Evaluation and Application of AHP, MAUT and ELECTRE for Infrastructure management

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Evaluation and Application of AHP, MAUT and ELECTRE for Infrastructure management

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ABSTRACT: Infrastructure management renders a number of decision-making problems from assets condition inspections to maintenance planning and resources optimisation. Since management of infrastructure pertains to not only technical requirements but also to societal and economic developments, these decision problems have multiple and often conflicting objectives. Various methods of MCDA based on the decision theory and game theory are proposed to aid-in decision-making problems. Owing to the wide area of applications and extensive variation in MCDA methodology, the selection of appropriate MCDA method pertaining to the specific needs of infrastructure management and decision maker is a difficult task. In this paper, two synthesis-based methods (i.e. AHP and MAUT) and an outranking method (i.e. ELECTRE III) is applied on same maintenance decision making problem to evaluate them for their scalability, ease of use, risk consideration, and few other aspects. The results of evaluation suggest that a) without a computerised tool the scalability of these methods is tedious task b) only MAUT considers the risk attitude of a decision maker c) AHP and MAUT both require the data to be converted to definite scale for analysis, for instance, to Saaty scale of comparison and to utility functions respectively and d) unlike other two, ELECTRE works on preference structure and yields partial pre-orders. These aforementioned results are obtained by application of AHP, MAUT, and ELECTRE III on the maintenance planning decision problem of 22 road bridges from Netherlands road network. Despite the inherent methodology differences of these methods, the result of case study shows minor difference in ranking yielded by considered MCDA methods.

1 INTRODUCTION

European road network consist of more than 5 million km of road, thus providing a vital link for economic competitiveness and social development (ERF 2010). According to a report by European Union Road Foundation ERF (2013), roads form 71.8% of total transport modal in Europe, while rail being only 17.4%. With roads infrastructure being the backbone of nations' economy, the condition of roads infrastructure is rapidly deteriorating due to aging, increased usage and significant lack of investment and maintenance funding since 2008 (ERF 2013). The deteriorating infrastructure brings higher risk of accidents, increased noise, reduced service quality, congestion, extended travel times and increased CO_2 emission.

Due to multiple involved challenges, agencies have to deal with number of performance requirements. This involves decision-making on maintenance scope, maintenance treatment, future benefit of chosen maintenance treatment, acceptable service level, incurring cost, resulting user delay, and impact on environment. Decision-making based on subjective measures (e.g. judgement, past experiences) and use of life-cycle cost analysis have yielded promising results in past where cost and condition state of an asset were main factor for maintenance decision-making. However, these method are usually unable to accommodate number of performance aspects related to economy, society, environment, etc.

Multi-Criteria Decision Making (MCDA) provides systematic framework to consider and optimise number of performance aspects based on decision makers' preferences as well as on objective data. Among others, Patidar (2007), de Almeida et al. (2015) and Kabir et al. (2014) are excellent sources presenting the use of MCDA methods for infrastructure management and maintenance decision-making. Owing to the wide area of applications and extensive variation in MCDA methodology, the selection of appropriate MCDA method pertaining to the specific needs of infrastructure management and decision maker is a difficult task. The literature reports the use of multiple methods of MCDA for similar decision problem. For example, de Almeida et al. (2015, Table 4) presented number of publications per MCDA method for the maintenance decision-making problem.

In this paper, three methods of MCDA, namely Analytical Hierarchy Process (AHP), Multi-attribute Utility Theory (MAUT) and ELECTRE III (Elimination and choice expressing reality) have been compared by applying them on similar set of data for the maintenance decision-making. These methods are evaluated for their scalability, ease of use, encoding to definite scale, risk considerations, ability to accommodate stakeholders' preferences and understandability of results. Therefore, the objective of this paper is two fold: first to illustrate the application of various methods of MCDA for facilitating in maintenance decision-making process and second to provide a recommendation on which method of MCDA is most useful considering the number of usability criteria.

The rest of the paper is structured as follows: Section 2 provides a broader classification of MCDA methods and report few studies where MCDA methods has been applied on maintenance decision-making problem. In Section 3, an evaluation scale is provided to analyse the applicability of AHP, MAUT and ELECTRE III. Section 4 provides the details of case study by applying MCDA methods on real-case data. The results obtained from different MCDA methods is compared and discussed in Section 5 along with recommendation on methods applicability. Finally, Section 6 provides the conclusion of this study.

2 MCDA METHODS IN DECISION-MAKING OF INFRASTRUCTURE MAINTENANCE

A literature review published by de Almeida et al. (2015) shows a increasing trend on the use of MCDA methods applied on infrastructure maintenance and reliability decision problems. Few methods of MCDA have particularly gained attention in this regard e.g. Pareto Front, MAUT, AHP, MAVT, Goal programming, different versions of ELECTRE and TOPSIS (Technique for Order by Similarly to Ideal Solution). Considering the different solution approaches of these MCDA methods, they can be classified into three types (Guitouni and Martel 1998) (Allah Bukhsh et al. 2018):

- Synthesis methods: These are weighted aggregation methods that provide the relative ranking of all the alternatives under considerations based on the preference structure of the decision maker. The example of synthesis methods are AHP, MAVT, MAUT, and TOPSIS.

- Outranking methods: These methods seek to eliminate all the alternatives that are explicitly dominant. For instance, one alternative outranks another if it performs considerably well on all the attributes. The example of outranking methods are ELECTRE and PROMETHEE (Preference Ranking Organisation Method for Enrichment of Evaluations).

- Interactive methods: These methods have a strong base in mathematical principles where the objective is defined in a set of targeted values. Goal programming and Pareto front are interactive methods.

As noted in Allah Bukhsh et al. (2018), interactive methods are being applied extensively in maintenance optimisation problems to search for the non-dominant solution that satisfies multiple objectives. However, interactive methods are based on complex heuristic search procedures e.g. genetic algorithms, particle swarm analysis and they don't take into account the preferences of the stakeholders (de Almeida et al. 2015).

In this paper, we will be applying two MCDA methods belonging to synthesis class and one outranking method to maintenance decision problem. The synthesis methods reduce the actual data values into certain normalisation e.g. utility scores, weighted mean, etc to enable the comparison of heterogeneous scales of attributes e.g. cost in euros, delay in hours. While, outranking methods take the preferences of stakeholder(s) and enable the comparison of heterogeneous scales of attributes without reducing them into certain value functions or standard scales (e.g. scale of pairwise comparison).

3 EVALUATION SCALE OF MCDA METHODS

In the past, number of methods of MCDA have been developed for different decision-making situations. Each method of MCDA follows its own procedure to assess criteria, to define the weights and drive their importance, the mathematical models used, and the ability to accommodate the stakeholder(s) preferences (De Montis et al. 2000). In this paper, AHP, MAUT and ELECTRE III is applied on the same maintenance decision-making problem. The purpose is to evaluate each of this method to determine difference in their results as well as to examine their applicability on maintenance decision-making problems. An evaluation scale derived from (De Montis et al. 2004) and (Cinelli et al. 2014) is provided below:

- Scalability
- Ease of Use
- Encoding to definite scale

- Uncertainty / Risk consideration
- Stakeholders' preferences
- Understandability of results

Note that, the assessment of AHP, MAUT and ELECTRE III is performed by authors of this paper by using the evaluation scale.

4 CASE STUDY

To illustrate how the different methods of MCDA can be applied for the maintenance decision-making, we used data of twenty-two randomly chosen bridges from Netherlands road network. The provided data contain information of bridges' age, geometry, condition index on the element level, traffic intensity, planned maintenance activity on element level, unit cost of chosen maintenance treatment and maintenance duration. Using this raw data, we computed condition index on overall bridge-level, owner cost incurred due to maintenance activity, user delay cost and environmental cost for each of the bridge. The computed data is provided in Table 1. The details of these attributes computation can be found at (Allah Bukhsh et al. 2018, Section 4).

To compare the results of AHP, MAUT and ELECTRE, these twenty-two bridges will be ranked in a preferred order for maintenance where the objective is a) to minimise the owner cost, b) to minimise condition index (where lower value represent better condition), c) to reduce impact on road users as a result of maintenance (expressed in user delay cost) and d) to minimise environmental impact (expressed as environmental cost). It is important to notice that these objectives are conflicting with each other e.g. to minimise the impact on users, the agency might need to use more resources which will result in increased owner cost. Thus, a decision based on only single attribute can not be made instead there must be an equal representation of all the attributes in the final ranking of bridges.

In the following, the brief algorithm details of each MCDA methods is provided along with their application on case study data.

Table 1: Data of twenty-two bridges

Alternatives	CI	OC	UDC	EC
Bridge A	2.77	139.35	39.70	0.86
Bridge B	1.89	126.41	27.50	0.21
Bridge C	2.15	115.67	25.57	0.57
Bridge D	2.73	42.94	3.41	0.02
Bridge E	2.00	68.16	12.40	0.53
Bridge F	2.12	149.21	47.89	0.23
Bridge G	2.10	169.56	57.79	0.48
Bridge H	2.42	88.60	13.11	1.25
Bridge I	2.22	45.82	35.89	1.26
Bridge J	2.34	115.93	30.80	0.43
Bridge K	2.42	39.42	12.69	0.23
Bridge L	2.46	69.61	12.12	0.03
Bridge M	1.92	38.14	7.99	0.03
Bridge N	2.18	84.89	14.42	1.05
Bridge O	2.43	46.89	4.59	0.01
Bridge P	1.67	175.33	28.51	0.68
Bridge Q	2.08	161.48	55.25	0.37
Bridge R	2.30	158.89	51.04	0.22
Bridge S	2.58	65.90	8.79	0.10
Bridge T	1.96	62.22	22.83	0.42
Bridge U	2.02	84.82	25.70	0.28
Bridge V	2.34	152.60	42.91	0.27

CI = Condition Index, OC = Owner Cost, UDC = User Delay Cost, EC = Environmental Cost

4.1 *Analytical Hierarchy Process*

Analytical hierarchy process (AHP) is a group decision making method which has been used in wide variety of decision situations. It provides a comprehensive framework to define objectives, their quantifying criteria, and to evaluate alternative solutions. AHP performs pairwise comparison to assign the relative importance of each criterion in a decision situation.

AHP Algorithm

The procedure of using AHP for decision making is outlined as follows (Saaty 2008):

1. Identify the objectives, alternatives and mostly importantly criteria to evaluate the alternatives.

2. Perform pairwise comparison between two criteria at a time to establish the priorities among criteria.

3. Assign the level of importance by criteria values using the Saaty's relative scale of importance [1] which will convert the subjective judgements of decision makers into ratio scale.

4. The step of pairwise comparison is performed on each criteria values.

5. To calculate the final weighted scale, the performance matrix is normalised between 0 to 1 by

$$\bar{e_{ij}} = \frac{e_{ij}}{\sum_{k=1}^{n} e_{ij}}$$

   where e_{ij} represents an element in matrix M. $\bar{e_{ij}}$ represents an element of normalised matrix.

6. The next step is to calculate the geometric mean of normalised matrix to compute the largest values that represent the aggregated preference.

[1] Online link to scale: http://bit.ly/2miLLbB

Table 2: Pairwise comparison of criteria to derive their relative importance

	Relative importance of criteria				Normalised matrix				Geometric mean
Attributes	CI	OC	UDC	EC	CI	OC	UDC	EC	total
Condition index (CI)	1	0.33	3	7	0.22	0.20	0.32	0.31	0.26
Owner cost (OC)	3	1	5	9	0.67	0.60	0.54	0.40	0.54
User delay cost (UDC)	0.33	0.20	1	5	0.07	0.12	0.10	0.22	0.12
Environmental cost (EC)	0.14	0.11	0.20	1	0.03	0.06	0.02	0.04	0.03
Sum	4.47	1.64	9.20	22	1	1	1	1	0.97

7. Next, normalise the actual data matrix to reduce them between 0 to 1 by following the Step 5.

8. Finally, the geometric mean of each criteria is multiplied by normalised matrix to get the final ranking score.

AHP Application

The first step is to identify the objectives, criteria and alternatives. In our case study, each of these aspects are clearly established. As mentioned earlier, *the objective is to rank the bridges in an order where owner cost, condition index, user delay cost and environmental cost could be minimised*. While, the alternatives are those twenty-two randomly chosen bridges from Netherlands road network.

In order to define, if owner cost is more important than condition index, or user delay cost is preferred over environmental cost, the pairwise comparison between criteria is performed. The pairwise comparison is based on the Saaty's fundamental scale of importance where two criteria are compared on the scale of 1 to 9. While, 1 represent equally importance and 9 represents one criteria is extremely more important than another. Table 2 shows the detailed steps where each criteria is compared with another to compute the geometric mean. The values of geometric mean shows that owner cost is most important followed by condition index, user delay cost and environmental cost.

Generally, the data of criteria differs in their scale and magnitude. For example, owner cost could be in euros while the user delay can be computed in hours. Therefore, the normalisation of data is performed to make them comparable. In this case study, all the data value were already reduced to cost except for the condition index. After the data normalisation, the final step is to perform matrix multiplication between geometric mean of criteria and normalised data values. The final aggregated score provides the ranking of bridges, which is derived by decision makers preferences represented in form of geometric mean. The final result computed by AHP is provided and discussed in Section 5.

4.2 *Multi Attribute Utility Theory (MAUT)*

MAUT, proposed by Keeney and Raiffa (1993), is based on the expected utility theory which reduces the criteria values into utility scores. In MAUT terms, the criteria is referred as attributes. In contrast to AHP, MAUT is able to capture not only the preference structure of a decision maker but also the uncertainty and risk tolerance aspects. For algorithm and application details on same case study data, an interested reader may refer to (Allah Bukhsh et al. 2018).

MAUT Algorithm

The algorithm to apply MAUT is provided as follows (Keeney and Raiffa 1993):

1. Assuming that the objectives, criteria and alternatives has been defined, the first step is to compute the single utility function of each attribute/criterion by following formula

$$U_i(x_i) = A - B * e^{(\frac{-x_i}{RT})} \tag{1}$$

Where:

$$A = \frac{e^{(\frac{-Min(x_i)}{RT})}}{\left[e^{(\frac{-Min(x_i)}{RT})} - e^{(\frac{-Max(x_i)}{RT})}\right]} \tag{2}$$

$$B = \frac{1}{\left[e^{(\frac{-Min(x_i)}{RT})} - e^{(\frac{-Max(x_i)}{RT})}\right]} \tag{3}$$

$$RT_i = \frac{-CE_i}{ln\left(\frac{-0.5U_i(Max(x_i)) - 0.5U_i(Min(x_i)) + A}{B}\right)} \tag{4}$$

Where:

- $U_i(x_i)$ = Single utility value for attribute i of an alternative x
- A, B = Scaling constant
- e = The exponential constant i.e. 2.718
- $Min(x_i)$ = Minimum value of an attribute i across all alternatives
- $Max(x_i)$ = Maximum value of an attribute i across all alternatives
- RT is risk tolerance.

Since there exist cyclic dependency to compute A, B and RT, the following equation can be used to compute RT value by trail and error approach

$$e^{\frac{-CE}{RT}} = 0.5 * e^{\frac{-Max(x_i)}{RT}} + 0.5 * e^{\frac{-Min(x_i)}{RT}} \tag{5}$$

2. Calculate the risk tolerance based on expected value (EV) and certainty equivalent (CE) where EV is median of worst and best value of an attribute and CE is chosen by following principle

$$RiskAttitude = \begin{cases} \text{Risk Neutral}, & \text{if EV} = \text{CE} \\ \text{Risk Avoiding}, & \text{if EV} >= \text{CE} \\ \text{Risk Taking}, & \text{if EV} < \text{CE} \end{cases}$$

3. Assign the relative importance weights k to each attribute i based on decision maker's preferences

4. Considering that the preference of decision maker for one attribute is independent to another, the aggregative utility score for each alternative is computed by using additive form

$$U(x) = \sum_{i=1}^{n} k_i U_i(x_i) \quad (6)$$

Where:
- U(x) = Multi-attribute utility of alternative x
- k = Weighting factor of each attribute i
- $U_i(x_i)$ = Single attribute utility of each attribute i for an alternative x

5. Assign the ranks based on the magnitude of the aggregative score considering the maximisation of minimisation function

MAUT Application

In this section, the MAUT is applied to the data of twenty-two bridges to rank them in an order where owner cost, condition index, user delay cost and environmental cost can be kept minimum. The first step is to compute the single utility function (SUF) for each attribute. The SUF is computed based on exponential utility function (see Equation 1) in order to incorporate the uncertainty and risk tolerance aspects of a decision maker.

The concept of utility function and computation is inspired by lottery and gambling where with equal probability to obtain best value or worst value, a gambler needs to take certain risk. Since, calculation of SUF is computationally extensive process, the calculation details of only owner cost attribute is outlined here. For details, an interested reader may refer to (Allah Bukhsh et al. 2018).

Figure 1 presents the lottery step to compute the CE(certainty equivalent)/indifference point of owner cost. Considering the minimum value of 38.13 owner cost i across all the alternative and maximum value of 175.33, the EV (expected value) is 106. EV value is used as a reference point to compute the CE as shown in Step 2. We have assumed here that a decision maker has risk avoiding attitude, therefore the indifference point/CE value is 80. The RT value is 27 which is calculated by trail-and-error approach by substituting

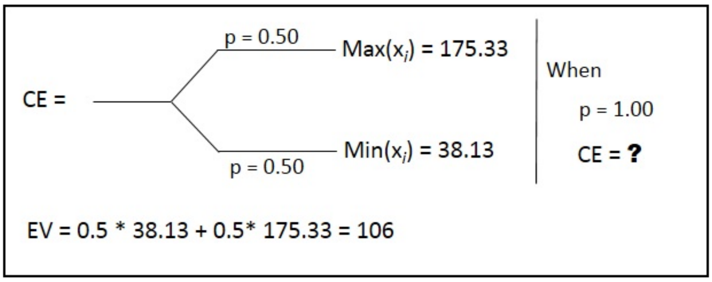

Figure 1: Lottery setup to discern the CE of owner cost

CE, min, and max in Equation 5. Equation 1 takes following form after computing scaling constants.

$$U_{oc}(x_{oc}) = 1.00 - 4.13 * e^{-x_{oc}/27} \quad (7)$$

By following the similar process as mentioned above, EV, CE and RT of condition index, user delay cost and environmental cost is calculated. Table 3 shows the all the computed values of these attributes.

Table 3: Value of Single Utility Function of Attributes

Attributes	$Min(x_i)$	$Max(x_i)$	EV	CE	RT
CI	1.67	2.77	2.22	1.70	0.7
OC	38.13	175	106	80	27
UDC	3.41	57.79	30.59	25	14
EC	0.002	1.25	0.629	0.5	0.5

CI= Condition Index, OC = Owner Cost, UDC = User Delay Cost, EC = Environmental Cost

After the utility values of all the attributes are computed, the next step is to assign the importance weights to each attribute. The importance of these attributes is kept similar as shown in Table 2, where owner cost is most important followed by condition index, user delay cost and environmental cost. Finally, the aggregative utility score for each alternative is computed by Equation 6. Since our objective was to minimise the values of attributes, the lower the aggregative utility score achieve higher rank. In other words, the lower overall utility score is preferred for maintenance first as compared to higher aggregative scores.

4.3 *ELECTRE III*

ELECTRE was proposed by Roy (1968) for the decision aid. There are various versions of ELECTRE, each targeted for different type of decision problems. ELECTRE III is used for ranking problem where it is possible to assign relative importance weights to criteria.

ELECTRE has concepts of thresholds and outranking. The thresholds are given by a decision makers which define the outranking relationship between alternatives. The outranking relationship is measured by concordance index and discordance index. Concordance index measure the strength of support, which states as alternative a is at least as good as alternative b for most of the criteria. While discordance index measures the strength for those criteria which are against this hypothesis.

ELECTRE III Algorithm

A step by step procedure to apply ELECTRE III is explained as follows (Pena et al. 2007):

1. Like AHP and MAUT, the performance matrix outlining the criteria and alternatives is the first step of ELECTRE III.

2. Since ELECTRE is an outranking method, where an alternative outranks another alternative to establish its priority for a particular criterion, few threshold values depending on the problem statement has to be set by a stakeholder/decision maker.

   - Preference threshold [p]: A difference above which a decision maker strongly prefers an alternative a over an alternative b for criteria i.
   - Indifference threshold [q]: A difference below which a decision maker is indifferent for an alternative a over an alternative b for criteria i.
   - Veto threshold [v]: A value provided by a decision maker which blocks the outranking relationship between two alternatives for criteria i.
   - Weights [w]: The value stating the relative importance of criteria/attributes. It is a similar concept as also discussed in Section 4.1 and 4.2.

3. Calculate the concordance index per criterion. Concordance index measures the strength of support stating that alternative a is at least as good as alternative b.

$$C_i(a,b) = \begin{cases} 0, \text{ if } g_i(b) \geq \; g_i(a) + p_i(g_i(a)) \\ 1, \text{ if } g_i(b) \leq \; g_i(a) + q_i(g_i(a)) \\ \text{Otherwise, } \frac{g_i(a)+p_i(g_i(a))-g_i(b)}{p_i(g_i(a))-q_i(g_i(a))} \end{cases}$$

   where:
   -$g_i(a)$ is a value of an alternative a for criterion i
   -p is preference threshold and q is indifference threshold

4. Calculate overall concordance index as follows

$$C(a,b) = \frac{\sum w_i C_i(a,b)}{\sum w_i}$$

5. Calculate the discordance index for each criterion.

$$C_i(a,b) = \begin{cases} 0, \text{ if } g_i(b) \leq \; g_i(a) + p_i(g_i(a)) \\ 1, \text{ if } g_i(b) \geq \; g_i(a) + q_i(g_i(a)) \\ \text{Otherwise, } \frac{g_i(b)-g_i(a)-p_i(g_i(a))}{v_i(g_i(a))-p_i(g_i(a))} \end{cases}$$

   where:
   -v is veto threshold

6. Calculate credibility index as follows

$$S(a,b) = \begin{cases} \text{C(a,b), if } D_i(a,b) \leq C(a,b) \forall i \\ \text{O}therwise \\ \text{C (a,b)} \prod_{D_i(a,b) \geq C(a,b)} \frac{1-D_i(a,b)}{1-C(a,b)} \end{cases}$$

7. Determine the rank order by ascending or descending distillation.

ELECTRE III Application

ELECTRE III is a method which requires a decision maker to have detailed understanding of decision problem. This method mainly relies on the threshold values provided by a decision maker. For the demonstration purpose, the authors of this paper played the role of decision maker to state the value of preference threshold, indifferent threshold, veto threshold and weights. While, the objective of bridges ranking and the relative importance of attributes are kept same as stated in Section 4.1 and 4.2. Table 4 shows the defined thresholds for each attribute.

Table 4: ELECTRE III thresholds values

	Attributes			
Thresholds	CI	OC	UDC	EC
Preference [p]	0.5	15	10	0.7
Indifference [q]	0.5	10	5	0.2
Veto [v]	1	1	1	1
Weights [w]	0.28	0.32	0.25	0.14

CI= Condition Index, OC = Owner Cost, UDC = User Delay Cost, EC = Environmental Cost

Once the thresholds has been defined, the next step is to generate the concordance matrix by following Step 3, where each alternative is compared with another for each criterion. Since, this case has four criteria, this step yields four concordance matrix which are aggregated based on the weight of each criteria by following Step 4. Similar to concordance, the discordance index for each alternative for each criterion is computed by following Step 5.

The last step is to compute the credibility index which combines concordance index and discordance matrices by checking which criteria are in favour of outranking relationship and which of them opposes it. Finally, the rank of each alternative is determined by distillation process.

The comparison of alternative per criterion is a lengthy process as multiple concordance and discordance matrices are required to be generated. For this application, we have used an open source software J-Electre v1.0[2].

5 RESULTS AND DISCUSSION

This section discusses the results of applying AHP, MAUT and ELECTRE III on the data of twenty-two bridges. Each of the method is also evaluated based on the scale defined in Section 3.

For AHP, if all the data is of quantitative nature then the main focus is to derive the relative importance of criteria/weights by pairwise comparison. While for the MAUT, in addition to relative weights, the emphasis is on selection of utility function and to reduce the data to utility scores. The application procedure of ELECTRE III is considerably different than other two (AHP, MAUT) where the focus is on comparison of alternatives instead of criteria/attributes. Moreover, ELECTRE III enables the comparison of heterogeneous scales of attributes e.g. cost in euros, delay in hours, etc. without reducing them into value functions or standard scales (e.g. scale of pairwise comparison). Because of this, ELECTRE III do not provide a definite ranking of alternatives as a final result (Figueira et al. 2013).

Table 5 provides the final ranking of twenty-two bridges where the objective was to have minimal owner cost, reduced condition index score, minimal user delay and environmental cost. The ranking of each bridges can be compared back to its original data presented in Table 1. It is interesting to see that each of the MCDA method have ranked Bridge *M* highest while this bridge does not have lowest condition index and lowest user delay cost. This is because MCDA methods systematically account for all the attributes involved in decision-making instead of ranking on the bases of single attribute only.

We have assumed that the ranking provided by different MCDA methods are similar, if there is only difference of one or two ranks. With this assumption notice the ranking of Bridge *B, C, D, E, F, G, H, K, L M, N, O,Q, R, S, T,* and *U*, which have difference of only one or two ranks for each method. This is because of the relative importance weights of attributes and stakeholders' preference for each of considered MCDA methods were kept similar. However, there is also a notable difference in ranking for Bridge *A, I, J, P,* and *V*. For example, MAUT has ranked Bridge *A* on 22 while ELECTRE has ranked it at 17. Similarly for Bridge *V*, which is ranked at 17 by AHP and at 21 by MAUT. These difference in ranking can be referred back to the actual data values where for one method the highest maintenance cost causes a bridge to ranked lowest while for another method the lower

[2]https://github.com/Valdecy/J-Electre

Table 5: Ranking of twenty-two bridges computed by AHP, MAUT and ELECTRE III

	AHP		MAUT		ELECTRE III
Alternatives	Score	Rank	Score	Rank	Rank
Bridge A	0.061	18	0.972	22	17
Bridge B	0.048	14	0.748	13	13
Bridge C	0.048	13	0.826	15	14
Bridge D	0.026	3	0.350	3	2
Bridge E	0.032	5	0.588	7	7
Bridge F	0.060	16	0.854	16	18
Bridge G	0.068	22	0.865	18	21
Bridge H	0.043	12	0.793	14	11
Bridge I	0.036	9	0.492	5	5
Bridge J	0.050	15	0.873	19	16
Bridge K	0.026	4	0.333	2	4
Bridge L	0.033	8	0.671	9	8
Bridge M	0.022	1	0.141	1	1
Bridge N	0.040	11	0.738	12	10
Bridge O	0.026	2	0.383	4	3
Bridge P	0.061	19	0.694	10	15
Bridge Q	0.064	21	0.854	17	22
Bridge R	0.063	20	0.896	20	20
Bridge S	0.032	6	0.647	8	6
Bridge T	0.032	7	0.570	6	9
Bridge U	0.038	10	0.716	11	12
Bridge V	0.061	17	0.901	21	19

maintenance cost and higher condition index assign the relative higher rank to a bridge.

In the following, we provide few remarks for each of the considered MCDA method based on our experience to apply them to maintenance decision-making problem.

Scalability : Without the use of computerised software, it is complicated for each of these methods to include an alternatives and criteria/attribute. With a new alternative and/or attribute, the whole application procedure, irrespective of method type, would need to be performed again.

Ease of use : AHP is the most easy to use method as compared to MAUT and ELECTRE. However, in case of qualitative data, the application of AHP becomes a lengthy process due to increased number of pairwise comparisons.

Encoding to definite scale : AHP and MAUT both require an encoding to a certain scale. This is required in order to enable heterogeneous data values to be comparable. The scale conversion is performed by Saaty's scale of relative importance for AHP and by using utility function in MAUT. ELECTRE III does not require any conversion of data and work with the actual data values.

Uncertainty / Risk consideration : MAUT is the only method that takes into account uncertainty aspect of data and stakeholders' preferences. This is done by performing the trade-offs in having best solution and worst solutions. AHP and ELECTRE III do not incorporate the concept of uncertainty.

Stakeholders' preferences : The considered MCDA methods take into account the stakeholders' preferences in one manner of another. AHP require the stakeholders' preferences to define the relative importance weights of criteria. MAUT require the stakeholders to define the indifference point for each attribute. Similarly, in ELECTRE III the threshold values are defined by stakeholders.

Understanding of results : Since AHP and MAUT require the data conversion into a definite scale, the output produced by these two methods are easy to understand. Both of these methods generate a aggregated score for each alternative. While in ELECTRE III no definite aggregated scores are generated. Therefore, an additional method of distillation is applied to create alternatives ranking.

To summarise, AHP and MAUT are useful methods where a global aggregation per alternative and a definite ranking is required. If a stakeholder is uncertain of his preferences over the data values, then MAUT can be a method of preference. ELECTRE III can be used when a stakeholder have clear understanding of his preferences over the data. At times, ELECTRE III has been refereed as a method that incorporate fuzzy nature of a decision-making in form of thresholds. However, the experience gained with the application of ELECTRE III in this study suggests that in case of minor differences in thresholds values the overall ranking score is changed. This is because the overall application of ELECTRE III to compute concordance and discordance matrices solely relies on threshold values.

6 CONCLUSIONS

Maintenance decision-making is a multi-faceted problem which demands the consideration of number of attributes. MCDA methods provide a systematic framework where objective data along with the subjective preference of stakeholders are combined for decision making. In this paper, the application of three methods of MCDA is provided to illustrate how they can facilitate in maintenance decision-making problem. We have found that, if weighting structure of the criteria and the stakeholders' preferences is kept similar, the different methods of MCDA even having different application procedure is able to provide similar results. AHP method can be used for those maintenance decision making problem where alternatives are not large in number and a definite ranking of alternatives is required. While MAUT is method of preference when there exist large number of alternatives and a stakeholder is uncertain of his preference choices. MAUT is one of few of MCDA methods that incorporates the concepts of uncertainty and utility theory. ELECTRE III can be a method of choice where a decision maker has good understanding of his preferences over the data values. However, ELECTRE III require the definition of multiple threshold values, which makes its application a tricky activity

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