj values, which will define the final alternatives ranking as follows:

Table 5. Measures Sj and Rj.

Measure	A1	A2	A3	Ranking
S	0.375	0.546	0.515	A_1, A_3, A_2
R	0.132	0.118	0.147	A_2, A_1, A_3
QS	0.000	1.000	0.819	A_1, A_3, A_2
QR	0.500	0.000	1.000	A_2, A_1, A_3

Table 6. VIKOR Final Measures Qj.

Value of ν	A1	A2	A3	Ranking
$\nu = 0.25$	0.375	0.250	0.955	A_2, A_1, A_3
$\nu = 0.50$	0.250	0.500	0.909	A_1, A_2, A_3
$\nu = 0.75$	0.125	0.750	0.864	A_1, A_2, A_3

Since for $\nu = 0.50$ alternative A_1 is first ranked, so as that $Q(A_j) - Q(A_i) = Q(A_2) - Q(A_1) = 0.25$, it may be said that alternative A_1 has sufficient advantage to A_2 to be finally selected, underlining that that it is also first ranked by a majority rule (S, QS) and thus has stable first position.

PVIKOR method: Using the same inputs and transformed normalized values, evaluation for the final Q_j values of alternatives is as presented below:

Table 7. PVIKOR Final Measures Qj .

Value of ν	A1	A2	A3	Ranking
$\nu = \mu = 0.33$	0.167	0.406	0.940	A_1, A_2, A_3

But since Q(A_j) - Q(A_i) = Q(A_2) – Q (A_1) = 0.239 < DQ = 0.25, A_1 does not have sufficient advantage to A_2 and thus both may be taken into the account.

PROMETHEE method: Assumed is linear criteria, with the following values of p_k:

Table 8. p_k values for PROMETHEE ranking.

Criteria	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6	Criteria 7	Criteria 8
p_k	40	0.5	30	50	20	0.5	5	300

Tables of the preferences follow:

Table 9. Individually evaluated preferences for all criteria.

P_1	A_1	A_2	A_3	P_2	A_1	A_2	A_3	P_3	A_1	A_2	A_3
A_1	0	1	1	A_1	0	1	0	A_1	0	1	0
A_2	0	0	0.25	A_2	0	0	0	A_2	0	0	0
A_3	0	0	0	A_3	1	1	0	A_3	1	1	0

P_4	A_1	A_2	A_3	P_5	A_1	A_2	A_3	P_6	A_1	A_2	A_3
A_1	0	1	1	A_1	0	0	0	A_1	0	0	0
A_2	0	0	0.66667	A_2	1	0	0	A_2	1	0	0
A_3	0	0	0	A_3	1	1	0	A_3	1	0.25	0

P_7	A_1	A_2	A_3	P_8	A_1	A_2	A_3
A_1	0	1	1	A_1	0	0	1
A_2	0	0	1	A_2	0	0	1
A_3	0	0	0	A_3	0	0	0

Using the same weights as in the Table 4, the following preferential indexes are calculated, leading to the following table of total preferential indexes:

Table 10. Preferential indexes.

$P(A_i, A_j)$	A_1	A_2	A_3
A_1	0,000	0,603	0,515
A_2	0,265	0,000	0,400
A_3	0,485	0,386	0,000

Table 11. Final values for the alternatives.

$P(A_i)$	P^+	P^-	P
A_1	1,118	0,750	0,368
A_2	0,664	0,989	-0,325
A_3	0,871	0,914	-0,043

Thus the PROMETHEE also suggest alternative A_1 as the first ranked.

Conclusions

All three methods suggested alternative A_1 as the best, where with PVIKOR it shares the first position with A_2.

Table 12. Rankings by methods.

Method	*Ranking*
VIKOR	A_1, A_2, A_3
PVIKOR	$A_1/ A_2, A_3$
PROMETHEE	A_1, A_3, A_2

The disadvantage of these methods is that they require the decision maker to pre-determine criteria weights and for PROMETHEE even the thresholds of indifference for the selected model preference functions. Feedback to decision makers and the inability of progressive profiling his/her preference is lacking and such a requirement is sometimes too stringent for the decision maker, that he/she is not able to meet. For this reason, for selection of tunnels' doors it is easier to use VIKOR since it has lower requirements for the decision maker's pre-defined preference. This paper justified use of multicriteria decision aid models for the selection and procurement of the tunnel doors, what is a new contribution in this area, and it may be advised even as a part of public procurement procedure after previous detailed assessment for the specific requirements, what is recommended for the further research.

Further research should include testing of applicability and appropriateness of more multicriteria decision aid methods, so as potential use within the public procurement procedures for selected procurement areas.

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