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Zaharah Allah Bukhsh[a], Irina Stipanovic[a], Giel Klanker[b], Alan O' Connor[c] and Andre G. Doree[a]

[a]Faculty of Engineering Technology, Department for Construction Management and Engineering, University of Twente, Enschede, The Netherlands; [b]Rijkswaterstaat Ministry of Infrastructure and the Environment, Utrecht, The Netherlands; [c]Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland

ABSTRACT

Bridge infrastructure managers are facing multiple challenges to improve the availability and serviceability of ageing infrastructure, while the maintenance planning is constrained by budget restrictions. Many research efforts are ongoing, for the last few decades, ranging from development of bridge management system, decision support tools, optimisation models, life cycle cost analysis, etc. Since transport infrastructures are deeply embedded in society, they are not only subject to technical requirements, but are required to meet the requirements of societal and economic developments. Therefore, bridge maintenance planning should accommodate multiple performance goals which need to be quantified by various performance indicators. In this paper, an application of Multi-Attribute Utility Theory (MAUT) for bridge maintenance planning is illustrated with a case study of bridges from the Netherlands road network. MAUT seeks to optimise multiple objectives by suggesting a trade-off among them and finally assigns a ranking to the considered bridges. Moreover, utility functions of MAUT appropriately account for the involved uncertainty and risk attitude of infrastructure managers. The main contribution of this study is in presenting a proof-of-concept on how MAUT provides a systematic approach to improve the decision-making of maintenance planning by making use of available data, accommodating multiple performance goals, their uncertainty, and preferences of infrastructure managers.

1. Introduction

In recent years, infrastructure asset management has been applied as a strategic governance approach with the aim of achieving more value from assets by making use of less resources. By combining engineering and economic principles with sound business practises, asset management strives for cost-effective investment decisions throughout the life-cycle of infrastructure (Tao, Zophy, & Wiegmann, 2000). Among other infrastructure objects, bridges present a vital link in any roadway network. From an economic viewpoint it is crucial that bridges provide their designed function as part of the infrastructure network in an efficient manner. At one hand, bridges present the 30% value of the whole network while the length of bridges compared to the whole length of road networks is only approximately 2% (Chen & Miles, 2004). On the other hand, due to longer lifespan, road bridges infrastructure are exposed to ageing, adverse climate effects and increased public demands. This puts a lot of pressure on infrastructure managers to not only improve the availability and serviceability of bridges but also to re-think the maintenance planning procedures due to the increasing budget restrictions and increased capacity demands by users. It is estimated that the ratio of expenses per route km of bridges or tunnels is 10 times the average expenses per route km of roads (Deterne, 2010).

Bridge maintenance planning is a process of deciding the scope, timing, costs and benefits of future maintenance activities on a specific bridge while taking into account the relative importance of the bridge with respect to the overall road network. For over 20 years various Bridge Management Systems (BMS) have been used around the world to develop maintenance plans and allocate available budgets. These systems typically include single-objective optimisation analyses. For example, Life Cycle Cost (LCC) analysis and reliability based concepts are well established methodologies for single-objective analysis. Although useful for allocating budgets on the object-level, these BMS's are usually not taking into account other performance aspects related to economy, society, environment, etc. (Bush, Henning, Ingham, & Raith, 2014). LCC provides a solid base for the assessment of maintenance and budget distribution needs over the certain time period on the object-level. However, LCC doesn't taken into account multiple objectives for the network-level bridge maintenance planning and instead yields exhaustive and detailed cost values for a number of bridges which are difficult to compare and prioritise.

Van Dam, Nikolic, and Lukszo (2012) recommended that asset management should no longer be viewed as a solely technical process, but instead should be viewed as a socio-technical process. Since transport infrastructures are deeply embedded in society, they are not only subject to technical changes, but they also have to meet the requirements of societal and economic developments. Therefore, bridge maintenance planning should be performed at the network level where multiple performance

CONTACT Zaharah Allah Bukhsh ✉ z.allahbukhsh@utwente.nl

goals can be considered. Multiple bridge performance aspects widen the scope of maintenance planning where a number of related performance goals other than minimising owner cost must be considered. The example of such performance aspects are structural performance of the bridge, safety and security of users and workers, environmental impact, economic impact on the users, and impact on agency's and officials' reputation (political aspect). In addition to various aspects, these related performance goals can have a conflicting nature e.g. to minimise the impact on users, the agency might need to use more resources which will result in increased owner cost. Considering the large number of bridges on the network, it is intractable for an infrastructure manager to quantify the performance goals for each bridge and systematically perform the trade-offs among them in order to select those bridges that optimise the various performance goals. Moreover, at times, an infrastructure manager is uncertain of his preferences due to incomplete or unavailable data and due to lack of experience. So, the need to optimise multiple and/or conflicting performance goals based on the preference uncertainty marks maintenance planning a complex decision-making problem.

For the first time, Von Neumann and Morgenstern (1945) introduced the Expected Utility Theory which deals with such decision problems where a decision-maker choose from a finite set of outcomes to balance involved risk and uncertainty by exploiting the concept of lottery. The lotteries are based on the concept of gambling where a decision-maker can keep changing the values over a finite set of outcomes until an indifference point is reached. The main goal of these lotteries defined over attributes is to maximise the expected utility of the alternatives. To define a utility function over lotteries, the five axioms i.e. completeness, transitivity, continuity, monotonicity and substitution related to preference structure must be followed. For the detailed theorem and axioms, a reader can follow (Hens & Rieger, 2010, Chapter 2). Keeney and Raiffa (1993) suggested a formal decision-making approach namely Multi-Attribute Utility Theory (MAUT) based on Von Neumann and Morgenstern (1945) theory of Expected Utility. MAUT is also one of the fundamental method of Multi-Criteria Decision-Making (MCDA) due to its ability to consider probabilistic consequences.

In this paper, an application of MAUT for bridge maintenance planning is demonstrated. MAUT considers the multiple objectives (performance goals) represented with attributes (performance indicators), and consistently captures risk attitude of decision makers as well as uncertainty in preferences (i.e. which value to choose from finite set of outcomes) when the probability to achieve the results is not definite. The purpose of this paper is to illustrate the application of MAUT for network level maintenance planning where multiple performance goals, defined as objectives, can be optimised. We are referring to the *network level* maintenance planning because here the decision-making process is related to the selection of a single or group of bridges for maintenance that fulfils the defined objectives instead of focusing on different maintenance treatments for a single bridge only. The final results of MAUT will provide the ranking of a number of bridges based on the trade-offs of multiple performance goals.

One of the contributions of this paper is the methodological evaluation for the technical, economic and environmental impacts assessments of bridge maintenance decisions. The main added value of the paper is that it has used available data from the road agency only and has shown how the decision-making process could be improved by implementing other aspects, other than owner cost, into the evaluation process. By giving the quantification procedure, the decision-making process can be fully followable and transparent. Nevertheless, the application of MAUT is providing the option to a decision-maker to explicitly integrate risk and choice preferences. The rest of the paper is structured as follows: an overview of MCDA methods and the motivation to select MAUT is presented in Section 2. Section 3 discusses the need for a shift in bridge maintenance planning from object-level to network-level. The description of a case study along with the quantification process of performance goals is outlined in Section 4. Section 5 illustrates the application of MAUT for bridge maintenance planning by ranking the bridges based on trade-offs of multiple objectives. Finally, Section 6 provides the discussion and conclusion of this study.

2. Multi-Criteria Decision-Making (MCDM) for maintenance planning

For an extensive and busy road network, maintenance planning is a complex decision-making problem. The complexity is originated mainly due to multiple objectives defined by performance goals, which are often competing and conflicting with each other. According to Keeney and Raiffa (1993), in multi-objective optimisation, 'It is often true that no dominant alternative will exist that is better than all other alternatives in terms of all objectives'. In other words, there is never a solution that optimises all the involved performance goals/objectives simultaneously, for instance, they could be to maximise the reliability level of infrastructure vs. minimise the agency cost, to minimise the user delay vs. minimise the labour cost and many others.

For the optimisation of multiple objectives, a decision-maker has to make certain trade-offs to gain the value from one performance aspect (e.g. reliability) on the cost of another (e.g. owner cost). The concepts of decision sciences and particularly methods of Multi-Criteria Decision-Making (MCDM) suggest a number of analytical frameworks that facilitate decision-makers to perform such trade-offs, and rank the alternatives in an order that fulfils the defined objectives in the most optimal way. In the following, an overview of MCDA methods used for maintenance planning is provided.

2.1. Methods of MCDM

According to a recent literature review of MCDM applied on maintenance and reliability research (de Almeida, Ferreira, & Cavalcante, 2015), an increasing trend on the application of MCDA methods for optimisation of resources, strategies and intervention have been noticed. A few methods of MCDA have particularly gained attention in this regard e.g. Pareto Front, MAUT, AHP (Analytical hierarchy process), MAVT, Goal programming, ELECTRE (Elimination and choice expressing reality) and TOPSIS (Technique for Order by Similarly to Ideal Solution). Traditionally, these methods of MCDM are classified into three types (Guitouni & Martel, 1998):

- Synthesis method: 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, TOPSIS.
- Outranking method: 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 method: 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.

With respect to the application of MCDA methods, the interactive methods are being applied extensively in maintenance optimisation problems to search for the non-dominant solution that satisfies the 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 decision-makers (de Almeida et al., 2015). While, outranking methods take the preferences of decision-makers and enable 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). Due to this, these methods fail to enable the trade-offs among the different attributes and don't provide a definite ranking of alternatives (Figueira, Greco, Roy, & Słowiński, 2013).

Considering the multi-faceted nature of maintenance optimisation problems, the synthesis methods of MCDA are proven to be most promising. AHP is well-known and widely applied MCDA method but it requires pairwise comparison among alternative which is inconceivable when alternatives are large in number. TOPSIS works on the aggregation function by calculating the distance between a positive ideal solution and a negative ideal solution. While, MAVT is a variant of MAUT, which is a deterministic additive model and does not take into account the probabilistic aspects of decision-making. Since, the planning of maintenance procedures are never definitive, the selected synthesis method of MCDA must take into account the preference uncertainty and risk tolerance of decision-maker. Utility theory provides a systematic approach to capture the decision-makers preferences under uncertainty (Ishizaka & Nemery, 2013).

As mentioned earlier, based on the quantitative axioms of Expected Utility Theory, Keeney and Raiffa (1993) introduced Multi-Attribute Utility Theory (MAUT) that reduces attributes' measure into utility values. Various functions e.g. linear, log, exponential, logarithmic, quadratic, etc. can be used to determine the utility of an attribute (Meyer, 2010). While the resulting utility function can only be four shaped i.e. convex, concave, S-Shaped and reverse S-shaped (LiCalzi & Sorato, 2006). This paper aims to capture the preferences uncertainty and risk tolerance of decision-maker for maintenance planning attributes. Therefore, we applied exponential utility functions to determine the utility values of attributes as suggested in Keeney and von Winterfeldt (2007). In the following, few relevant studies and a procedure to apply the MAUT for maintenance planning is provided.

2.2. Application steps of Multi-Attribute Utility Theory (MAUT)

MAUT has been extensively used in multiple fields, e.g. for projects in investment planning (Jano-Ito & Crawford-Brown, 2017; Pujadas, Pardo-Bosch, Aguado-Renter, & Aguado, 2017), for health care (Claudio & Okudan, 2009; Sun, 2016), and for performance and budget assessment of water works (Ismaeel, 2016). A few studies in the context of infrastructure management are also found in literature that refer to MAUT as a base for mathematical modelling, for inspection and maintenance (de Almeida et al., 2015; Garmabaki, Ahmadi, & Ahmadi, 2016), for bridge sustainability assessment (Dong, Frangopol, & Sabatino, 2015), for maintenance investment decision-making (Arif, Bayraktar, & Chowdhury, 2015) and for bridge network level optimisation (Frangopol & Liu, 2007). However, the application of MAUT for multiple objective maintenance planning in transport infrastructure systems by incorporating the preferences of decision-makers is not fully explored. Most of the literature studies mentioned MAUT as a part of larger framework and exploit its few relevant concepts. To explore the potential of MAUT for network level maintenance planning, this paper aims to apply MAUT for the maintenance planning decision-making, where an infrastructure manager/decision-maker has to deal with multiple objectives.

The steps to apply the MAUT on a maintenance planning problem are provided in Table 1 and discussed as follows (Keeney & Raiffa, 1993):

Step 1 to *Step* 3 define the scope of the maintenance planning and construct the data required for the MAUT. Based on the defined performance goals, the performance indicators are quantified. The identified performance indicators are referred as attributes. While the objects that are under consideration for maintenance are named as alternatives.

In *Step* 4, the utility function of each attribute's measure is calculated. As mentioned earlier there are several forms to calculate the utility functions, the exponential utility function is typically used to incorporate the risk and uncertainty factors (Keeney & Raiffa, 1993; Keeney & von Winterfeldt, 2007, Chapter 4 & 5). The exponential utility function presents the decision-makers with the lottery question of a maximum value and a minimum value of an attribute where the indifference point has to be reached between the best and the worst possible values. Such an indifference point for a decision-maker is referred to as the *Certainty Equivalent (CE)*. While, the probability of obtaining the best possible value or the worst possible value is referred as *Expected Value (EV)*. The indifference point chosen by the decision-maker represents his/her attitude towards risk and risk tolerance. As listed below, an indifference value where CE is equivalent to EV represents risk neutral behaviour. If the value of CE is lower than EV, the decision-maker has a risk avoiding attitude, whereas the CE value greater than EV shows the risk taking attitude. Consequently, the risk avoiding

Table 1. Steps to apply MAUT on maintenance planning problem.

Steps	Descriptions
Step 1	Define the scope of problem i.e. the set of objects/network for which maintenance is being planned
Step 2	Identify the performance goals or objectives of the maintenance planning
Step 3	Quantify the related performance indicators (attributes) to represent the objectives in utility functions
Step 4	Calculate exponential Single Utility Functions (SUF) by
	• Prepare the lottery question of best and worst values of attributes
	• Capture the risk attitude of decision-maker with the Certainty Equivalent
	• Illustrate the utility values of each attribute for all alternatives
Step 5	Perform the value trade-off among attributes based on decision-maker's preferences
Step 6	Considering the nature of attributes, calculate the final aggregative utility values from SUF by additive or multiplicative form
Step 7	Ranking based on value trade-offs and performance goals (objectives)
Step 8	Finally, analyse the result and perform the other related scenarios

attitude has positive risk tolerance whilst a risk taking attitude has a negative risk tolerance value (Krishnamurty, 2006).

$$\textbf{Risk Attitude} = \begin{cases} \text{Risk Neutral, if EV } = \text{ CE } (\textit{Linear shaped}) \\ \text{Risk Avoiding, if EV } >= \text{ CE } (\textit{Concave shaped}) \\ \text{Risk Taking, if EV } < \text{ CE } (\textit{Convax shaped}) \end{cases}$$

With the consideration of decision-makers' uncertainty in eliciting indifference points (CE) under risk consideration, the final computed utilities of an attribute lies between $U(x_{min}) = 0, U(x_{max}) = 1$.

In *Step* 5, trade-offs among the attributes are made in order to find a solution that maximise the performance goals/objectives. These trade-offs characterise the relative importance of attributes for the defined objectives/performance goals.

For the final aggregation of utility functions, in *Step* 6, the additive or multiplicative form can be used. The additive form requires the attributes to be mutually and preferentially independent. Preferentially independent means the preferences on the level (i.e. values) of an attribute X is not dependant on the levels of an attribute Y. For instance, let X: Maintenance treatment (coating, cleaning) and Y: Cost(100, 250). If a decision-maker prefers *cleaning* treatment irrespective of its *cost* and prefer *100 cost* regardless of chosen maintenance treatment then X and Y are mutually and preferentially independent. While, if a decision-maker prefer *coating* regardless of *cost*, but the *cost* depends on the maintenance treatment chosen then X is preferentially independent of Y but not mutually preferentially independent since Y depends on X. When attributes are not mutually and preferentially independent then multiplicative form is used (Krishnamurty, 2006).

Finally, in *Step* 7, a number of alternatives having qualitative or quantitative attributes are ranked based on the Single Utility Function (SUF) and trade-off values. In *Step* 8, the ranking can be further analysed by applying various scenarios with different trade-off values. As discussed above, MAUT provides a step-by-step procedure to accommodate a number of attributes related to alternatives for the realisation of multiple objectives based on the preferences of a decision-maker.

3. Object to network-level maintenance planning

In the current state of the practice, most Bride Management Systems (BMS) are very effective at storage and retrieval of the raw data needed for maintenance planning. With these data, it is possible to analyse the change of performance over time and to identify those bridges that are in need of maintenance. Based on that, life cycle costs for different maintenance scenarios can be calculated and compared. To express and manage the spectrum of possible futures (i.e. maintenance scenarios), the concept of a 'candidate' is suggested (Patidar, 2007). A 'candidate' is defined as a life-cycle activity profile for one bridge, consisting of a sequence of agency activities, including do-nothing, in each of a sequence of future time periods. Development of other candidates (i.e. maintenance scenarios) treatments for a single bridge and a selection of the best one is an important aspect of decision-making by the infrastructure manager. The planner then repeats this process for the other bridges in the network. By iterating between bridge and network level, one or more optimal scenarios can be reached, resulting in the selection of a number of bridges for maintenance in a certain period. It should be noted that the focus of existing BMS's are still mainly on bridge condition level and owner's costs, rarely taking into account other impacts of the bridge, such as environmental impacts, availability, importance on the transport network and society as a whole.

In the course of developing network-level bridge maintenance plans, infrastructure managers typically face a variety of objectives and constraints. Examples of objectives are to maximise cost effectiveness, to minimise vulnerability to damage, to maximise average condition, and to optimise a utility index that combines various objectives. Constraints include budgetary limits that cannot be exceeded or a minimum level of average bridge performance (Patidar, 2007). These multiple objectives which are often conflicting in nature present a complex decision-making problem for maintenance planning. Such complex decision-making problems demands clear statements of objectives and their quantification in the form of defined performance indicators. To enable the trade-offs among multiple competing objectives, it is necessary to identify a set of performance goals and a set of performance indicators to quantify them.

The COST Action TU 1406 (2015) aims to bring together both the research and practising community in the field of bridge assessment, which will incorporate different aspects of bridge performance goals, based on technical, environmental, economic and social factors. Within the COST Action TU 1406 bridge performance indicators have been collected through a large survey, with the aim to produce guideline documents linking collection and quantification of performance indicators, performance goals, standards, and practises with decision-making processes (Stipanovic, Høj, & Klanker, 2016; Strauss, Ivanković, Matos, & Casas, 2016).

Table 2. Performance goals quantified by performance indicators and quantification process.

Performance goals (Objectives)	Aspect	Performance Indicator	Calculation (Quantification process)
Improve assets' reliability	*Reliability*	i)*Condition Index*	*Visual Inspection,* Analysis of finding
		ii) Reliability Index	Probabilistic model for different limit states (Hazards)
Minimise agency cost	*Economy*	i) Construction Cost	Design project, quantities
		ii)*Maintenance Cost*	*Maintenance activity, Quantities produced, Costs (labour, materials, machines, etc.)*
		iii) End of Life Cost	Life cycle analysis output
To minimise environmental impact	*Environment*	i) *Environmental Impact*	*Chosen maintenance activity, Quantities of materials produced,Transport distance, LCC analysis (de Bruyn et al., 2010)*
		ii) Noise	Vehicle noise, machine noise
To minimise impact on users	*Society*	i)*User delay cost*	*Extra travel time, Number of users affected, cost of an hour of a user, duration of maintenance activity*
		ii) User costs	Vehicle operating costs, travel time costs, accident costs
To keep the network safe	Safety	i) Accident Rate	No. of traffic accidents, number of fatalities, number of injuries

This paper presents how the existing data, namely different performance indicators, at road agencies can be used for the quantification of multiple performance goals. Table 2 outlines the performance goals, identified performance indicators, and their quantification process. The performance goals and relevant performance indicators used in the study are highlighted in *italic*. Performance goals highlight the objectives of the network-level maintenance planning where the performance indicators enable us to quantify and measure the defined goals and their consequences on the number of bridge alternatives. Performance indicators are also sometimes referred to as measures, attributes or criteria. Considering the application of MAUT presented here, we will refer performance indicators as attributes (i.e. bridge condition index, owner cost, user delay cost and environmental cost) and to the list of bridges as alternatives.

4. Bridges maintenance planning: a case study

This section presents a case study to illustrate how utility functions and MAUT can be used in decision-making processes for maintenance planning. Let us consider for the maintenance planning that an infrastructure manager (i.e. decision-maker) is presented with 100s of bridges that are in need of repair, while at the same time, he is confronted with the constraints of limited budget, network availability and safety, among many others. Moreover, the infrastructure manager wants to perform maintenance only where he can minimise the owner costs and maximise the object's reliability level. Such a decision-making problem requires the assessment and selection of alternatives (i.e. bridges), where a trade-off among the objectives can be made and most of the constraints can be met.

To demonstrate how the MAUT and utility function can facilitate in decision-making of maintenance planning, the data of twenty-two randomly chosen road bridges from the Netherlands road agency Rijkswaterstaat is used. The data provided from the agency included description of the twenty-two bridges in terms of bridges' age, geometry, condition index on the element level, traffic intensity, planned maintenance activity on the element level, unit cost of chosen maintenance option, and maintenance duration. Generally, the condition indexes of the Netherlands road bridges are found to have optimum range (i.e. 1: Very good to 3: Fair, on the scale from 1 to 6), therefore, there are not many maintenance treatments considered. The bridge data included the maintenance costs of the various maintenance treatments (e.g. replacing top-layer, coating, cleaning, etc.).

No decision regarding the selection of other optional maintenance treatments corresponding to different maintenance costs were made for this case study. Moreover, the causal factors e.g. age of the bridge, the material used in bridge, the span of a bridge are not considered independently during the decision-making procedure of this maintenance planning case as inspection and condition index assessment activities must take into account these factors (Rashidi & Gibson, 2011). Since, twenty-two bridges were chosen randomly from the Netherlands road network, we did not establish any correlation with respect to bridge location and its impact on surrounding objects in the road network. In other words, bridges as an individual entity are considered assuming that the maintenance of these twenty-two bridges is under consideration only.

For this illustrative application of MAUT, the twenty-two bridges are required to be ranked where the objectives are (a) *to minimise condition index (where lower value represents better condition)*, (b) *to minimise owner cost*, (c) *to minimise the impact on users (expressed as user delay costs)* and (d) *to minimise environmental impact (expressed as environmental costs)*. Considering the aforementioned objectives, the ranking of the bridges will be based on the minimisation of owner cost, condition index, user delay cost and environmental cost. However, the provided data do not have these data attributes readily available. Therefore, these attributes have to be quantified from the available raw data to be used in MAUT analysis. Following sections outline the quantification process to compute system level condition index, owner cost, user delay cost and environmental cost from the provided data of twenty-two bridges.

4.1. Condition index

Condition indices represent the overall 'health' of a bridge. In the Netherlands system, a six level condition assessment score is used to assess the condition of a bridge where 1 represents very good condition and 6 represents out of service state. The objective is to minimise the condition index, which means the lower the condition index the better will be service level of the bridge. In the case study data, a bridge as a structure is divided into seven elements: Superstructure, Bearings, Abutments, Joints, Pavement, Railing and Guardrail. With these

sub-elements, each bridge has seven visually assessed condition indexes representing the structural performance of each bridge's element. In order to get the overall understanding of the bridge condition, these element-level condition values must be aggregated to a single system-level condition value, namely the Bridge Condition Index (BCI).

In practice there are numerous ways, varying by country and agency, to compute the BCI, aggregated from the element-level to the system-level, using worst element score, weighted average method, ratio scale (ATKINS, 2002; Chase, Adu-Gyamfi, Aktan, & Minaie, 2016; Hooks & Frangopol, 2013; Patidar, 2007; Stratt, 2010). For this case study, we have applied the weighted average method, where the relative weights to each element are established by an expert. The concepts from Analytical Hierarchy Process (Saaty, 1990a) is used for this purpose. To determine the importance of each element for the overall structural integrity of a bridge, an expert must consider the failure history of an element by type, frequency of maintenance required by the elements and the failure consequence of an element on the overall bridge. The pairwise comparison of Superstructure, Bearings, Abutments, Joints, Pavement, Railing and Guardrail has been performed. Each of these seven elements is compared with each other based on the Saaty's fundamental scale of importance (Saaty, 1990b). This scale defines the five levels of importance between two elements, where 1 represents the equal importance between two elements and 5 suggests that one element is extremely important than the other. Finally, the relative importance of each element is obtained as follows:

- Formalised a matrix M for all the elements based on the gathered input
- Normalised the matrix from 0 to 1 by summing each column and dividing individual element importance values by its column's sum
- Finally, calculating the average of each row of the matrix to gain the relative weights/importance of each element

The relative importance score for each element determining their level of importance in overall structural performance of the bridge is provided in Table 3. The Table shows that the superstructure is most important for the overall structural integrity of the bridge where railing and guardrails are least important. Once the relative importance of each element is obtained, the BCI is calculated by computing Equation (1):

$$CI_s = \sum_{i=1}^{7} \left(CI_i * W_i \right) \qquad (1)$$

where:

$CI_s =$ Bridge condition index at system level s

$CI_i =$ Condition index of an element i

$W_i =$ Weighted score of an element i

elicited by an expert (provided in Table 3)

4.2. Owner cost

Owner cost is a monetary value borne by an agency as result of construction, maintenance and/or end of life cost. In this

Table 3. Weighted score of bridge elements.

No.	Elements	Weighted score
1	Superstructure	0.3185
2	Bearings	0.2104
3	Abutment	0.1813
4	Joints	0.1288
5	Pavement	0.0618
6	Railing	0.0510
7	Guardrail	0.0478

case study, only maintenance cost is considered for the owner cost which is the money spent on the maintenance activity of a particular bridge. In order to get a unit maintenance cost per m_2 of a bridge, the maintenance cost per activity type is multiplied by the quantity of the material used, which is then divided by the size of deck area of the bridge (m_2). The maintenance cost is provided on element-level (seven elements in this case) for the chosen maintenance option, which is then summed-up to represent the cost for a bridge as a whole. The formula to calculate the maintenance cost is provided as follows:

$$MC = \frac{\sum_{i=1}^{7} \left(UCA_i * Q_i \right)}{A} \qquad (2)$$

where:

$MC =$ Total maintenance cost per m_2 of the bridge

$UCA =$ Unit cost of maintenance activity per element i

$Q =$ Quantity of the area/volume per element i

$A =$ Deck area of a bridge (m_2)

4.3. User delay cost

User delay cost represents the monetary value of extended travel time of road users due to the presence of work-zones on road. The user delay cost depends on a number of factors as mentioned in Tighe, Eng, and McCabe (2005), Wang and Goodrum (2005), Daniels, Ellis, and Stockton (1999), (a) extra travel time due to the imposed speed restriction (b) number of users affected defined by traffic intensity in terms of average traffic per hour passing over the bridge on a working day, (c) the cost of an hour of the user time, and (d) finally the duration of the maintenance activity. The cost of an hour of user travel time vary per country based on the income levels. For western Europe, the values mostly varies between 6€ for Germany to 12.12€ for Sweden, except for Switzerland which is 31.73€. For further details, please refer to Wardman, Chintakayala, de Jong, and Ferrer (2012).

In this study, we used 9€ including VAT as cost of an hour of a all-purpose commuting user for the Netherlands determined by Kouwenhoven et al. (2014). We used this value since the case study was considering the traffic intensity and bridge data from the Netherlands road network. The computed user delay cost is divided by deck area of a bridge to keep the calculation procedure consistent with other attributes. In this estimation of user delay cost, no difference between passenger traffic and freight traffic is considered. Though, the user delay cost for different users type can be computed by estimating the percentage

Table 4. Environmental effect categories and shadow prices (TNO-MEP, 2004).

Sr. No.	Environmental effect category	Shadow price (/ kg equivalent)
1	Abiotic depletion elements (ADP) (/Sb eq)	0.16
2	Abiotic depletion fossil (ADP) (/Sb eq)	0.16
3	Global warming potential (GWP) (/CO2 eq)	0.05
4	Ozone depletion potential (ODP) (/CFK-11 eq)	30
5	Photochemical ozone formation potential (POCP) (/C2H2 eq)	2
6	Acidification potential (AP) (/SO2 eq)	4
7	Eutrofication potential (EP) (/PO4 eq)	9
8	Human toxicity potential (HTP) (/1,4-DCB eq)	0.09
9	Freshwater aquatic ecotoxicity potential (FAETP) (/1,4-DCB eq)	0.03
10	Marine aquatic ecotoxicity potential (MAETP) (/1,4-DCB eq)	0.0001
11	Terrestic ecotoxicity potential (TETP) (/1,4-DCB eq)	0.06

of traffic per user type in ADT_t with respect to $V_o t$.

$$UDC = \frac{ETT * ADT_t * V_o t * N_t}{A} \quad (3)$$

where:

$$ETT = \frac{L}{V_r} - \frac{L}{V_s}$$

where:

UDC_t = User delay cost
ETT = Extra travel time
L = Length of the working zone (km)
V_r = Reduced velocity in working zone during maintenance(km/h)
V_s = Standard velocity during normal condition(km/h)
ADT_t = Avg. traffic per hour
$V_o t$ = Value of a time per person per hour
N_t = Duration of certain maintenance activity (in hours)
A = Deck area of a bridge (m_2)

4.4. Environmental cost

Environmental cost represents monetised value of environmental impacts of different activities during the bridge life cycle. The impact on the environment is caused mostly by the materials production and transport during the construction process, maintenance activities, and end of life of an object. According to the environmental study of Hegger and de Graaf (2013), most of the environmental impacts are caused due to the use of construction material during initial construction and the subsequent maintenance. Therefore, only the effect on the environment per kg per material produced for maintenance activity is considered in this estimation of environmental cost. Similarly to maintenance cost, the environmental cost is calculated on the element-level which is then summed-up to the system-level to represent the overall environmental cost of a maintenance activity for a particular bridge.

The determination of environmental cost due to maintenance activity is based on three aspects. First, the environmental effect per impact category based on material type, provided by GaBi software database (Thinkstep, 2015), is considered (EE_i). Second, the material quantity per kg produced for the maintenance activity is estimated (Mq_j). Finally, to monetise environmental effect into euros, the environmental effect per impact category values are multiplied by their shadow prices (SP_i) established by Rijkswaterstaat (TNO-MEP, 2004, for English version (de Bruyn et al., 2010)). Table 4 presents the environmental effect categories along with their shadow prices. The CO_2 emission caused by traffic during the downtime period of a bridge, such as the maintenance and repair period is not included in the calculation of environmental impact values due to their negligible impact. Equation (4) provides the details of environmental cost estimation.

$$EC = \sum_{e=1}^{7} \left[\frac{\sum_{i=n}^{m} EE_i * SP_i}{A} \right] \quad (4)$$

$$EE_i = \sum_{j=n}^{m} EE_{i,j} * Mq_j$$

where:

EC = Environmental cost
EE_i = Environmental effect per impact category i
SP_i = Shadow prices per impact category i
i = Environmental impact category n until m(see Table 4)
$EE_{i,j}$ = Environmental effect per impact category i per kg of material j produced
Mq_j = Material quantity per kg j
j = Different material types
A = Deck area of bridge (m_2)
e = Element e of a bridge

5. Multi-attribute Utility Analysis for maintenance planning – case study

With the definition of performance goals and quantification of performance attributes in Section 4, MAUT is applied to the case study data. The first step to apply the MAUT is to determine Single Utility Function (SUF) for each attribute. Various functions (e.g. log, cardinal, linear, power, quadratic) can be used to determine the utility scores of attributes (Meyer, 2010). Utility functions and Expected Utility Theory have wide spread use,

specifically in economics and game theory, where the scientific literature suggest different procedures to compute utility scores and to capture uncertainty (Chung, 1994; Levy & Markowitz, 1979).

In this paper, we have mainly followed the computation procedures suggested by Keeney and Raiffa (1993). To determine the SUF, Keeney and von Winterfeldt (2007) recommend the use of linearity function where the value of an attribute is useful in itself and use of exponential utility functions where the utility score must exhibit the risk aversion and/or risk proneness. To compute the global aggregated scores for each alternative, SUF capturing the preferences uncertainty and risk attitude is determined in Section 5.1. The relative importance of attributes with respect to decision-maker preferences is given in Section 5.2. The final global aggregation based on additive form is provided in Section 5.3, and finally, Section 5.4 outlines the results of MAUT application. The similar MAUT application procedure has been found in the cases of supplier selection problem (Min, 1994), product line selection (Thevenot, Steva, Okudan, & Simpson, 2006) and patients prioritisation in emergency unit (Claudio & Okudan, 2009).

The equations to calculate SUF for each attribute is given by Equation (5) to Equation (9) (Kirkwood, 1999).

$$U_i(x_i) = A - B * e^{\left(\frac{-x_i}{RT}\right)} \tag{5}$$

where:

$$A = \frac{e^{\left(\frac{-Min(x_i)}{RT}\right)}}{\left[e^{\left(\frac{-Min(x_i)}{RT}\right)} - e^{\left(\frac{-Max(x_i)}{RT}\right)}\right]} \tag{6}$$

$$B = \frac{1}{\left[e^{\left(\frac{-Min(x_i)}{RT}\right)} - e^{\left(\frac{-Max(x_i)}{RT}\right)}\right]} \tag{7}$$

$$RT_i = \frac{-CE_i}{ln\left(\frac{-0.5U_i(Max(x_i)) - 0.5U_i(Min(x_i)) + A}{B}\right)} \tag{8}$$

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 = Risk tolerance

Since there is a cyclic dependency to calculate A, B and RT, the Equations (5)–(8) have to be solved iteratively. Theoretically, RT can be approximately equal to the maximum value x of an attribute i for which a decision-maker is willing to accept the $Min(x_i)$ and $Max(x_i)$ with equal probabilities instead of obtaining 0 for certain. As reported earlier, the concepts of the utility function are inspired by gambling where with the equal probability to obtain $Min(x_i)$ or $Max(x_i)$ values, a gambler needs to take a certain risk. To compute the exact risk tolerance

value, RT must satisfy the following Equation (9). The trail-and-error approach can be used to satisfy the following relation by exploiting the Goal Seeker function of MS Excel (Middleton, 2006).

$$e^{\frac{-CE}{RT}} = 0.5 * e^{\frac{-Max(x_i)}{RT}} + 0.5 * e^{\frac{-Min(x_i)}{RT}} \tag{9}$$

where CE is a certainty equivalent for each attribute which is calculated by presenting the decision-maker with a lottery question. The indifference point between the $Min(x_i)$ and $Max(x_i)$ for a Decision-maker is the value of CE. The value of RT shows the willingness of a decision-maker to take a risk. RT value is negative for the risk taking behaviour while positive for risk avoiding behaviour. In order to avoid the complexity involved in eliciting RT, we assume that the decision-maker always have risk avoiding behaviour which is a positive value.

5.1. Assessment of single utility function

In this section, the utility function of each attribute is calculated. It is worth mentioning that the utility of an attribute is relative to the decision-maker's choices which can change over time. In this exercise, the authors played the role of decision-makers where the preference values mimic real decision situations. To represent the lottery question along with the risk attitude of a decision-maker, we adopted the convention from Claudio and Okudan (2009).

5.1.1. Single utility function of condition index

The system-level condition score of each bridge is calculated from seven sub-elements by Equation (1). As mentioned earlier in Section 4.1, a lower condition index represents a bridge in a good condition. Therefore, the objective is to improve the service level of bridge by minimising the condition index score.

It is important to notice that the bridges chosen for the case study are generally found to have good condition with condition scores ranging from 1.67 to 2.73 (see Table 6). Therefore, in the lottery question presented in Figure 1, the difference between the maximum condition score and minimum condition score is very small. The Expected Value (EV) of condition index is determined by considering the 50% probability of obtaining $Max(x_i)$ i.e. 2.73 and 50% probability of obtaining $Min(x_i)$ i.e. 1.67. The obtained EV is equal to 2.22. Assuming the risk avoiding attitude of a decision-maker, the chosen indifference point, also called Certainty Equivalent (CE), is 1.70 which means 1.7 is an acceptable condition score for the bridges. The risk tolerance value is calculated by satisfying the Equation (9) with a trail-and-error method. Due to risk avoiding attitude of a decision-maker depicted in CE, the chosen RT value as small as 0.7. The exponential single utility function of each of twenty-two bridges is calculated by solving the Equations (6)–(8) iteratively,
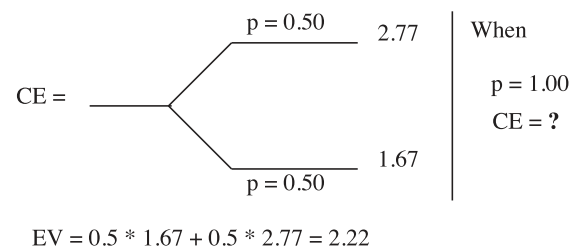

EV = 0.5 * 1.67 + 0.5 * 2.77 = 2.22

Figure 1. Lottery setup to discern the CE of bridge condition index.
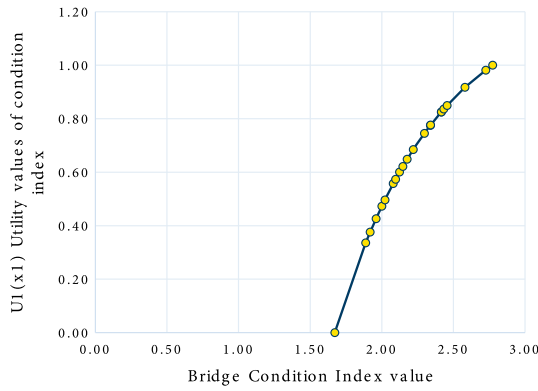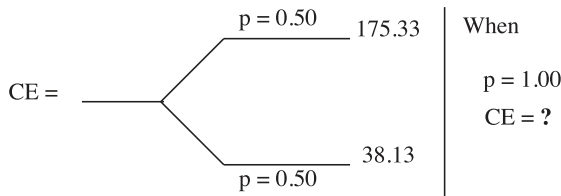
Figure 2. Utility plot of condition index.

which finally yields following Equation (10). Figure 2 shows the utility plot of condition index values where the utility values increase steadily.

$$U_1(x_1) = 1.26 - 13.72 * e^{-x_1/0.7} \qquad (10)$$

EV = 0.5 * 38.13 + 0.5 * 175.33 = 106

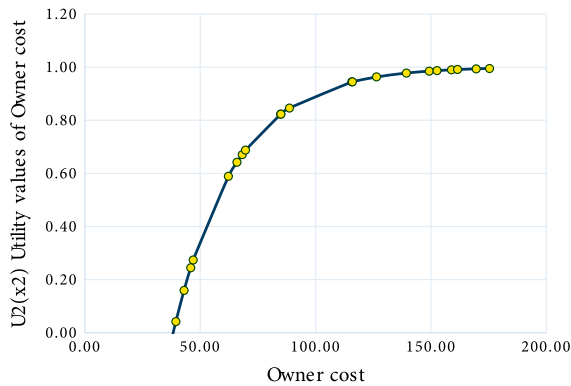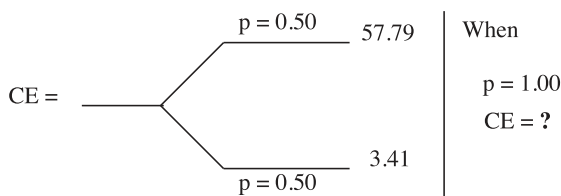**Figure 3.** Lottery setup to discern the CE of owner cost.

Figure 4. Utility plot of owner cost.

EV = 0.5 * 3.41 + 0.5 * 57.79 = 30.59

Figure 5. Lottery setup to discern the CE of user delay cost.

5.1.2. Single utility function of owner cost

The owner cost of all the twenty-two bridges is calculated based on Equation (2). The lottery question provided in Figure 3 can be read as 50–50% probability of having best (i.e. minimum) owner cost or worst (i.e. maximum) owner cost.

The data of owner cost for 22 road bridges are provided in Table 6. Considering the maximum cost i.e. 175.33 and minimum cost i.e. 38.13, the computed EV is equal to 106. The purpose is to reduce owner cost as much as possible, therefore the indifference point or certainty equivalent between the maximum and minimum cost is approximated to be 80. Assuming the risk avoiding behaviour, the obtained RT value is 27 which is computed by substituting the values of CE, min, max and trail-an-error value of RT in Equation (9). By solving the Equations (6)–(8) iteratively, the exponential utility of each owner cost value is calculated as in Equation (11).

$$U_2(x_2) = 1.00 - 4.13 * e^{-x_2/27} \qquad (11)$$

Figure 4 provides a plot of the utility values for the owner cost, which shows the abrupt increase in utility values (y-axis) with respect to owner cost (x-axis). It can be said that the lower owner cost gets the small utility values in order to be ranked higher in the (aggregated) minimisation function.

5.1.3. Single utility function of user delay cost

The user delay cost of each bridge is computed by the Equation (3). Figure 5 represents the lottery question presenting the minimum and maximum user delay cost of bridges (see Table 6 for the data), where the computed EV value is 30.59. The objective of this lottery question is to have minimum user delay cost. The indifference point between the minimum and maximum user delay cost is reached at the value 25.

By iteratively solving the Equations (6)–(8) and by satisfying the Equation (9), the value of scaling constant of A, B and RT is computed, which is provided in Equation (12).

$$U_3(x_3) = 1.00 - 1.34 * e^{-x_3/14} \qquad (12)$$

Based on the values defined in Equation (12), the exponential utility values of user delay cost for each bridge is calculated and presented in Figure 6. The higher user delay costs obtain higher utility scores, which are not preferred in the minimisation function.
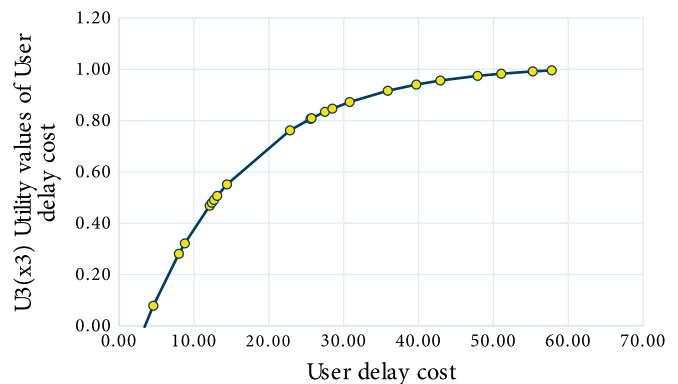

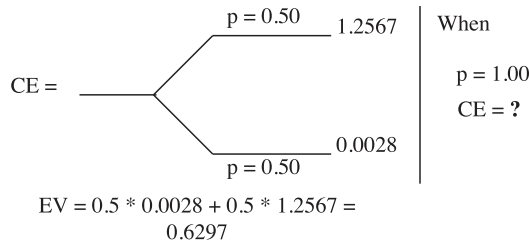**Figure 6.** Utility plot of user delay cost.

$$CE = \quad \overbrace{\qquad}^{\begin{array}{l} p = 0.50 \quad 1.2567 \\ \\ 0.0028 \\ p = 0.50 \end{array}} \quad \left| \begin{array}{l} \text{When} \\ \\ p = 1.00 \\ CE = ? \end{array} \right.$$

$$EV = 0.5 * 0.0028 + 0.5 * 1.2567 = \\ 0.6297$$

Figure 7. Lottery setup to discern the CE of environmental cost.
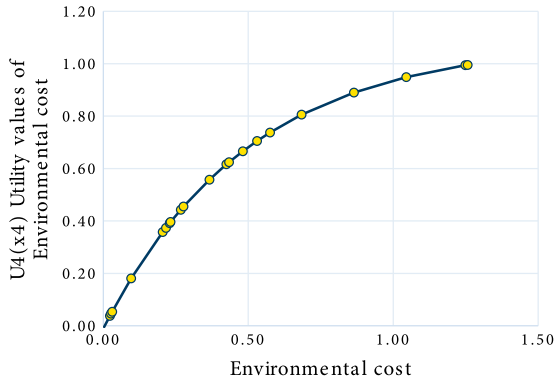

Figure 8. Utility plot of environmental cost.

5.1.4. Single utility function of environmental cost

The environmental cost of the bridges is determined by Equation (4). Since, environmental cost is not a very dominant factor in maintenance planning and maintenance tasks, the shadow prices per environment effect category is very low, provided in Table 6.

The lottery question in Figure 7 provides the minimum and maximum amount of environmental cost of all the bridges. The EV with the 50–50% probabilities of obtaining the minimum and maximum value of environmental cost is computed as 0.62. Assuming the risk avoiding attitude of a decision-maker regarding environment, the CE value is chosen to be 0.5. Similarly, the RT value computed by solving Equation (9) is 0.50, which is not very low considering the minimum and maximum value bounds of environmental cost . The calculation of exponential single utility function of environmental cost of each bridge is determined by Equations (6)–(8), which yields Equation (13). The plot of environmental cost in Figure 8 depicts the uniform increase in the utility values associated with environmental values.

$$U_4(x_4) = 1.08 - 1.09 * e^{-x_3/0.5} \tag{13}$$

5.2. Attributes trade-offs

As mentioned in Section 4, the decision problem of maintenance planning requires the ranking of twenty-two bridges in an order where condition of a bridge can be maximised and at the same time owner cost, user delay cost and environmental cost can be minimised. While, the minimisation of one attribute might result in maximisation of the other one. For instance, to minimise the user delay cost an agency might needs to employ more

resources which will result in increased owner cost. Therefore, a trade-off among these attributes has to be performed. The procedure recommended by Keeney and Raiffa (1993) for assigning the weighting factor to attributes is adopted for this purpose. A direct rating method is used which is represented as follows:

$$k(x_i) = \frac{rate(x_i)}{\sum_{j=1}^{n}(x_j)} \tag{14}$$

where:

$$k(x_i) = \text{Weighting factor of each attribute } i$$
$$\text{across all alternatives}$$
$$rate(x_i) = \text{Rate/weight assigned by expert for attribute } i$$
$$\sum_{j=1}^{n}(x_j) = \text{Total of all the weights assigned by}$$
$$\text{an expert to } n \text{ attributes}$$

Based on general preferences of infrastructure managers as also shown in Triantaphyllou, Kovalerchuk, Mann, and Knapp (1997), each attribute obtain a weighting score out of 100 that depict its importance in the maintenance planning scenario. Table 5 shows the obtained weights for each attribute. Since, the bridges chosen for this case study have relatively good condition, the owner cost gets the highest importance weight instead of condition index. Following owner cost, the condition index is in second place and user delay cost is at the third place. The preferences structure shows that the environmental costs still have the least importance during maintenance planning.

It is worth noticing that the rating of these attributes are relative to each decision-maker. The importance of these attributes in maintenance planning can largely vary from one decision-maker to another. Hence, different scenarios can be visualised in the overall ranking of the bridges.

5.3. Aggregated utility

The final step in the MAUT analysis is computation of aggregated utility of each alternative (i.e. bridge). A selection on the use of additive or multiplicative aggregation form has to made based on the preference (in)dependency among attributes. For this case, the values maintenance cost, condition index, user delay cost and environmental cost are dependent on each other but this does not automatically imply that a decision-maker must take into account the values of other attributes while stating preferences on one attribute. In other words, a decision-maker can prefer the minimum maintenance cost, while at the same time prefer the maximum improvement in a condition index. This preference makes the maintenance cost and condition index mutually and preferentially independent of each other. Considering this, we used the additive form to compute the global aggregated score for each alternative as shown in Equation (15). Since this is minimisation problem the small aggregated score represents the most preferred alternative.

$$U(x) = \sum_{i=1}^{n} k_i U_i(x_i) \tag{15}$$

Table 5. Relative rating of attributes (k).

Performance aspects	Performance indicator	Obtained weight*	Direct rating
Reliability	Condition index	80	80/280 = 0.29
Economy	Owner cost	90	90/280 = 0.32
Environment	Environmental cost	40	40/280 = 0.14
Availability	User delay cost	70	70/280 = 0.25

* Each attribute obtain weight out of 100.

where:

$$U(x) = \text{Multi-attribute utility of alternative } x$$
$$k = \text{Weighting factor of each attribute } i \text{ (see Table 5)}$$
$$U_i(x_i) = \text{Single attribute utility of each attribute } i$$
$$\text{for an alternative } x$$

5.4. Results

By calculating the aggregated utility from the single utility functions of attributes, the ranking of all bridges is obtained. The bridges are ranked based on the minimisation of an aggregated utility function where a bridge is ranked higher having the minimum condition index, owner cost, user delay cost and environmental cost.

Table 6 outlines the actual data, single utility values, aggregated additive utility values and final ranking of each bridge. The final ranking takes into account the relative importance of each attribute in form of k (see Table 5) and risk attitude of decision-maker during the computation of a single attribute utility function. Moreover, it also incorporates the uncertainty of decision-makers preference by enabling them to choose an indifference point between the best and worst possible value. It is important to mention that with the application of MAUT, the end goal is not to provide the ranking of alternatives but to transform the subjective decision-making process towards more objective ways where the utility values represent decision-makers' preferences. Notice that the higher rank have the smaller additive utility scores. This is because of the minimisation of objective functions, where the smaller values get the smaller utility score.

Bridge M is ranked highest based on the defined objectives, where the minimisation of owner cost is most important following with minimisation of condition index on second number, user delay cost on third and finally environmental cost. It is interesting to notice the ranking of *Bridge A* and *Bridge P*. It could have been assumed that bridges having the highest owner cost will be ranked at the lowest. However, *Bridge P* having the highest owner cost is ranked at number 10, similarly *Bridge A* is ranked at lowest rank (i.e. 22) but doesn't have highest owner cost. This is because of the relative importance of the attributes as shown in Table 5, where the condition index is second most important attribute for prioritisation of the bridges. It is also noted that Bridges (i.e. G, J, R, and V) that are ranked at number 18–21 have very small difference in their aggregated multiplicative values. The main reason is that these bridges have condition index score in the range of 2.10–2.34, which is very small in difference. Such small difference in values ends up providing the very close additive utility scores to the bridges alternatives. Figure 9 depicts the ranking of all the bridges with the obtained utility scores where a lower utility score represent the higher rank.

Table 6. Ranking of bridges based on utility (minimisation) function.

	Bridges	Attributes				Single utility values				Additive	
No.	Name	CI	OC	UDC	EC	U(CI)	U(OC)	U(UDC)	U(EC)	Utility values	Rank
1	Bridge A	2.77	139.35	39.70	0.86	0.98	1.00	0.89	0.94	**0.9621**	22
2	Bridge B	1.89	126.41	27.50	0.21	0.96	0.34	0.36	0.83	**0.6649**	11
3	Bridge C	2.15	115.67	25.57	0.57	0.94	0.62	0.74	0.81	**0.7883**	16
4	Bridge D	2.73	42.94	3.41	0.02	0.16	0.98	0.04	0.00	**0.3358**	2
5	Bridge E	2.00	68.16	12.40	0.53	0.67	0.47	0.71	0.48	**0.5711**	5
6	Bridge F	2.12	149.21	47.89	0.23	0.99	0.60	0.39	0.97	**0.7897**	15
7	Bridge G	2.10	169.56	57.79	0.48	0.99	0.57	0.67	1.00	**0.8272**	18
8	Bridge H	2.42	88.60	13.11	1.25	0.85	0.83	0.99	0.51	**0.7763**	14
9	Bridge I	2.22	45.82	35.89	1.26	0.24	0.68	1.00	0.92	**0.6454**	9
10	Bridge J	2.34	115.93	30.80	0.43	0.95	0.78	0.62	0.87	**0.8325**	20
11	Bridge K	2.42	39.42	12.69	0.23	0.04	0.83	0.40	0.49	**0.4284**	4
12	Bridge L	2.46	69.61	12.12	0.03	0.69	0.85	0.05	0.47	**0.5886**	7
13	Bridge M	1.92	38.14	7.99	0.03	0.00	0.38	0.05	0.28	**0.1836**	1
14	Bridge N	2.18	84.89	14.42	1.05	0.82	0.65	0.95	0.55	**0.7233**	13
15	Bridge O	2.43	46.89	4.59	0.00	0.27	0.84	0.00	0.08	**0.3456**	3
16	Bridge P	1.67	175.33	28.51	0.68	1.00	0.00	0.81	0.85	**0.6466**	10
17	Bridge Q	2.08	161.48	55.25	0.37	0.99	0.56	0.56	0.99	**0.8052**	17
18	Bridge R	2.30	158.89	51.04	0.22	0.99	0.75	0.37	0.98	**0.8301**	19
19	Bridge S	2.58	65.90	8.79	0.10	0.64	0.92	0.18	0.32	**0.5744**	6
20	Bridge T	1.96	62.22	22.83	0.42	0.59	0.43	0.62	0.76	**0.5894**	8
21	Bridge U	2.02	84.82	25.70	0.28	0.82	0.50	0.45	0.81	**0.6751**	12
22	Bridge V	2.34	152.60	42.91	0.27	0.99	0.78	0.44	0.96	**0.8411**	21

Note: CI = Condition Index, OC = Owner Cost, EC = Environmental Cost, UDC = User Delay Cost, U = Utility.
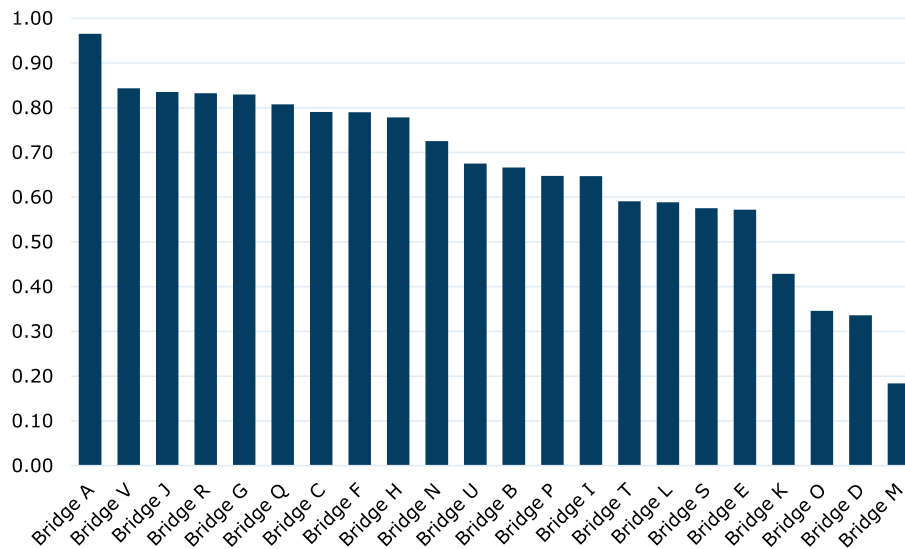
Figure 9. Ranking of the bridges for maintenance planning.

6. Discussion and conclusions

This paper provides the proof-of-concept to apply the MAUT for optimisation of network level bridge maintenance planning. This is illustrated by considering a sample of twenty-two randomly chosen bridges from the Netherlands road network. MAUT provides a systematic procedure to transform the subjective preferences of an infrastructure managers into objective values while optimising multiple objectives during the maintenance planning process. The approach of MAUT illustrated in this paper is not aimed to replace the existing maintenance planning tools but it can be an add-on function that is able to facilitate the further optimisation of limited resources based on the goals of maintenance (e.g. minimise cost, maximise reliability).

As illustrated, MAUT yields the ranking of the bridges by computing exponential utility functions and their final aggregation by capturing the preference uncertainty and risk tolerance of decision-makers. For the case presented in this study, the ultimate ranking is based on a minimisation function of condition index, owner cost, user delay cost and environmental cost, where owner cost is rated most important. Based on the attributes scaling factors and the defined objectives the ranking of the bridges can be totally different for the exact same values. This is because the values assigned by utility functions become higher or lower based on the weights assigned to the attributes to represent their relative importance. The final ranking obtained as a result of aggregation of utility functions suggest that a bridge with higher rank contributes the most in the realisation of defined performance goals.

Though the proof-of-concept expresses the usefulness of MAUT for the network-level bridge maintenance planning, there are also certain limitations to consider. It is noted that the range of data values or data distribution used for the MAUT exercise plays a fundamental role. The attributes having a very small difference between the maximum and minimum scores will yield final utility scores which are very similar to each other (e.g. see Table 6 Bridges G, J, R, V). These similar scores, though

still can be ranked, make it difficult for a decision-maker to objectively justify his/her choices. In addition, the procedure to calculate the utility function is complex and can be time-consuming when the number of alternatives, in our case bridges, are large in number. This can be solved by employing computation aids where the utility functions can be computed by a computer program. Another limitation is due to the changing values of cost, condition index, etc. with time. This means the ranking defined by MAUT is valid for certain period of time during which the performance indicators values are considered as constant.

The future research efforts seeks to mitigate these limitations by developing a computer aided program that will minimise the tasks of manual implementation of MAUT and enable the ranking of rather large number of alternatives based on defined objectives. Moreover, an extension of this case for through network-level maintenance planning is also part of future work, in which number of different performance indicators e.g. bridge's age, location, impact of surrounding objects, possibility to cluster maintenance activities by type or locations, will be considered.

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Disclosure statement

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