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A Multi-Criteria Utility Approach to Bridge Maintenance Prioritization

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ABSTRACT

Maintaining bridges optimally presents a challenge for the decision-makers because of the complexity of the objectives. Bridges should have a maintenance planning system for a better organization and controlling mechanism. These systems allow the decision-making process to be performed simpler and the limited public fund to be spent better. In this study, the multi-attribute utility theory (MAUT) is applied as a practical multi-objective decision-making method to prioritize 20 bridge networks in Western Turkey. The objective of this study is to use MAUT to a bridge maintenance problem in Turkey and providing improvements to the existing Turkish bridge management system (BMS) decision-making method in the literature. The criteria list given in the Turkish BMS is reexamined, and one more criterion is added. The current prioritization method is replaced with the MAUT approach to explain the uncertainty situation by taking the risk preferences of the decision-makers. Additionally, the additive utility independence assumption of MAUT is inquired to avoid a suboptimal solution for bridge maintenance planning. The results show that how calculating risk preferences, interrogating more decision-makers with different expertise, and adding a new objective criterion might change the priority order for the same dataset.

1. Introduction

Bridges have an essential role in infrastructure systems as they lead to the optimal or near-optimal utilization of the geographical restrictions. The lack of infrastructure is a significant limitation to achieve full economic growth for the developing countries (1). Many bridges in the world cost billions of dollars to construct. Maintaining and renovating those bridges could add up to the total expenditure each year. Maintenance planning of the bridges allows decision-makers to benefit from setting a bridge maintenance schedule with a limited amount of resources and constraints by prioritizing the bridges in the inventory. Such systems are the means for the decision-makers to follow a strategic development towards their goals. Since the budgets -especially in the developing and low-income countries- are limited, decision-makers should use the public fund at optimum. Therefore, bridges should be employed for a maintenance planning system to have a better

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organization, and controlling mechanism as these systems allow the decision-making process to be performed easier and the limited public fund to be spent better.

To perform a comprehensive decision-making process in providing bridge maintenance planning, bridge management systems (BMS) are used throughout the world. 25 BMS from 18 different countries are used to manage over 1 million objects (2). The BMS works in a systemic and integrated method, which allows decision-makers of the respective BMS to decide the best for the selected objectives and goals. The BMS might not consider all aspects of a bridge maintenance problem, such as social, environmental, and risk factors. As bridges are valuable transportation elements, thorough maintenance planning must be implemented, including systematic performance goals and eligible decision-makers from different expertise.

There are lots of performance goals and criteria in a bridge management problem; so, the multi-objective and multi-faceted nature of the decision problem make it complex to solve. Therefore, multi-attribute utility theory (MAUT) is considered as an alternative to maintenance planning. MAUT describes the problem, defines objectives, and sets attributes that quantify the determining factors to the selected using the objectives. MAUT interrogates the uncertainty aspect of the problem by capturing the risk preferences of the decision-makers by asking certain types of questions to them. Hence, the findings are quantified in the form of utility functions for unique attributes.

The objective of this study is to apply MAUT to a bridge maintenance problem in Turkey and providing improvements regarding the existing Turkish BMS decision-making method in the literature (3). The prioritization in bridge management systems is not fully explored in the literature. We attempt to prioritize 20 bridges in Turkey at a maintenance perspective by considering the MAUT. The criteria list is given in Masoumi (3)'s study is revisited, and one more criterion added, and the current prioritization methodology is replaced with the MAUT. Additive utility independence assumption of Utility Theory is inquired as pointed out in the study by Kalan *et al.* (4).

2. Literature

Multiple-criteria decision making analysis (MCDM) is commonly used in many study areas such as mathematics, decision analysis, information systems, economics. It is an active subject of research since the 1970s. MCDM set a solution to complex, uncertain, and multiple objective problems with a logical and systematic approach. MCDM deals with harder and more complex issues thanks to the advancement of technology. Decision-making is a useful tool, an integral part of transportation and bridge management literature. Several multiple criteria decision-making (MCDM) methods exist in the literature to handle the decision-making processes for unique cases because of the complex nature of the maintenance problems. Since there are many performance measurements with multiple targets, it is crucial to decide the alternatives with the trade-offs to optimize the system with desired goals and objectives (5). MAUT's most important advantage as an MCDM method is that it captures the risk preferences of the decision-makers that reflect uncertainty situations by attaining utility values. Many of the MCDM methods do not distinguish between certainty and uncertainty situations, while uncertainty is an essential aspect of a bridge maintenance problem (6).

3. Multi-Attribute Utility Theory

MAUT is a decision-making method that provides a single aggregated utility function through several utility functions of different criteria selected to solve a problem (7). It has been widely used in a variety of disciplines (8–10). The fundamental approach in this theory is the elicitation of the utility attitude of the chosen decision-makers among different alternatives by calculating the global utility functions for each performance measure and goal where they are represented in a criterion set. The individual derived services of criteria are merged into a single general utility function. Therefore, each alternative gets a utility score by this amalgamated utility function, and hence, these utility scores could be used for prioritizing these alternatives among themselves.

Garmabaki *et al.* studied the maintenance optimization using MAUT to develop an optimal inspection program. They established a method for maintenance planning using reliability, availability, and risk as performance goals (11). De Almeida *et al.* states that MAUT applies to maintenance problems such as maintenance strategy selection, design selection, condition-based maintenance, risk analysis, and prioritization of failures (12, 13). Also, the most common criteria for the MCDM in maintenance modeling papers in the literature are; cost (68.3%), reliability (37.6%), availability (17.2%), time (11.8%), weight (8.1%), risk (4.8%) and safety (2.7%) (13). Zietsman performed research on sustainable transportation decision making on transportation programs and projects, comparing Tshwane, South Africa, and Houston, Texas, and showed that MAUT could be a decision-making tool for transportation corridors (14). Thompson *et al.* (2006) performed multi-objective optimization for BMS using MAUT. They presented a new analytical framework providing the least long-term cost solutions to decision-makers while delivering sufficient safety, minimum traffic flow disruption, and risks for the examined bridge network (15). Bai *et al.* presented a method for bridge maintenance using MAUT. Candidate projects are tested using network-level performance measures before applying the MAUT function to determine the optimal project selection. Assuming utility functions as additive does not always hold for bridge maintenance planning projects (16). Frangopol *et al.* propose a generalized framework to measure the bridge life-cycle performance and the cost stressing the importance of analysis, prediction, optimization, and decision making under uncertainty using multi-objective optimization processes. Also, the authors argue the effects of climate change on life-cycle performance, such as the increased soil erosion rates and soil moisture levels' impact on the foundation of the bridge networks (17). Structural health monitoring (SHM) could get information about the state of the existing bridge and make better decision-making for the bridge management process. Capello *et al.* implemented expected utility theory as a quantitative analytical framework allowing the identification of the monetarily best decisions using the SHM as the guide to the decision process in two steps. In the first step, the solution is formulated using a single-stage decision process that lets the decision-maker have only one option. In the second step, the authors have expressed the solution with a multi-stage decision process that enables decision-makers to take multiple actions over time (18). Although there are few studies on transportation, bridge sustainability, and bridge maintenance, the research on optimizing bridge networks using MAUT is still open for development.

4. Methodology

MAUT is selected as the multi-criteria decision-making tool because MAUT explores the decision making under the risk scenario rather than investigating certainty situations where risk preferences are not considered. Also, the choices of multiple decision-makers can be determined so that the results reflect the judgments of experts in different fields.

While amalgamating the individual utility functions into a general utility function, instead of using a single method, both the mid-value splitting method and the gambling method are combined and implemented. The gambling method inquires the decision-maker's attitude towards a criterion if a risky situation occurs. In a gamble question, the decision-maker is asked to give up the criterion's best utility situation with the worst utility situations of the other criteria to get a set of best utilities of all criteria. However, there is a risk of losing everything, which means all the criteria will be in the worst utility situation. In this question, the decision-maker chooses a probability value between 0% and 100% of winning this gamble. Therefore, this value represents the risk attitude of decision-makers towards that given criterion. This gamble question is just asked for one criterion (the most crucial criterion for the decision-maker), and other criteria's AHP values are scaled according to this chosen gamble value, as suggested in (19). Thus, this implementation captures the risk preference of the decision-makers easier than performing it for all three different criteria.

In the amalgamation process, the AHP method is used to assign different weightings for different criteria. Saaty (1987) defines the Analytic Hierarchy Process (AHP) as a general theory of measurement that is used to derive ratio scales from paired comparisons (20). AHP is also used as a unique method in multi-objective optimization for bridge management systems to develop relative weights for bridge management problems (15). After elicitation of the weights through AHP, these weightings are scaled through the use of gamble values. Therefore, this allows us to decide on whether to use an additive or multiplicative amalgamation method.

In the development of the multi-criteria utility function, two unique methods are used to aggregate the single utility functions into a multi-attribute utility function: additive and multiplicative forms. Commonly, additive utility independence, which aggregates the weight of the attributes additively, is assumed in the literature. Here, however, the decision-makers are asked a gamble to make a test to determine the existence of the additive utility independence. Additive utility independence is not found. Therefore, the multiplicative method is implemented for the analysis.

4.1 Utility Functions

Keeney and Raiffa defined that utility function captures decision-makers' preferences regarding the selected attribute's attitude towards risk for each attribute (19). This is like value functions that assign a value for each criterion, but it differs from the value function in capturing the risk preferences of the decision-makers. It is a hard task to create a multi-attribute function, so first, single-criterion utility functions are created, and then multi-attribute utility function is derived from the aggregation of the single-criterion utility function. For instance, the objectives of the problem are selected, and attributes, namely X1, X2, X3,..., Xn, are defined. Then, we can argue that xi represents a specific level of Xi, and the utility function can be described as u(x)=u (x1, x2, x3,…,xn) for n attributes.

4.1.1. Creating single utility functions

Utility functions describe a value from zero to one for each attribute, capturing the risk preferences. Hence, the preferences of decision-makers under risky situations are elicited. These preferences are quantified through the questions in the structure as follows;

Situation 1: you will select a particular attribute value

Situation 2: or you will play the lottery of the:

50%, the maximum value of the attribute value is obtained

50%, the minimum attribute value is obtained

A particular attribute value is asked for a decision-maker to be indifferent to Situation 1 and 2. Inquiring maximum and minimum attribute values with a 50% gamble rate would give X50 utility value. Gamble method is applied two more times from X50 to maximum and X50 to a minimum to attain X25 and X75 utility values. The framework of the gambling method to get X25, X50, and X75 values is shown in Figure 1.

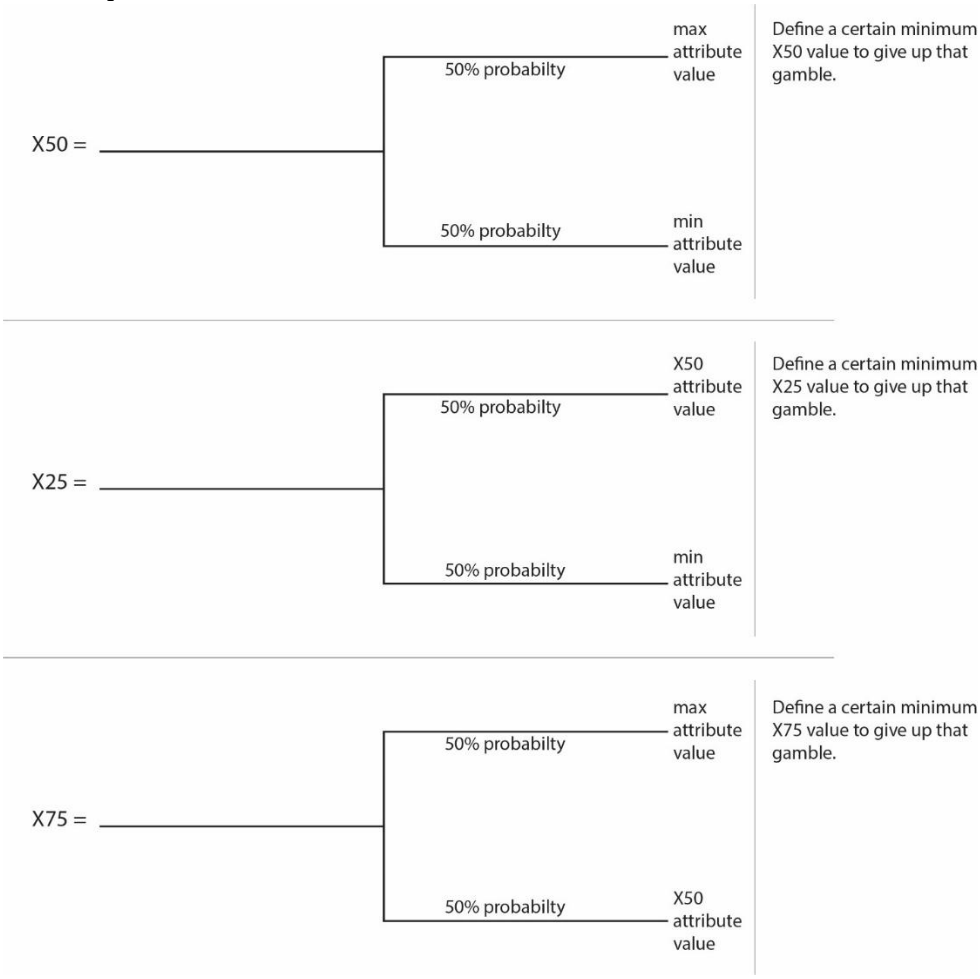

Fig. 1. Gamble Method Setup to get X25, X50, X75 attribute values

From the results, five attribute values for X0, X25, X50, X75, X100 can be obtained. The risk preferences of the decision-makers can be further observed by plotting each attribute value for the specified utility values, and the utility function can be fitted according to the judgments of each decision-maker. A negative exponential growth model is used for this research to represent the risk-taking behavior specified in Equation 1.

$$u(x) = A - B * e^{-x}/c \quad (1)$$

The data is fitted to the decision-makers' judgments for X25 X50 and X75 attribute values. Microsoft Excel's solver function minimizes the residuals for attribute values judged by the decision-makers from the fitted function. Excel solver finds the optimum solution to determine the A, B, and C values minimizing the sum of the square of residuals. Therefore, obtained A, B, and C values are plugged into Equation 1 (the single utility function for the selected attribute).

Three different risk preferences can be observed from the single utility functions. The concave shape shows risk-avoiding; the linear form shows the neutral and convex shape, shows a risk-taking attitude.

4.1.2 Relative weights

In MAUT, a direct weighting is commonly used to develop relative weights for the attributes. Direct weighting is simple, but it does not test the preferences of the decision-makers precisely as other weighting methods because of a lack of conflicts between the attributes. Therefore, the analytic hierarchy process was implemented. Analytic hierarchy progress is a method of MCDM that makes a pair-wise comparison of two elements based on the professional judgments of the advantages and disadvantages of experts. It is preferred commonly by the ease of its use for weighting coefficients. These coefficients represent the preference and decision of the expert. It allows testing relative weights while comparing the attributes directly with more details since we compare the importance of each attribute with another one. AHP decomposes the multi-attribute decision making into a hierarchy of decision making. For its hierarchical structure, decision making with many elements is easy to construct. Two attributes are compared with each other according to one attribute's importance to another. The fundamental scale of importance from Saaty's (1987) research was applied for this study to quantify the verbal responses to corresponding values.

Numerical pair-wise comparisons are plotted to construct a matrix that shows the relative importance of the elements of the matrix where A12 signifies the relative importance of the attribute 1 to attribute 2 according to the fundamental scale. A generic AHP matrix with n attribute is shown in Equation 2.

$$A = \begin{pmatrix} 1 & A_{12} & \dots & A_{1n} \\ A_{21} & 1 & \dots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \dots & 1 \end{pmatrix} \tag{2}$$

The main diagonal of the AHP matrix comprises 1's such as A11, A22, …, Ann =1 because the relative importance of the same attribute has equal importance. The values of the lower triangle are the transposed values of the upper triangle. For instance, if A12 = 9, A21 must be 1/9 because A12 responds to the pair-wise importance of X to Y and A21 responds to the pair-wise importance of Y to X. Consistency is an essential factor of an AHP problem because the results of the pair-wise comparisons must be consistent in the overall matrix. Consistency is calculated from the eigenvalue solution for the weights shown in Equation 3.

$$A'w' = \lambda_{max} w' \tag{3}$$

where λmax is the largest eigenvalue of A'. Consistency Index (CI) of the matrix is given with Equation 4 for n attribute AHP process.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

Saaty (20) derives the average random consistency index (RI) from a sample of 500 randomly generated matrix. Comparing CI with RI would give out the consistency rating of the AHP problem. Saaty (20) argues that consistency rating smaller than 10% is acceptable since Saaty discusses that inconsistency is essential for letting new knowledge to change preference order.

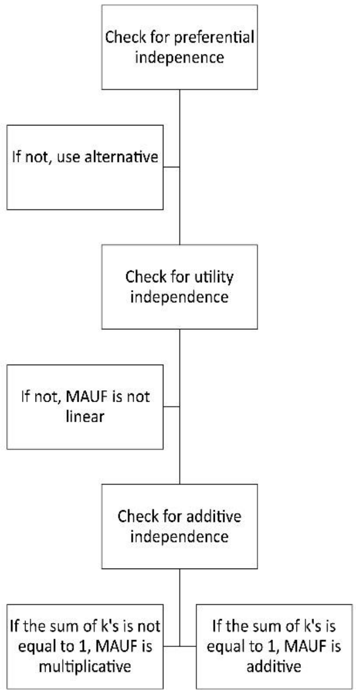

Fig. 2. Attribute the independence algorithm to define the nature of the MAUF

Utility independence has the same utility value as an attribute for unique values of other attributes. For instance, the attribute set of (X, Y, Z) is selected, and the gambling method applies to determine X50, which gives 50% utility for the chosen X attribute value. If the result of the gambling method is the same for unique attribute values of Y and Z, utility independence exists for the (X, Y, Z) attribute set. Lack of utility independence makes the utility function multilinear. Relative weights for n attributes are calculated using the AHP or direct weighting method. The test of AI is performed by the gamble shown in Figure 3.

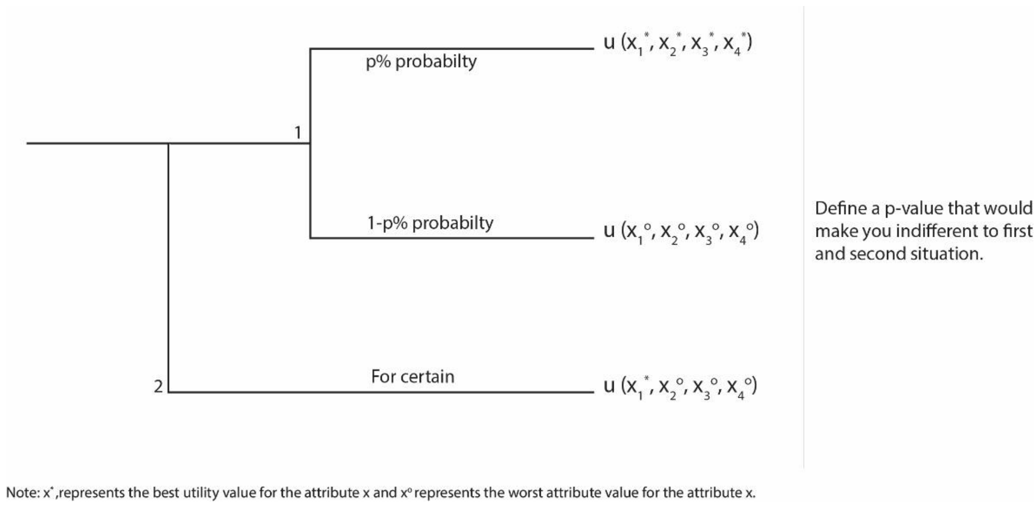

Fig. 3. Additive independence test, gamble question

The decision-maker is asked for a probability value p% to give up the best utility value for w1 and worst utility values for all attributes to take the gamble of getting best utility values with p% or getting worst utility values with 1-p% assuming w1>w2>w3>…>wn. Keeney defined the p-value as k1 and other k values for w2, w3,…, wn is derived from the ratio of k1/w1 (19). The calculated values of k1, k2, … , kn are summed up, and if the sum of the k-values (Equation 5) is equal to 1, the utility function is additive. If not, the utility function is multiplicative (Equation 6).

$$if\ k = \sum_{i=1}^{n} k_i\ = 1\,, additive\ independence\ exist \tag{5}$$

$$if\ k = \sum_{i=1}^{n} k_i\ \neq 1\,, additive\ independence\ does\ not\ exist \tag{6}$$

For the additive utility function, the multi-attribute utility function is aggregated from the single utility function with Equation 7,

$$U = \sum_{i=1}^{n} k_i\, u_i \ldots (7) \tag{7}$$

For the multiplicative utility function, the multi-attribute utility function is aggregated from the single utility function with Equation 8,

$$U + \sum_{i=1}^{n} k_i u_i + k \sum_{i=1}^{n} k_i k_j\, u_i u_j + k^2 \sum_{i=1}^{n} k_i k_j k_k u_i u_j u_k + .. + k^{n-1} k_i k_j \ldots k_n u_i u_j \ldots u_n \tag{8}$$

Where j>i and j>k and

Where k is calculated with Equation 9,

$$k + 1 = \prod_{i=1}^{n} [k(k_i u_i)] + 1 \tag{9}$$

Existence of preferential independence and utility independence is assumed and not included in this study, and additive independence is not assumed. Therefore, the necessary AI tests were held.

5. DATASET AND ANALYSIS

Multi-Attribute Utility Theory (MAUT) approach was applied to the bridge network maintenance problem to prioritize the bridge inventory. Data is obtained from Masoumi (3), where a bridge management system in Turkey is developed using 20 bridges (name and location of the bridge, bridge traffic, bridge condition, physical bridge properties, and cost properties) in Western Turkey to quantify the factors.

Different engineering fields, such as transportation, management, and structural engineering, can question network-level bridge maintenance problems. This questionnaire is conducted with five experts in academics, 2 in traffic, 2 in structural, and 1 in bridge asset management field. The experts from different areas made the decision-making process more inclusive rather than enquiring about the problem from a single point of view. Also, conducting the survey with more decision-makers created a consensus that is more agreeable for obtaining better overall results.

Keeney and Raiffa created a framework that involves six topics to use MAUT on a multi-attribute decision-making problem (19). The first three topics establish the bridge management problem by defining issues, objectives, and attributes. Also, the required data to create to construct the multi-attribute utility function is obtained by quantifying the attributes. In the fourth topic, the single utility functions are created from the results of the mentioned questionnaire that measures the risk preferences of five decision-makers. The fifth topic involves making a trade-off among the attributes to attain relative weights, quantifying the importance of the attributes on a scale of 0 to 1. The aggregation process of the calculated single utility functions is discussed in the sixth topic, and the multi-attribute utility function is defined for this bridge maintenance problem.

5.1 Definition of Objectives

We have the data of 20 bridges from Western Turkey, and those bridges need some maintenance with a limited budget. The problem is to determine to prioritize the bridges because all the bridges cannot be maintained because of the budget constraints. If an inventory of some bridges could be listed according to the priority, the decision-makers could easily decide which bridges to repair with a limited budget.

In the utility theory, the ultimate objective of the decision-making problem is gaining the "overall utility." Since there is no single objective can represent all elements of a bridge management problem alone, some sub-objectives are determined to represent elements of the problem. These sub-objectives aim to achieve the "overall utility" for all parties involved. In the literature of bridge maintenance problems, minimization or maximization of the following attributes are selected as objectives: Cost minimization, preservation of bridge condition, traffic safety, bridge importance, environmental impact. The objectives will achieve "overall utility." They represent all groups that are involved, such as agencies, users, and decision-makers.

For this research objectives are selected as:

- Maximizing User Impact
- Preservation of Bridge Condition

- Minimizing Agency Costs
- Insuring Work-zone Safety

Naturally, the objectives conflict with each other because there is not a single solution that optimizes all. Therefore, the objectives are selected as performed in NCHRP report generic objectives for bridge management problems (15).

5.2. Definition of Attributes

It is essential to define attributes for each objective that represents all the aspects of the problem. Subjective quantitative scales for attributes will measure objectives. In this research, attribute scales were selected locally according to data instead of a global scale. For instance, bridge condition rating is selected for the objective of preservation of bridge condition, and the scale set to 1.05-1.68, which is the maximum and minimum values in the dataset. The global scale for bridge condition rating is 1-4, which is very large. For this research, we think selecting the scale locally would be better because of the small and closely scattered data. Keeney proposes four desirable properties to define a set of attributes for the objectives (19).

- Complete: Attributes must be complete, covering all parts of the problem.
- Operational: Attributes must be defined unambiguously so that decision-makers can make an apparent judgment between the alternatives.
- Non-redundant: Attributes must be kept non-redundant not to have multiple attributes representing the same objective.
- Minimal: Dimension of the attributes must be kept minimal. As the number of attributes increases, the problem becomes more complex and challenging than intended.

Therefore, the attributes for the objectives of the case study are defined according to those four desirable properties. The range of selected attributes can be observed in Table 1.

- Maximizing User Impact:

X1: Importance Factor

- Preservation of Bridge Condition:

X2: Bridge Condition Factor

- Minimizing Agency Costs:

X3: Cost-Effectiveness Factor

- Ensuring Work-zone Safety:

X4: Work-zone Safety Factor

5.2.1 Importance factor

VDOT recommends an importance factor based on average annual daily traffic (AADT) to represent the relative importance of the bridge to the overall highway network (22). The range of the attribute is selected locally as 850-59500 AADT that minimum AADT would give the minimum utility, and the maximum AADT would cause maximum utility. As the maintenance planner point of view, we would like to maintain bridges which are used by many daily users so that more people can benefit from the maintenance work to achieve the maximum utility. The user impact would be minimal with a bridge by maintaining a bridge with small AADT. Therefore, it has lesser importance on the overall highway network. The importance factor is described in Equation 10.

$$IF = AADT \tag{10}$$

VDOT defines other parameters to enhance the importance factor (22). Still, in this research, only AADT is used since only the daily users of a bridge are representative to determine the importance of the bridge to the overall network.

5.2.2 Bridge Condition Factor

The bridge condition factor represents the overall physical condition of a bridge. In Turkey, bridge condition rating ranges from 1 to 4, where 1 represents the excellent physical condition, and 4 represents the worst physical condition. The research by Masoumi (3) calculated the bridge condition ratings with the following Equation 11.

$$BCR = \sum_{i=1}^{3} CSI_i * w_i \tag{11}$$

Where,

BCR= Bridge condition rating

CSI= Condition state index for element i

wi= Weighted score of the element i

There are three major elements for assessing the condition of state: superstructure, substructure, and accessories. The physical conditions of that three elements are quantified with visual inspection and non-destructive testing methods by Masoumi (3) in 2014, and condition state indexes are weighted and aggregated to a bridge condition rating. The bridges chosen for this research were in excellent condition, so; the range is determined locally as 1.68 to 1.05 where the maximum bridge condition rating gives the maximum utility, and minimum bridge condition rating would cause minimum utility. Bridge condition rating of 1 state the excellent condition; therefore, maintaining a near excellent condition bridge would not give much utility because the bridge in question is not in urgent repair. Maintaining bridges with the worse physical condition would provide the maximum utility since inconveniences because of the physical condition are noticeable, and fixing a bridge that produces inconvenience would cause maximum utility.

5.2.3 Cost-effectiveness factor

Cost-effectiveness Factor (CEF) is a function of the ratio of optimal repair cost to rehabilitation cost that measures the effectiveness of the funds used to maintain a bridge. Damage of the bridge elements is categorized into "repair now" and "repair later" actions. Optimal repair cost defines the repair cost of the "repair now" action elements that means maintaining the aspects that need immediate response would be optimal. However, rehabilitation cost includes both "repair now" and "repair later" cost so, maintaining "repair later" elements alongside the bridge maintenance would not be optimal. Therefore, CEF is defined with Equation 12.

$$CEF = 1 - \frac{optimal\ repair\ cost}{rehabilitation\ cost} \tag{12}$$

The range of the CEF is selected locally as 0.43-1 that minimum CEF results in minimum utility, and maximum CEF results in maximum utility. For instance, the CEF value of 1 means that the highest effectiveness can be obtained from that maintenance work since all the rehabilitation is optimal. That situation would provide the maximum utility. A low CEF value means non-optimal maintenance work that would not offer much utility.

5.2.4 Work-zone safety factor

Work-zone safety factor (WSF) measures the extra cost to take safety actions during the maintenance due to road deficiencies. Economic effects such as taking extra safety measures for the workers, bringing additional engineering equipment to work in deficient roads, and closing down the bridge to traffic for tough maintenance situations are estimated. This estimate is added to the extra cost for maintenance for the bridges that have road deficiencies such as reduced roadway width or shoulder length. WSF is calculated with Equations 13, 14, and 15.

$$WSF = \frac{design\ width}{desired\ width} \tag{13}$$

$$design\ width = (2 * design\ shoulder\ width) + (no.of\ lanes * design\ lane\ width) \tag{14}$$

$$desired\ width = (2 * design\ shoulder\ width) + (no.of\ lanes * desired\ lane\ width) \tag{15}$$

Desired shoulder and desired lane width values were selected from the AASTHO Highway Design Manual according to the percentage of trucks, road type, and other parameters (23).

The range of the WSF is 0.88-1. The maximum value of WSF would give the maximum utility, and the minimum value of WSF would cause minimum utility. For instance, the WSF value of 1 means that the road design is proper according to the AASTHO highway design manual; therefore, the accident risk because of the road deficiency is minimal. A low WSF value means that road deficiency is present for the bridge in question. Thus, additional costs must minimize the accident risk because of road deficiency.

5.3 Creating Single Utility Functions

A questionnaire was prepared for the decision-makers to calculate the single utility functions, to determine the relative weight of the attributes and the additive utility independence. Decision-makers were informed about the network-level bridge maintenance problem and the definition of the attributes. Three gamble method questions were asked for each attribute to construct the single utility functions as the process is explained.

5.3.1 Single utility function of importance factor

$$u_1(x_1) = 1.250 - 1.237 * e^{-x_1/2.628*10^{-5}} \tag{16}$$

Figure 4 shows the plot of utility values for IF. Risk avoiding behavior is observed because of the concave shape of the function. The judgments of the decision-makers for X25, X50, and X75 values are marked on the plot.

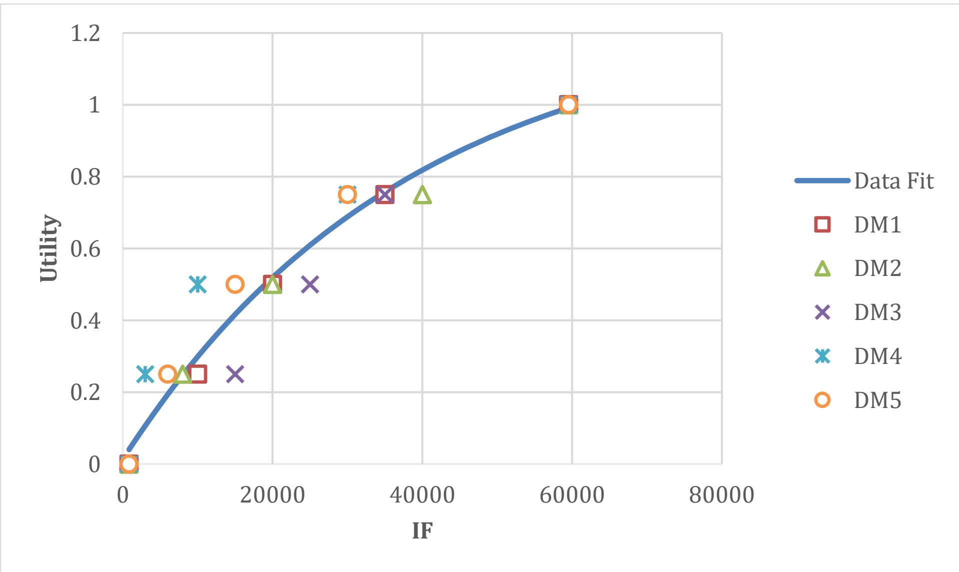

Fig. 4. Single utility function of IF

5.3.2 Single utility function of bridge condition factor

$$u_2(x_2) = 1.416 - 10.65 * e^{-x_2/1.930} \tag{17}$$

Figure 5 represents the single utility function of BCR. Risk-averse judgment from the decision-makers due to the concave shape of the function.

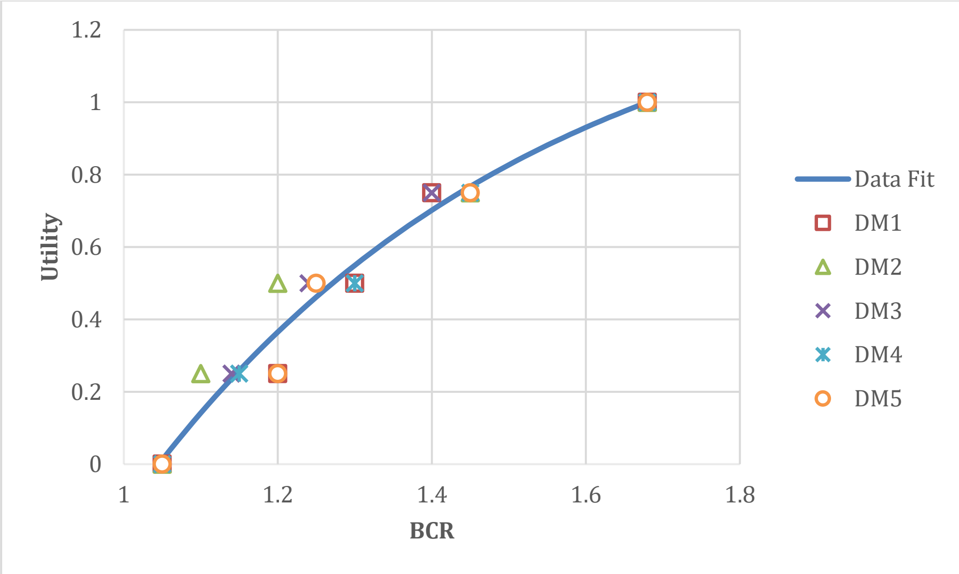

Fig. 5. Single utility function of BCR

5.3.3 Single utility function of cost-effectiveness factor

$$u_3(x_3) = 1.287 - 3.809 * e^{-x_3/2.538} \tag{18}$$

Figure 6 shows that the risk preference of decision-makers shows risk-avoiding behavior because of the concave shape of the function.

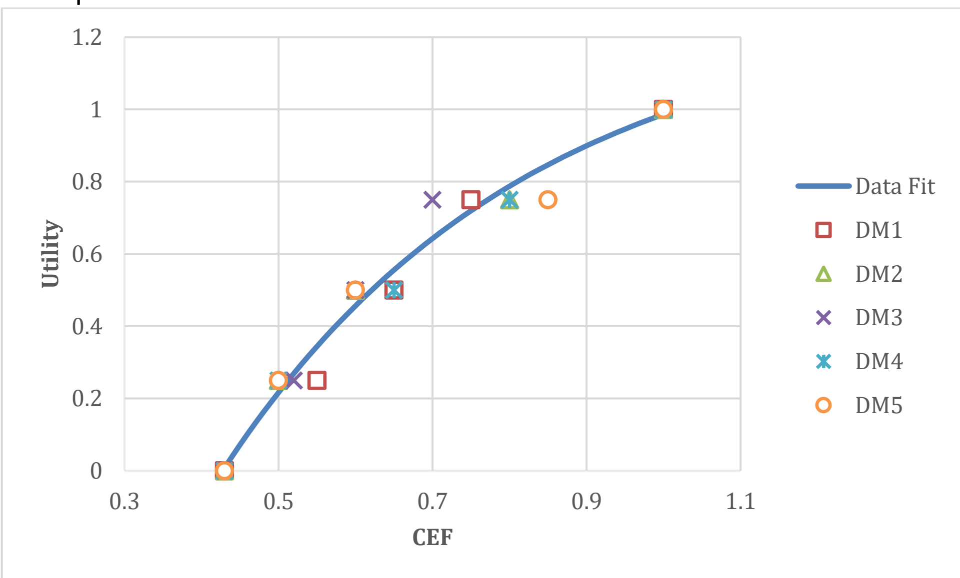

Fig. 6. Single utility function of CEF

5.3.4 Single utility function of work-zone safety factor

Finally, the single utility function for WSF is shown in Equation 19, and Figure 7 signifies the single utility function of WSF according to the risk preferences of five decision-makers.

$$u_2(x_2) = 1.166 - 173003 * e^{-x_2/13.54} \tag{19}$$

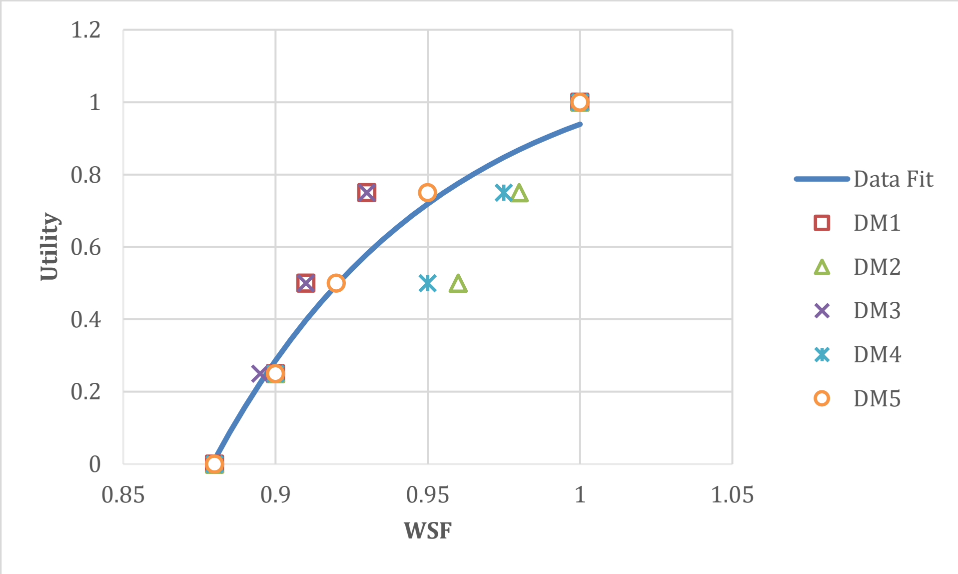

Fig. 7. Single utility function of WSF

Figure 8 shows the distribution of the 20 selected bridges for this study on the single utility functions of four attributes IF, BCR, CEF, and WSF on parts a, b, c, and d, respectively.

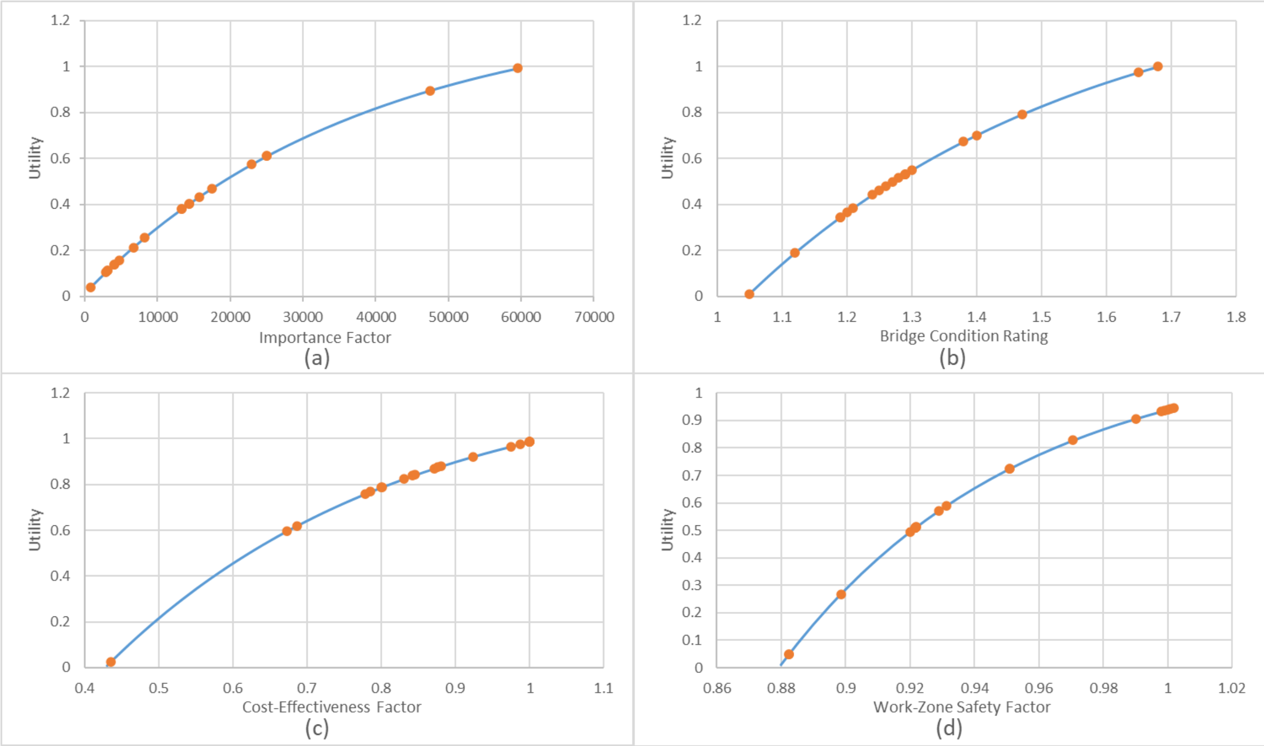

Fig. 8. Distribution of 20 bridges on single utility functions

5.4 Performing Value Trade-off Among the Attributes

As we specified four objectives for the bridge maintenance problem, specific attributes to be maximized or minimized are defined. Minimizing or maximizing an attribute value might affect the other attribute values since a solution that satisfies all objectives fully does not exist. Therefore, certain trade-offs among the attributes must be made. NCHRP report suggests two weighting methods to make the trade-offs, direct weighting, and analytical hierarchy process (15). The analytical hierarchy process is used in this study, as we discussed in the Methodology.

Five decision-makers from the different fields were asked six questions comparing the importance among the attributes pair-wisely. Decision-makers made their judgments about the significance of two attributes. Each attribute was given weight on a scale of 0-1. The importance factor was chosen as the most important attribute, as the bridge inventory had an excellent physical condition. Thus, the bridge condition rating was in second place. Decision-makers placed the cost-effectiveness factor in third place following the BCR. Finally, the word-zone safety factor was in less place since decision-makers judged the cost of taking extra safety precautions because of road deficiency as minor importance in bridge maintenance planning.

The consistency factor that defines the reliability of the pair-wise decisions was calculated just below 10%, which is favorable by Saaty's research (20). Therefore, pair-wise comparisons are consistent with the overall importance ranking.

5.5 Creating a Multi-Criteria Utility Function

Single utility functions are aggregated into a multi-attribute utility function with three necessary steps.

- Intriguing additive independence
- Scaling attribute weights linearly to determine to scale constants k-values.
- Aggregating multi-attribute utility function.

Additive independence of the utility function is intrigued by a gambling process shown in Figure 4. Decision-makers are asked about two situations. In the first situation, we get the maximum utility for the most crucial attribute (with the AHP process) and the minimum utility values for all the other attributes for sure. The second situation incorporates a gamble with a probability of p% to get the best utility values for all attributes or 1-p% of getting the worst utility values for all attributes. Decision-makers are asked for a p-value that made them indifferent to the two situations mentioned.

$$k_1 = \frac{p_{DM1} + p_{DM2} + p_{DM3} + p_{DM4} + p_{DM5}}{5} \tag{20}$$

$$k_i = \frac{k_{i-1} * w_i}{w_{i-1}} \; for \; i = 2,3,4 \tag{21}$$

The most critical attribute was determined as the importance factor (k1), and other attributes are sorted from largest to smallest as BCR (k2), CEF (k3), and WSF (k4). The determined p-value represents k1, and the other k-values are linearly scaled from the attribute weights shown in equations 20 and 21. The sum of the k-values is determined as smaller than one; therefore, the nature of the multi-attribute utility function is determined to be multiplicative. K-values are averaged, and overall constant k is calculated from equation 9. The overall function to calculate the global utility value for prioritizing the twenty bridges are shown in Equation 22.

$$u(x_{1,2,3,4}) = \sum_{i=1}^{4} k_i u_i + k \sum_{\substack{i=1 \\ j>i}}^{4} k_i k_j u_i u_j + k^2 \sum_{\substack{i=1 \\ j>i \\ k>j}}^{4} k_i k_j k_k u_i u_j u_k + k^3 k_1 k_2 k_3 k_4 u_1 u_2 u_3 \tag{22}$$

The problem is defined with a method that maximizes the objectives so that a maximum value of utility is preferable to the other alternatives. The data of the global utility values of twenty bridges are discussed in the next section.

6. RESULTS AND DISCUSSION

Utility values for respective attribute values are shown in Table 1. Also, single utility values for each attribute are specified, and the global utility values are aggregated with relative weights and multiplicative aggregation. The results of the global utility values of twenty bridges are also shown.

The bridges are ranked from maximum to minimum aggregated utility scores, and the results are compared to the research Masoumi (3), which prioritized the same bridge inventory in 2014.

Table 1

Bridge ranking using MAUT and comparison to Masoumi's study

Bridge	Attributes				Single Utility Values				Multiplicative	Ranking	
ID	IF	BCR	CEF	WSF	U(x) IF	U(x) BCR	U(x) CEF	U(x) WSF	Total Utility	MAUT	Masoumi
A	59546	1.28	0.97	1.00	0.99	0.52	0.97	0.94	0.82	1	1
B	47460	1.05	0.80	0.99	0.90	0.01	0.79	0.91	0.59	2	2
F	25070	1.26	0.88	0.93	0.61	0.48	0.88	0.56	0.57	3	6
D	25070	1.2	0.87	0.92	0.61	0.37	0.87	0.51	0.56	4	4
C	22954	1.21	1.00	0.92	0.57	0.39	0.99	0.51	0.55	5	3
H	15702	1.25	1.00	0.92	0.43	0.46	0.99	0.51	0.52	6	8
I	14321	1.24	0.92	0.97	0.40	0.44	0.92	0.83	0.50	7	9
G	14321	1.3	0.83	0.90	0.40	0.55	0.82	0.27	0.50	8	7
K	13329	1.19	1.00	0.92	0.38	0.34	0.99	0.51	0.50	9	11
E	17487	1.12	0.78	0.95	0.47	0.19	0.76	0.72	0.49	10	5
P	2917	1.65	0.79	1.00	0.10	0.98	0.77	0.94	0.45	11	16
Q	3191	1.68	0.84	0.92	0.11	1.00	0.84	0.51	0.43	12	17
T	13329	1.19	0.44	1.75	0.38	0.34	0.03	1.17	0.43	13	20
J	4716	1.29	0.99	1.00	0.16	0.53	0.98	0.94	0.42	14	10
S	6713	1.29	0.80	0.95	0.21	0.53	0.79	0.72	0.42	15	19
N	3191	1.47	0.88	0.88	0.11	0.79	0.87	0.05	0.41	16	14
M	8236	1.27	0.69	0.93	0.25	0.50	0.62	0.59	0.39	17	13
L	840	1.4	1.00	1.00	0.04	0.70	0.99	0.94	0.38	18	12
R	4059	1.38	0.67	0.92	0.14	0.67	0.60	0.51	0.35	19	18
O	4059	1.29	0.85	0.88	0.14	0.53	0.84	0.05	0.33	20	15

The priority order transformed; however, first and second-order resulted in the same. Bridge A came out early in priority because of its high IF, which has the most top criteria number. Bridge B follows that with high IF and relatively high BCR and although Bridge F has a higher value for IF, it came out in third place because of the very low value of BCR. Bridges D, C, and H placed in rank 4-6 because they also have relatively high IF, and despite its small IF, Bridge I and G came out in rank 7-8 with very high BCR. The other rankings can be observed in Table 1. The results show that IF has a crucial role in prioritizing bridge maintenance planning since the 8 out of 10 most prioritized bridges in the data set to have high IF. It highlights the decision-makers' desire to maximize user impact. Hence, WSF does not have a critical role in prioritizing as WSF's total contribution to the overall utility ranges from 0 to 5%. It is also noticeable from the utility value gap between bridge A and other bridges. There is a 22-point utility difference from its closest alternative, whereas the utility difference between the other alternatives is relatively small.

By comparing results from Masoumi's (3) research, we show the change of priority order of the same set of bridges. This change displays the effect of using a utility model, taking risk preferences of the decision-makers in uncertainty situations, and not assuming additive independence while aggregating multi-attribute utility function. It is notable that analyzing the judgment of five different decision-makers from diverse expertise, presented more democratic and more agreeable results compared to Masoumi (3)'s research. Another contribution is that additive utility independence is not assumed contrary to the studies of Zaharah *et al.* and Jeon (24, 25), assuming additive independence can generate suboptimal solutions for transportation asset problems (4).

The Work-zone safety factor is added as a fourth attribute as an addition to Masoumi (3)'s study. Despite its small part in overall utility, we believe that it is crucial to have a factor that captures road deficiencies for an operational aspect of the problem.

Limitations of this study include poor representation of IF with the only criteria that characterize the IF is AADT because of the limited data about the characteristics of the traffic. It could be further expanded by enriching IF with future AADT, truck ratio, and bypass length. Therefore, data collection and vast data for traffic characteristics are essential when investigating a bridge maintenance problem.

7. Conclusion

This study presents an application of MAUT on a bridge maintenance problem. AHP is used to determine the trade-offs among the attributes. The additive independence of the utility function is intrigued. Dataset was selected among 20 bridges in Western Turkey to apply MAUT maximizing objectives chosen for the maintenance planning. Single utility functions are derived to represent attributes that represent the objectives listed as; importance factor, bridge condition rating, cost-effectiveness factor, and work-zone safety factor. These utility functions correspond to the risk preferences of the five selected decision-makers from different expertise for the uncertainty situation of bridge maintenance. MAUT differs from other MCDM with that aspect of taking risk preferences (*6*). The trade-off among the attributes is decided with AHP, and the single utility functions are aggregated multiplicatively with not assuming additive independence. Finally, the final ranking of the bridges is presented according to their utility values. A comparison is made with the study of Masoumi (*3*) that used the same set of bridges.

For future studies:

•With a more extensive dataset, a detailed criteria hierarchy can be constructed.

•With detailed maintenance information, prioritization decisions can be made in terms of different maintenance strategies.

•An optimization model can be integrated into a prioritization model with limited budget scenarios for a certain period of years.

Author Contributions
Conceptualization, Ilgin Gokasar and Isik Okur; methodology, Ilgin Gokasar and Isik Okur.; software, Ilgin Gokasar and Isik Okur.; validation, Ilgin Gokasar and Isik Okur; formal analysis, Ilgin Gokasar and Isik Okur; investigation, Ilgin Gokasar and Isik Okur; resources, Ilgin Gokasar and Isik Okur; data curation, Ilgin Gokasar and Isik Okur; writing—original draft preparation, Ilgin Gokasar and Isik Okur; writing—review and editing, Ilgin Gokasar and Isik Okur; visualization, Ilgin Gokasar and Isik Okur; supervision, Ilgin Gokasar. All authors have read and agreed to the published version of the manuscript.

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