BRIDGE MAINTENANCE PRIORITIZATION USING MULTI-ATTRIBUTE UTILITY THEORY

by

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ABSTRACT

BRIDGE MAINTENANCE PRIORITIZATION USING MULTI-ATTRIBUTE UTILITY THEORY

Bridge maintenance planning is a complex problem because of the complexity of the objectives. Handling this issue optimally is a challenge. There is a need of bridge planning process to organize and control the bridge inventory for a better decision-making process and the overall public utility. Among the other alternatives, multi-attribute utility theory (MAUT) is applied as a viable multi-objective decision-making method to prioritize 20 bridge networks in Western Turkey. The aim of this study is applying MAUT to a bridge maintenance planning problem in Turkey and providing improvements to the existing Turkish bridge management system (BMS) decision-making method in the literature. Existing attributes are examined and another criterion that intrigues the safety for the work-zone is added. The prioritization methodology is replaced with the MAUT approach to explain the uncertainty situation by taking risk preferences of the decision makers. Additionally, additive utility independence assumption of MAUT is inquired to for a more optimal solution. The results provide that how calculating risk preferences, interrogating more decision makers, unique point of views of the various expertise, and adding a new objective criterion might change the priority order for the same bridge dataset.

ÖZET

ÇOK NİTELIKLİ FAYDA TEORİSİ İLE KÖPRÜ SİSTEMLERİNİ ÖNCELİKLENDİRME

Köprü onarım planlaması optimize edilecek amaçların karmaşık olması dolayısı ile bir zorluk sunmaktadır. Köprü sistemleri, daha iyi bir organizasyon ve daha merkezi bir kontrol mekanizmasi gibi nedenlerle onarım planlama sistemlerine entegre edilmelidir. Bu tip sistemler, karar verme aşamasını kolaylaştırdığı gibi, sınırlı ödeneklerin daha verimli kullanılmasına da yardımcı olur. Bu çalışmada, çok nitelikli fayda teorisi (ÇNFT) ile Ege ve Marmara bölgesinde bulunan 20 köprü öncelik sıralamasına sokuldu. Bu çalışmanın amacı, ÇNFT'ine iyileştirmeler ve eklemeler yaparak hazırda varolan Karayolları köprü yönetim sistemi karar verme süreci ile karşılaştırmaktır. Varolan kriter listesi tekrar gözden geçirilerek yeni bir kriter daha eklenmiş ve Karayolları Köprü Yönetim sistemlerinde kullanılan önem sırası metodu kesin olmayan durumları daha iyi ele alması ve karar vericilerin risk tercihlerini yakalaması sebepleriyle ile ÇNFT yöntemi ile değiştirilmiştir. Bunun yanı sıra, literatürde varsayılan additif fayda bağımsızlığı sorgulanarak köprü onarım sistemleri için daha optimal sonuca ulaşmak hedeflenmiştir. Sonuçlar risk tercihlerini sorgulamanın, daha fazla ve daha farklı alanlarda uzmanlaşmış karar vericilerin varlığının ve yeni bir kriter eklemenin, aynı veri için köprü önem sırasını nasıl değiştirdiğini göstermiştir.

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LIST OF ACRONYMS/ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASTHO	American Association of State Highway and Transportation Officials
ADT	Annual Daily Traffic
AHP	Analytic Hierarchy Process
BaTMan	Swedish Bridge and Tunnel Management System
BMS	Bridge Management Systems
BrM	Bridge Management software
FHWA	The Federal Highway Administration of United States
GBMS	German Bridge Management System
IABMAS	International Association for Bridge Management and Safety
KUBA	Swiss Bridge Management System
LCCA	Life Cycle Cost Analysis
MAUT	Multi-Attribute Utility Theory
MCDM	Multiple-Criteria Decision Making Analysis
NCDOT	North Carolina Department of Transportation
NHI	National Highway Institute of United States
SGP	Spanish Management System
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UTA	Utilities Additives Me

1. INTRODUCTION

Infrastructure is an essential part of the developed world, and lack of infrastructure is a significant limitation to achieve the full economic growth of a developing country. (Kingombe, 2011) Countries that invested in infrastructure had achieved high-sustained economic growth and civil infrastructure systems are important to achieve the economic leap for the developing countries. Bridges have an important role in infrastructure systems as they let the optimal or near-optimal utilization of the geographical restrictions. Especially, bridges over the rivers and lakes and other geographical restrictions save time and resources for the users. Lengthwise, bridges are shorter than other road sections of the entire network, but they cost much higher to construct and maintain. Efficient maintenance provides good performance for the users and eliminates the risk of the bridge's physical failure, as the result of a physical failure would be catastrophic. While bridges are vulnerable and valuable infrastructure elements, they should be maintained and rehabilitated sufficiently to stop physical deterioration to progress. There are many bridges in the world that cost over billions of dollars to construct and maintain and renovate that bridges add up to the total expenditure each year. Therefore, there is a need of management and treatment system that helps to manage an inventory of bridges. Maintenance planning of the bridges lets decision-makers benefit from setting a bridge maintenance schedule with limited resources and constraints by prioritizing the bridges in the inventory. Such systems let 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 use the public fund wisely. Infrastructure objects, such as bridges, should be used in a maintenance planning system to have a better organization and controlling mechanism. These systems let the decision-making process easier and let decision-makers spend the limited public fund better.

Throughout the world, bridge management systems (BMS) are used to provide maintenance planning to the bridge inventory in question. The BMS works in a systemic and integrated method, allowing decision-makers of the respective BMS to decide the best for the selected objectives and goals. According to the IABMAS Report in 2014, there are 25 different BMS in 18 countries that have being used for over 1 million objects such as bridges, road sections and retaining walls. (Mirzaei *et al.*, 2012) Fifteen of the BMS shares the software with multiple users; so, many countries use the existing BMS of other countries instead of developing their own. In addition, most of the ownership of the BMS is country-level, either government or private organization. It is also observed that many BMS update the version annually or every 2-3 years. There is an active development of BMS each year. For the cost calculations, all the systems can handle intervention costs. However, some BMS take a step further on different subjects such as inspection cost, traffic delay cost, accident cost or environmental cost. In addition, the majority of the BMS store prediction information. They can predict changes in deterioration, effects of an intervention, optimal intervention strategies, and scheduling a work program. The decision makers used the information output to prepare budgets, set performance standards, match funding sources, and manage special transports. (Mirzaei *et al.*, 2012).

Even though BMS is used widely, they do not consider all aspects of a bridge maintenance problem, mainly social, environmental and risk factors. As bridges are valuable transportation elements, thorough maintenance planning must be implemented, and that system must include systematic performance goals and capable decision-makers from different expertise. In bridge management, there is more than just the technical engineering point of view; social, environmental and economic constraints and benefits should be analyzed. Other methods for assessing the decisions, maintenance and benefits of the bridge planning such as life-cycle cost analysis does not give a full insight of the problem due to single-objective nature of the method. 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 makes it complicated. There should be a method that considers the multi-objective nature of the bridge maintenance planning that is also reliable, basic and captures crucial criteria such as risk preferences. Therefore, multi-attribute utility theory (MAUT) is considered an alternative to maintenance planning as a multi criteria decision-making method (MCDM). MAUT describes the problem, defines objectives, and sets attributes that quantify the determined factors to the selected objectives. MAUT interrogates the uncertainty aspect of the problem by capturing the decision makers' risk preferences with gamble questions to determine the utility functions for the attributes. The utility functions are aggregated to a single multi-criteria utility function that gives a score to a bridge within its criteria to make the ranking process of the bridge inventory easier.

1.1. Aim of the Study

It is aimed to apply MAUT to a bridge maintenance problem and compare the results with a study of Turkish BMS. The mentioned study conducted a research to analyze the same set of bridges in 2014 (Masoumi, 2014). It is found from the literature search that the prioritization in bridge management systems is not fully explored. In this thesis, the attempt is to prioritize 20 bridges in Turkey at a maintenance perspective by considering the MAUT approach. Some improvements are proposed such as intriguing the additive utility independence, capturing the risk preferences with an enhanced method, sensitivity analysis to generate a better overall result for the ranking of the bridge inventory. Criteria list given in the research (Masoumi, 2014) is revisited and one more criterion that queries the accident risk factor is added and the current prioritization methodology of the research (Masoumi, 2014) is converted to MAUT approach that captures the risk preferences important for a bridge maintenance planning problem. For this study, the decisions and the risk preferences of five professionals with different expertise such as transportation specialist, engineering management specialist and structural specialist are analyzed with a questionnaire that was conducted face to face. Additive utility independence assumption of the utility theory is inquired as pointed out in the study of Kalan *et al.* (Kalan, Kurkcu and Ozbay, 2019). A sensitivity analysis was implemented to understand the weight-alternative relationship of the research better.

1.2. Thesis Organization

Outline of this thesis as follows. The multi criteria decision-making methods used in the literature for bridge maintenance problems and previous studies on MAUT are intrigued in Section 2. The theory of applying MAUT to a bridge management problem with mathematics of constructing single utility functions, trade-off among the attributes and aggregation from single utility functions to multi-attribute utility function are discussed in Section 3. Data is introduced and MAUT is systematic applied to the bridge maintenance problem in Section 4. Results are discussed in the end of the Section 4 and conclusions are given afterwards. Finally, the sensitivity analysis of the results are also given in the Section 4.

2. LITERATURE REVIEW

2.1. Bridge Management Systems

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. Fifteen of the BMS shares the software with multiple users; so, many countries use the existing BMS of other countries instead of developing of their own. Besides, most of the ownership of the BMS is country-level, either government or private organization. It is also observed that many BMS update the version annually or every 2-3 years. There is an active development of BMS each year. For the cost calculations, all the systems can handle intervention costs. However, some BMS take a step further on different subjects such as inspection cost, traffic delay cost, accident cost or environmental cost. In addition, most of the BMS store prediction information. They can predict, change of deterioration, effects of an intervention, optimal intervention strategies, and scheduling a work program. The information output is used by the decision-makers to prepare budgets, set performance standards, match funding sources, and manage special transports. (Mirzaei *et al.*, 2012) Here, some BMS used around the world are listed (Table 2.1). The 25 selected BMS are represented by the total object used in the system, country of origin, year of first version and cost information.

Table 2.1. Basic General Information of the 25 Selected Bridge Management Systems.

BMS	Country	Total Objects	First Version Year	Cost information				
				Inspection	Intervention	Traffic Delay	Accident	Environmental
AASTHOWare	USA	750908	2014		x			
ABIMS	USA	15842	1994		x			
APTBMS	Italy	1953	2004	x	x			
BaTMan	Sweden	45790	1987		x	x	x	
Bridgeman	Vietnam	4239	2010		x			
BRUTUS	Norway	20080	1995		x	x	x	x
DANBRO	Denmark	2250	1975		x			
DISK	Netherlands	5591	1985		x			
eBMS	Canada	1200	2006	x	x	x	x	x
Eirspan	Ireland	2997	2001		x			
FBMS	Finland	17065	1990		x			
GBMS	Germany	10000	N/A		x	x	x	x
GNWT	Canada	373	2002	x	x	x	x	x
KRMBS	Korea	6192	2005	x	x	x		
KUBA	Switzerland	31313	1989		x			
Lat Brutus	Latvia	1979	2002		x			
MRWA	Australia	2898	2011		x			
NSW	Australia	6143	1996		x			
OBMS	Canada	355	2008	x	x	x		x
PEI BMS	Canada	11100	2011		x	x	x	x
QBMS	Canada	5400	2010	x	x	x	x	x
RPIBMS	Japan	5018	2006		x	x		x
SGP	Spain	40045	2005		x	x		
SMOK	Poland	0	2001		x			
SZOK	Poland	33250	1997					

2.1.1. AASTHOWare

AASTHO owns AASTHO Bridge Management System. It is implemented in 2013; however, it is the continuation of the BrM/Pontis bridge management system. AASTHOWare has over 750000 objects (bridges, culverts, tunnels, marine structures, retaining structures, protection structures, etc.). AASTHOW are is the most extensive bridge management system compared with the other systems in the world. Construction data, inspection reports, intervention history, location, maximum load-carrying capacity and number of vehicles in ADT and AADT is stored in the inventory. Data is collected element-wise by the full support of AASTHO elements and user-defined elements; the damages and defects are quantified according to the structural unit and parent element. Structure level inspections are visual, but other destructive or non-destructive test results are included. The multi-objective engine of BrM assesses load-carrying capacity, safety and risks. Intervention planning is included in element level, structure level and multiple structures level as both predefined and user-selected schedules. AASTHOWare includes intervention cost, accident costs, traffic delay cost and other cost types. Prediction models such as deterioration models, effects of an intervention, optimal intervention strategies and work programs are embedded in AASTHOWare. The output could be used for budget preparation, setting performance standards, matching funding sources and managing special transports. FHWA and NHI provide education and certification for users and inspectors. (Mirzaei *et al.*, 2012)

2.1.2. BaTMan

Bridge and Tunnel Management System (BaTMan) is owned by the Swedish Transport Administration that has been implemented in 1987. It stores 1090 tunnels, 33000 bridges, 1700 retaining walls, 370 quays and 4200 other objects. The bridge management system BaTMan has an inventory that stores construction data (material, length, elements, drawings etc.), inspection reports, intervention history, location, maximum load-carrying capacity and number of vehicles per day. BaTMan data collection includes element level inspection with visual and some other non-destructive tests with a maximum interval of 6-years. Structure level data is aggregated from the element level inspections. The physical condition of the elements is rated 0-3 and physical condition of the overall structure is derived from the element-based inspection. BaTMan defines user-defined interventions proposed by inspectors for the existing defects; however, predefined standard interventions do not exist within the system. The software takes into account the costs of inspection, intervention, traffic delay, and planning and designing interventions. Accident costs and environmental costs are not included. BaTMan has no models for deterioration in the object level, but as a strategic level, simple models are proposed for long term planning module. Optimal intervention strategies are planned as up to 20 years; operation, maintenance, improvement and risk reduction are included. BaTMan prepares the budget, sets performance standards, matches funding sources and manages special transports. Swedish Transport Administration organizes yearly training courses for the inspector candidates and a theoretical examination is demanded from the inspector candidates. (Mirzaei *et al.*, 2012)

2.1.3. SGP

Spanish Management System (SGP) is owned by 'Ministerio de Fomento', first used in 2005. It has 24534 bridges and 13397 culvers in the system. [3] SGP holds an inventory database that keeps construction data, inspection reports, intervention history, locations of the objects, maximum load-carrying capacity and number of vehicles per day with heavy vehicle percentage included. SGP collects the data in element level by visual inspections, auxiliary means inspections and laboratory testing. The defects are quantified by damage indexes, damage measurements, damage descriptions, plans and graphical information. Elements have an index with an interval 0-100 based on the damage level and the damages are assessed with intensity, extension and evolution factors. Element based damages are used as an input to a decision algorithm to measure the structure index, a score between 0-100 to assess the overall condition of the bridge. SGP prioritizes a set of bridges with this index as a higher structure index has higher priority. SGP has a repair recommendation database; so, each damage type is listed in the catalogs of the SGP. For the structure level of intervention, SGP priorities the repairs according to the element damage state for a structure or a set of structures. SGP includes a cost calculation of intervention costs, traffic delay costs, indirect user costs and methods access costs. Inspection costs and accident costs are not included in SGP. Prediction information is not implemented in SGP but the inspectors insert an evolution index for deterioration. SGP uses the output for budget preparation, setting performance standards, matching funding sources, managing special transports and performing custom inquiries. SGP uses the funds available as input after that repairs and maintenance done with the funds are calculated as an output with a prioritizing algorithm. SGP has training courses for the inspectors and inspectors are expected to pass a test for the software's proficiency. In addition, it includes a manual for the users. (Mirzaei *et al.*, 2012)

2.1.4. KUBA

Swiss Bridge Management System is owned by the Swiss Federal Road Office that was implemented in 1989. 12574 bridges, 5496 culverts, 1236 tunnels, 10139 retaining structures, 1416 protection structures and various other structures. (Mirzaei *et al.*, 2012) Inventory information includes construction data, modeled as a hierarchical tree that includes construction type, user materials, construction method, dimensions, and quantity. Other than the construction data, there are inspection reports, intervention history, location and maximum loading capacity in the inventory. Visual inspections, damage description from the catalog, photos and damage plans are stored as element-based data. KUBA does not differentiate element-based data and structure level data. The physical condition of the elements is rated 1-5 and individual damages are grouped if affected by the same deterioration. KUBA has a predefined standard intervention based on the state of the structure and damage process but not on time. This also applies for the structure level and multiple structure level interventions. KUBA includes intervention costs, set-up costs, traffic control costs, design costs and costs of detailed inspections; however, inspection costs, accident costs, traffic delay costs and indirect user costs are not listed. KUBA uses a model by Markov chains for the physical deterioration and effects of the interventions are modeled. The structures' optimum strategy is based on the minimum life-cycle cost, and work programs are set based on the strategy for up to 25 years. KUBA is used for budget preparation and managing special transports and setting performance standards are under development process. Swiss Federal Road Office educates inspectors and users. (Mirzaei *et al.*, 2012)

2.1.5. GBMS

German Bridge Management System is owned by the German Federal Ministry of Transport, has nearly 10000 bridges in its inventory. (Mirzaei *et al.*, 2012) They hold a database that stores construction data, inspection reports, intervention history, and the bridge's location. They obtain the data with visual inspection by professionals at hand-near proximity to the damages' photos and plans. GBMS obtain the structure level data from the aggregation of the element-based data that was measured with a destructive and non-destructive inspection. For the cost calculation, GBMS includes intervention cost, accident costs, traffic delay costs, indirect user costs, scaffolding costs and traffic control costs. However, inspection costs are not included in GBMS. GBMS uses deterioration models to predict the changes in physical condition and performance.

In addition, it has optimal intervention strategies such as cost-benefit analysis in object level and financial or quality scenarios at the network level. GBMS plots 6-year work programs that plan actions to be taken over six year's period. Costs are used for budget planning and decision making from the output of financial and quality scenarios. 2-day basis training is offered to the users and the road administrations give further education. (Mirzaei *et al.*, 2012)

2.2. Multi-Criteria Decision Making

The base of the decision analysis is performance measurements, goals and objectives. Since there are many performance measurements with multiple objectives, it is essential to decide the alternatives with the trade-offs to optimize the system with desired goals and objectives. Multiple-Criteria Decision Making Analysis (MCDM) is commonly used in many study areas such as mathematics, decision analysis, information systems and economics. It is an active subject of research since the 1970s. Crawford *et al.* (1978). Performed a multi-objective decision analysis, selecting performance goals like tower size and the number of sub conductors. MCDM has set a solution to complex, uncertain and multiple objective problems with a logical and systematic approach. MCDM deals with harder and more complex problems thanks to the advancement of technology. MCDM methods applied for many domains, and it was fast during the 1990s. For example, many of the e-commerce companies used the MCDM practices for their businesses (Köksalan, Wallenius and Zionts, 2011a). There were many attributes for the open auctions in those websites such as quality, price, delivery and the auctions are optimized for the owners, users and the business with the MCDM methods. This phenomenon has an effect of some degree to the development of the e-commerce sector. Another important domain is engineering. In the 1990s, MCDM methods became a current practice for many fields of engineering such as aircraft industry, environmental decision-making, forest management and nuclear energy sector (Köksalan, Wallenius and Zionts, 2011a).

2.2.1. MCDM Methods

The classification of the Unique Criterion of Synthesis Methods, Outranking Methods and Interactive Methods are commonly accepted in the literature. (French and Roy, 1997; Belton *et al.*, 2002) Unique Criterion of Synthesis Method works with an aggregation function that is used for the decision-making preferences.

Comparing and testing alternative systems are simple. Each alternative is listed with a weighted aggregation method according to the decision maker's preferences. Known examples are TOPSIS, MAVT, UTA, SMART, MAUT, AHP, and EVAMIX. (Guitouni and Martel, 1998) Outranking approach uses a model with three compartments: a set of alternatives, a consistent family of criteria and a performance table. It eliminates alternatives that are outperforming. Known examples are ELECTRE, PROMETHEE, MELCHIOR and ORESTE. (Guitouni and Martel, 1998) Interactive Method has a mathematical base that the decision-maker could set the objectives with the set of values. Known examples are goal programming and Pareto front. (Guitouni and Martel, 1998; Allah Bukhsh *et al.*, 2019) Zaharah *et al.* argued that for the multi-faceted nature of maintenance optimization problems, synthesis methods of MCDM are proven the most promising method. (Allah Bukhsh *et al.*, 2019) Analytic Hierarchy Process advanced the decision-making during the 1990s and it became the most widely used tool in practice (Köksalan, Wallenius and Zionts, 2011b). AHP converts performance goals into a weighted set of values and it decomposes the matrix into pair-wise comparison matrices to compare, and at the end, it combines all of those matrices for a rating to compare the alternatives. (Saaty, 1977, 1987; Guitouni and Martel, 1998) TOPSIS works on an aggregation function that defines an ideal and negative-ideal solution. The alternatives are selected closest to the ideal solution and farthest to the negative-ideal solution (Hwang and Yoon, 1981; Guitouni and Martel, 1998). MAVT obtains the aggregated values with partial value functions to establish a value function (Guitouni and Martel, 1998).

2.2.1.1. Analytic Hierarchy Progress (AHP). Analytic hierarchy progress is a method of MCDM that makes pair-wise comparison of two elements based on the professional judgements of advantages and disadvantages of experts. It is preferred commonly by ease of its use for weighting coefficients. These coefficients represent the preference and decision of the expert. Saaty (1987) discusses that the special concern of the AHP is 'departure from consistency' as the dependence between the groups of elements is important. Because of its hierarchical structure, decision making with many elements are easy to construct. The disadvantage of this MCDM model is there might be problems of independency between the criteria. The method of pair-wise comparison limits the analysis, as it does not allow the comparison of an element to the complete set of groups. Therefore, consistency rating that ensures the reliability of the overall results are important since there could be some inconsistencies in ranking and judgement. For example, for the criteria A, B and C, one interviewee might say A is more important than B and B is more important than C and logically, A should be more important than B but AHP allows an option for the interviewee to make a possible error. Decision makers are asked to some questionnaire questions to compare the criteria verbally to assess the pair-wise importance. The decision makers may clarify the level of importance with nine unique response such as extremely more important, strongly more important, moderately more important, slightly more important and equally more important. They can also specify lesser importance with the same scale of importance. After that, the pair-wise comparisons are plotted to construct a matrix to calculate the relative weights. AHP is used in performance-type problems, resource management, corporate strategies, political strategy and planning (Velasquez and Hester, 2013).

2.2.1.2. Case-Based Reasoning (CBR). CBR is a method of MCDM that retrieves data and information from other cases similar to the problem in question. A MCDM solution is suggested from the data that compares the most relevant cases to the problem. It provides a basic solution, as there is no extra effort to gain additional information on the problem where it could take a lot of time and resources to handle the data especially if it is big in quantity. In addition, there is an existing database which requires no care or maintenance, and it improves over time thanks to the newly gained cases to the database. It is also easy to familiarize into different settings thus; it is easy to make changes on it. However, there are some major disadvantages of the CBR. There may be inconsistencies in the data, but CBR is not very sensitive to the inconsistencies as there may be out-of-date cases or there could be special cases under abnormal situations. Therefore, sometimes even if the cases are similar, CBR might give out inaccurate results because of the inconsistencies of the original case. CBR is used when there are extensive amount of cases on a specific subject such as comparison of businesses, insurance, medicine and engineering designs (Velasquez and Hester, 2013).

2.2.1.3. Data Envelopment Analysis (DEA). DEA is a MCDM method that uses linear programming techniques for the multiple objectives of decision-making. It processes the efficiency of the alternative cases, and it makes comparison to the case in question. DEA makes pair-wise comparison of efficiency against all the alternatives for the data, whereas the range of the efficiency is 0-1. Major advantage of the DEA is that it takes care of multiple inputs and outputs at the same time and it quantifies the efficiency. Thanks to this quality of the DEA, it is possible to discover pair-wise relationships between the alternatives that is not observed on other methods of MCDM. Wang *et al.* (2005) argue that DEA does not compute the data that is not precise so it makes the assumption of all input and output data is known which is not true in real-world situations. DEA is preferred in agriculture, medical, road safety, economical, utilities, retail and business problems where comparison of the efficiencies would be useful to analyze (Velasquez and Hester, 2013).

2.2.1.4. Fuzzy Set Theory. Fuzzy set theory is a version of the classical set theory, which is used for solving problems with imprecise data (Rajaoarisoa, Balmat and M'Sirdi, 2011). When there is multiple objective decision-making process, fuzzy set theory removes the ambiguity of the alternatives and makes the decision-making process easier. It has a wide range of utilization applies to many domains. Especially in the engineering field, fuzzy set theory such as control systems, image processing, robotics, power engineering (Velasquez and Hester, 2013).

2.2.1.5. Simple Multi-Attribute Rating Technique (SMART). SMART is a multi- attribute decision making method that converts weights of the attributes to utility values for ranking and comparing the results. It is a very simple process as it allows implementing multi-attribute utility theory for any weight calculation method with much less effort. The method uses a linear addition model that gives a value for each attribute as an overall score of performance. Then, the calculated weights of each alternative are calculated to obtain relative performance score for each criterion. In multi-attribute utility theory, relative scales of the attributes are determined from the maximum and minimum value of the attribute in question internally, but in SMART, it is calculated with a mathematical formula that determines a scale for all the attributes. SMART is used in construction, transportation, environmental and military problems. (Velasquez and Hester, 2013) It is good when there is not much data to work on.

2.2.1.6. Goal Programming (GP). Goal programming is a multi-attribute decision making method that optimize multiple objectives by attaining goals to the objectives. The weights of the variables are determined, and the objective is solved with a single deviation sum of the weights. It can be implemented into problems that have many variables and objectives. GP excels for extensive projects over other MCDM methods; however, it has some difficulties attaining weights to the attributes. This problem can be solved by implementing a weight measuring method such as analytical hierarchy process to have better results for the attribute coefficients. GP is used for medical industry, production planning, scheduling, and other management problems (Velasquez and Hester, 2013).

2.2.1.7. PROMETHEE. Preference ranking organization method for enrichment evaluation is a method of ranking multiple criteria. The selection can be made from the alternatives of the multiple objectives in PROMETHEE. Relative weighting of the attributes is determined and ranked by the prioritization function of the method. It is a popular method for multiple-criteria decision making since 1980s. PROMETHEE is used in environmental management, hydrology, water management and other types of engineering and finance managements (Velasquez and Hester, 2013).

2.2.1.8. TOPSIS. Technique for Order Preferences by Similarity to Ideal Solutions TOPSIS is a multi-criteria decision-making method that uses multi-dimensional computing to compare the alternatives to find a solution that is the most similar to the ideal solution and most different from the non-ideal solution. TOPSIS is user friendly, and it is easily implemented into a problem. Thus, TOPSIS is a simple MCDM method compared to other alternative methods as the number of attributes does not change the computation process whereas in the other MCDM methods such as AHP, the number of the alternatives changes the process of the computation significantly. TOPSIS is used in logistics, design, engineering management systems, business and marketing (Velasquez and Hester, 2013). The most important advantage of the TOPSIS is its simplicity over its alternatives.

2.3. Multi-Attribute Utility Theory

MAUT obtains the aggregated values that are obtained from the partial utility functions to create a utility function (Bunn, 1984). MAUT is extensively used in the literature and it is about optimizing a function that uses aggregation for every point of view. Keeney used multi-attribute utility theory on energy policy with utility functions to examine and decide different energy policies for decision-makers in the 1970s. (Keeney, 1977; Keeney and Raiffa, 1979) Keeney and Raiffa called this function utility function U that the decision-maker needs to construct. (Keeney and Sicherman, 1976) The utility function U calculate the utility of the alternatives by evaluating the global utility of the existing alternatives using the performance measures and goals set by the decision-maker. Each alternative gets a utility score, and the decision-maker may create a ranking between the alternatives. Different marginal utility functions can be selected as step, logarithmic, exponential, linear and quadratic to control the global utility. (‘Multi-attribute utility theory’, 2013) However, LiCalzi and Sorato argues that resulting utility functions can only have four shapes: Concave, convex, S-shaped and reverse S-shaped. (Licalzi and Sorato, 2006) It is used in many fields such as health (Brennan and Anthony, 2000), information science (Kabassi and Virvou, 2006; ‘Multi-attribute utility theory’, 2013), water resource management. (Raju and Vasan, 2007) Garmabaki *et al.* (2016). Studied maintenance optimization using MAUT to develop an optimal inspection program. They established a methodology with tools for maintenance planning using performance goals such as reliability, availability, and risk. De Almeida (2012) and De Almida *et al.* (2015). State that MAUT applies to the maintenance problems such as maintenance strategy selection, design selection, condition-based maintenance, risk analysis and prioritization of failures. 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%) (De Almeida, Ferreira and Cavalcante, 2015). Zietsman made research on sustainable transportation decision making on transportation programs and projects, comparing Tshwane, South Africa and Houston, Texas and showed that MAUT can be used as a decision-making tool for transportation corridors (Zietsman, Rilett and Kim, 2006). 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.

Whelan *et al.* argue that cost prediction models used in bridge management systems (BMS) in the North Carolina Department of Transportation (NCDOT) uses only the roadway system classification and deck area of the bridge as a predictor variable and that situation estimated the replacement cost of the existing bridge incorrectly. In addition, the current cost estimating approach used in the BMS is poor since they found out that coefficient of determination is negative and mean and standard deviation of the errors are large. They recommend that unit construction cost to be calculated with an equation derived from generalized linear regression (Whelan, 2019).

Montazeri and Touran propose a reliability-based decision-making framework for scheduled maintenance of deteriorating bridges while optimizing structural performance with the maintenance cost over the structure's life cycle using Pareto Frontier MCDM method. Therefore, decision-makers could set an optimal maintenance schedule for the bridges using Montazeri and Touran's framework. They obtained their results by applying their methodology to an existing bridge, and they demonstrated the efficiency and advantages of their procedure (Montazeri and Touran, 2018).

Cappello *et al.* argue that structural health monitoring (SHM) could be used to obtain information about the existing bridge's state and make better decision-making for the bridge management process. They implemented expected utility theory as a quantitative analytical framework that allows to the identification of the monetarily best decisions using the SHM as the guide to decision process. The study includes two steps. In the first step, the solution is formulated with a single-stage decision process that lets the decision maker to have only one option. In the second step, the authors have formulated the solution with a multi-stage decision process that lets decision makers to take multiple actions over the time (Cappello, Zonta and Glisic, 2016).

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. They claim that those uncertainties and their costs should be implemented in analysis, prediction, optimization and decision-making. The authors also argue the effects of climate change on life-cycle performance, such as the increased soil erosion rates and soil moisture levels' effect on the foundation of the bridge networks (Frangopol, Dong and Sabatino, 2017).

3. METHODOLOGY

Various methods are used for the network-level bridge maintenance problem. 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. Another advantage of MAUT is that choices of multiple decision-makers can be determined so that the results reflect the judgments of experts of different fields, thus making a more democratic decision-making process. Preference of the decision makers is constructed with regarding the value functions attained as utility. There are 3 major parts of constructing a multi-attribute utility function. These are weighting, scaling and amalgamation.

While assessing and constructing the single utility functions, instead of using a single method, both mid-value splitting method and gamble method was combined and implemented. That implementation captures the risk preference of the decision-makers better because three different gamble scenarios was considered constructing the utility function rather than a single gamble. Therefore, we calculated a more accurate data fit with more variable to construct the single utility functions.

Saaty defines the Analytic Hierarchy Process (AHP) as a general theory of measurement that is used to derive ratio scales from paired comparisons (Saaty, 1987). NCHRP Report for multi-objective optimization for bridge management systems distinguishes AHP as a feasible method to develop relative weights for bridge management problems (Thompson *et al.*, 2006). These paired comparisons measure the relative importance of each criterion with another.

In the development of the multi-criteria utility function, two different methods are used to aggregate the single utility functions into a multi-attribute utility function: additive and multiplicative forms. Commonly, additive utility independence that aggregates the weight of the attributes additively is assumed in the literature. However, that assumption was not made in this research and the decision makers were asked a gamble to make a test to determine the existence of the additive utility independence. Additive utility independence was not found, and multiplicative method was implemented for the analysis.

3.1. Utility Functions

Keeney and Raiffa defined that utility function captures decision-maker's preferences regarding selected attribute's individual attitude towards risk for each attribute (Keeney and Raiffa, 1993). It is like value functions that assigns a value for each criterion, but it differs from the value function with 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 $X_1, X_2, X_3, ..., X_n$ are defined. Then, we can argue that xi defines a specific level of Xi and we can describe the utility function as u(x) = u($X_1, X_2, X_3, ..., X_n$) for n attributes.

Value functions gets more complex in the multidimensionality situations; therefore, if possible, reducing the dimensionality of the value function is essential. After that, the obtained value functions are converted to single criterion utility functions under the assumption of mutual preferential independency, which intrigues the linearity of the function. For example, for the set of x and y, if (x_1, y_0) is preferred over (x_2, y_0), then (x_1, y) must be preferable to (x_2, y) for all y-values.

3.2. Creating Single Utility Functions

Like value functions, utility functions describe a value from zero to one for each attribute. However, the risk preferences are captured for the utility function, which is not included in value functions. Gamble method and mid-value splitting method are implemented to create single utility functions.

3.2.1. Gamble Method

Gamble method is a method to create a single-value utility function where the decision makers are asked a gamble that compares a certain situation with a situation of risk-taking. Attributes that minimizes and maximizes the selected objectives for the problem are selected and quantified and then, maximum and minimum values of the attributes are selected as a lottery where with 50% probability, the decision maker would obtain the best value and with 50% probability, the decision maker would obtain the worst value for the selected attribute. Since taking this gamble is risky, a certain situation is proposed to the decision makers to give up that risky gamble. For example, in an attribute range of 0-1 situation, with 50% chance the decision maker would obtain 1 (best value) but if they lose the gamble, they will get 0 (worst value). Therefore, a value of 0.2 is proposed to the decision makers to give up that risky gamble. If the decision maker in question does not take unnecessary risks, he/she might accept the value of 0.2 since getting the worst value would be catastrophic. However, if the decision maker has a risk-taking characteristic, he/she would not be content with the value of 0.2 since he/she might think he could get the best value.

Gamble method demands two different situations where;
Situation 1: you will select a certain attribute value
Situation 2: or you will play the lottery of the:
50%, the maximum value of the of the attribute value is obtained
50%, the minimum value of the of the attribute value is obtained

Therefore, it is a method that measures risk attitudes of decision makers towards multiple attributes which is very helpful for problems that involve uncertainty situations such as bridge maintenance problems.

3.2.2. Mid-Value Splitting Method

Mid-value splitting method is another method to create single-value utility functions. For the selected attributes, three questions are asked to decision makers to determine the improvement of the selected attribute that would make them equally content with the advance. X_{50}, X_{25} and X_{75} are determined from those three questions where Xn represents a value of attribute that makes the decision maker equally content with the jump from minimum attribute value to X_n and X_n to maximum attribute value. Finally, X_{25}, X_{50}, X_{75}, maximum attribute value and minimum attribute value are plotted to a graph that is in a scale of 0-100 utility values. The desired single utility function could be implemented to those five points.

3.2.3. Single Utility Functions

In this research, both gamble method and mid-value splitting methods are implemented to measure the risk preferences of the decision makers. We believe that implementing both techniques improved the single utility function as we obtained 3 point on the utility function thanks to the mid-value splitting method. We would obtain only 1 point on the utility function if we just used the gamble method.

A certain attribute value is asked for a decision-maker to be indifferent to Situation 1 and 2. Intriguing maximum and minimum attribute values with 50% gamble rate would give X_{50} utility value. Gamble method is applied two more times from X_{50} to maximum and X50 to minimum to attain X_{25} and X_{75} utility values. The framework of the gamble method to obtain X_{25}, X_{50} and X_{75} values are shown in Figure 3.1.

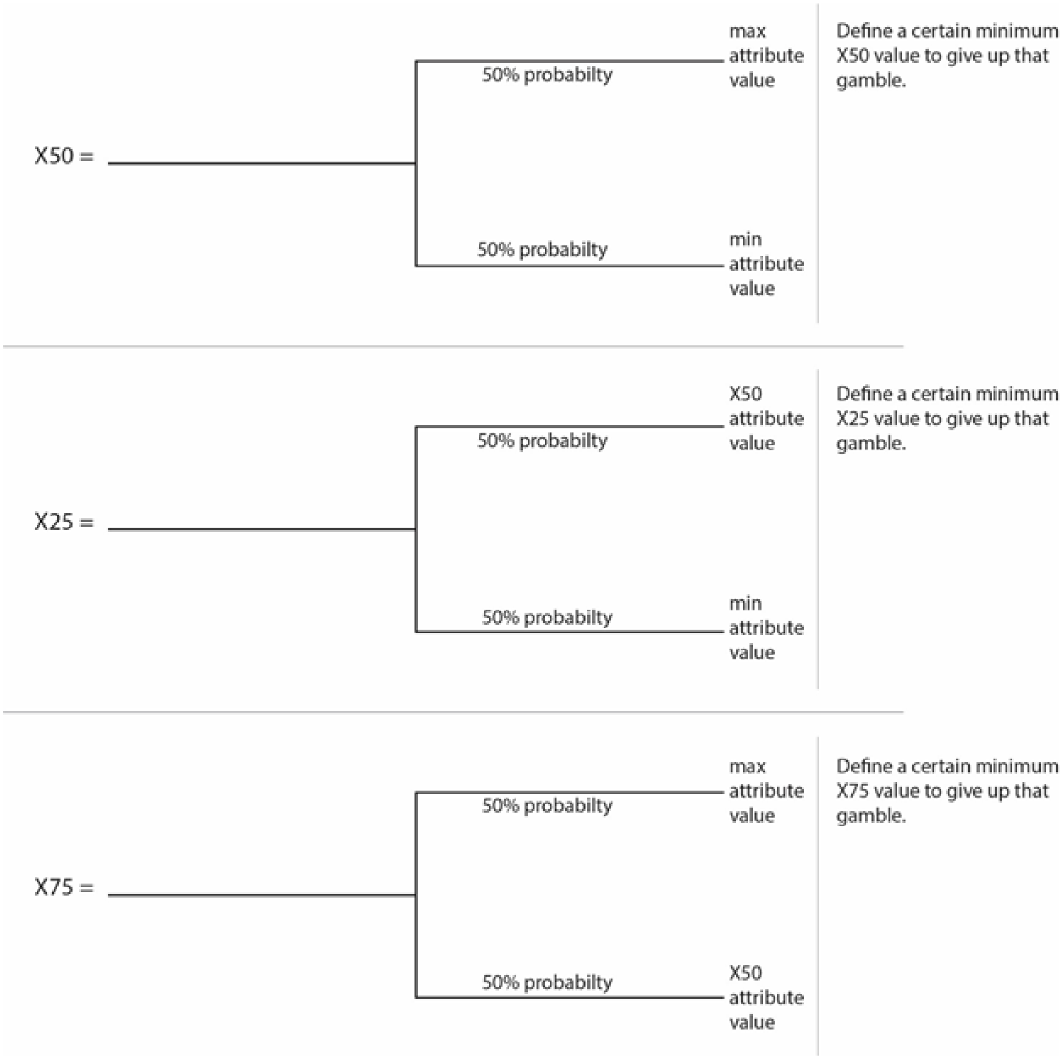


Figure 3.1. Gamble Method Setup to obtain X_{25}, X_{50}, X_{75} attribute values.

From the results, five attribute values for $X_0, X_{25}, X_{50}, X_{75}, X_{100}$ can be obtained. Risk preferences of the decision-makers can be further observed by plotting each attribute value for the specified utility values, the utility function can be fitted according to the judgements of each decision-makers. Negative exponential growth model is used for this research to represent the risk-taking behavior, specified in Equation (3.1).

$$u\left(x\right) = A - Bxe^{-x/c} \tag{3.1}$$

The data is fitted to the decision-maker's judgements for $X_{25}X_{50}$ and X_{75} 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 that minimize the sum of the square of residuals. Therefore, obtained A. B and C values are plugged in to the Equation (3.1) that indicates the single utility function for the selected attribute.

Three different risk preferences can be observed from the single utility functions. Concave shape shows risk avoiding, linear shape shows neutral and convex shape indicates risk-taking attitude of the decision makers.

3.3. Relative Weights

In the literature of MAUT, direct weighting is used commonly to develop relative weights for the attributes. Three steps of direct weighting are ranking the attributes, categorizing the attributes with the similar qualities according to the corresponding objectives, and finally allocating points. In the literature of bridge maintenance management, 100 points among the criteria is allocated according to the importance given to the attribute in question. (Thompson *et al.*, 2006) Then, the allocated points are normalized and therefore some of the direct weight of all attributes is equal to 1. In addition, a regression analysis could be conducted to the allocated points and the relative weights could be calculated from that analysis. Direct weighting is simple, but it does not test the preferences of the decision-makers precisely as other weighting methods because of lack of conflicts between the attributes.

Therefore, analytic hierarchy process was implemented. Analytic hierarchy progress is a method of MCDM that makes pair-wise comparison of two elements based on the professional judgements of advantages and disadvantages of experts. It is preferred commonly by 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. Because of 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 research was applied for this study to quantify the verbal responses to corresponding values as shown in Table 3.1 (Saaty, 1987).

Table 3.1. Saaty's Fundamental Scale of Importance and the Corresponding Values.

VERBAL RESPONSES	**CORRESPONDING VALUES**
X extremely more important than Y	9
X strongly more important than Y	7
X moderately more important than Y	5
X slightly more important than Y	3
X and Y equally important	1
Y slightly more important than X	1/3
Y moderately more important than X	1/5
Y strongly more important than X	1/7
Y extremely more important than X	1/9

Numerical pair-wise comparisons are plotted to construct a matrix that indicates 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 (3.2).

$$A = \begin{pmatrix} 1 & A_{12} & \dots & A_{1n} \\ A_{21} & 1 & \dots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \dots & 1 \end{pmatrix} \tag{3.2}$$

The main diagonal of the AHP matrix consist of 1's such as $A_{11}, A_{22}, ..., A_{nn} = 1$ 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 A_{12}= 9, A_{21} must be 1/9 because A_{12} responds to the pair-wise importance of X to Y and A_{21} responds to the pair-wise importance of Y to X in that case. Consistency is an important factor of an AHP problem because the results of the pair-wise comparisons must be consistent in the overall matrix and therefore, the consistency is calculated from the eigenvalue solution for the weights shown in Equation (3.3).

$$A'w' = \lambda_{max}w' \tag{3.3}$$

where λ_{max} is the largest eigenvalue of A'. Consistency Index (CI) of the matrix is given with the Equation (3.4) for n attribute AHP process.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.4}$$

Average random consistency index (RI) is derived by Saaty from a sample of 500 randomly generated matrix (Saaty, 1987). Comparing CI with RI would give out the consistency rating of the AHP problem. Saaty argues that consistency rating smaller than 10% is acceptable since Saaty discusses that inconsistency is important for letting new knowledge to change preference order (Saaty, 1987).

3.4. Aggregating Single Utility Functions

MAUT models are created to represent multi-attribute decision-making problems; the multi-faceted nature of the problem makes it difficult to create a utility function that represents the problem. Therefore, single utility functions are created from each attribute and it is aggregated to obtain the overall utility function. Keeney and Raiffa described three forms of independence that must be considered for the aggregation process. (Keeney and Raiffa, 1993) The elicitation flowchart is constructed by Farmer to determine the nature of the multi-attribute utility function by testing the independence among the attribute values shown in Figure 3.2 (Farmer, 1987). Keeney and Raiffa defined three independences for the amalgamation process of the single utility functions. (Keeney and Raiffa, 1993) These independencies are:

- Preferential Independence
- Utility Independence
- Additive Independence

Preferential independence is having the same preferential order for an attribute when the values of other attributes are changed. For instance, we can compare the value of the attribute X for (X, Y, Z) attribute set. If the preference order of X changes with different values of Y and Z for the decision maker, there is no preferential independence. However, if the decision maker is asked for a preference order for fixed values of X, Y and Z and he/she gives the same preference order for changed values of X, Y and Z, preferential independence exist for the attribute set of (X, Y, Z).

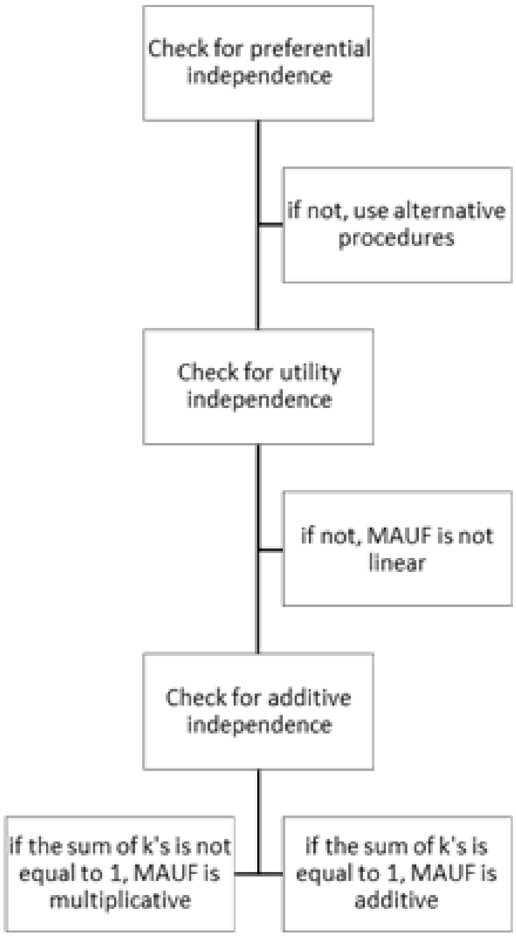


Figure 3.2. Attribute independence algorithm to define the nature of the MAUF.

Utility independence is having the same utility value for an attribute for different values of other attributes. For instance, attribute set of (X, Y, Z) is selected and gamble method is applied to determine X50 which gives the 50% utility for the selected X attribute value. If the result of the gamble method is 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.

Additive independence intrigues if the amalgamation method aggregates the single utility functions additively or multiplicatively. In the multiplicative case, the relationships between the single utility functions are added to the aggregation process. For example, for 3 utility functions A, B and C, the additive amalgamation only aggregates the A, B and C functions just like an addition. But in the multiplicative amalgamation, A, B and C function are aggregated with the effects of A-B, B-C, A-C and A-B-C. The test of AI is made by the gamble shown in the Figure 3.2. Decision makers are 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 $w_1 > w_2 > w_3 > ... > w_n$. Keeney defined the p-value as k_1 and other k values for $w_2, w_3 ..., w_n$ is derived from the ratio of k_1/w_1. The calculated values of $k_1, k_2, ..., k_n$ are summed up and if, the sum of the k-values (Equation (3.5)) is equal to 1, the utility function is additive if not, the utility function is multiplicative (Equation (3.6)). Relative weights for n attributes can be calculated with AHP or direct weighting method.

$$if\ k = \sum_{i=1}^{n} k_i = 1, additive\ independence\ exist \tag{3.5}$$

$$if\ k = \sum_{i=1}^{n} k_i \neq 1, additive\ independence\ does\ not\ exist \tag{3.6}$$

For the additive utility function, multi-attribute utility function is aggregated from the single utility function with Equation (3.7):

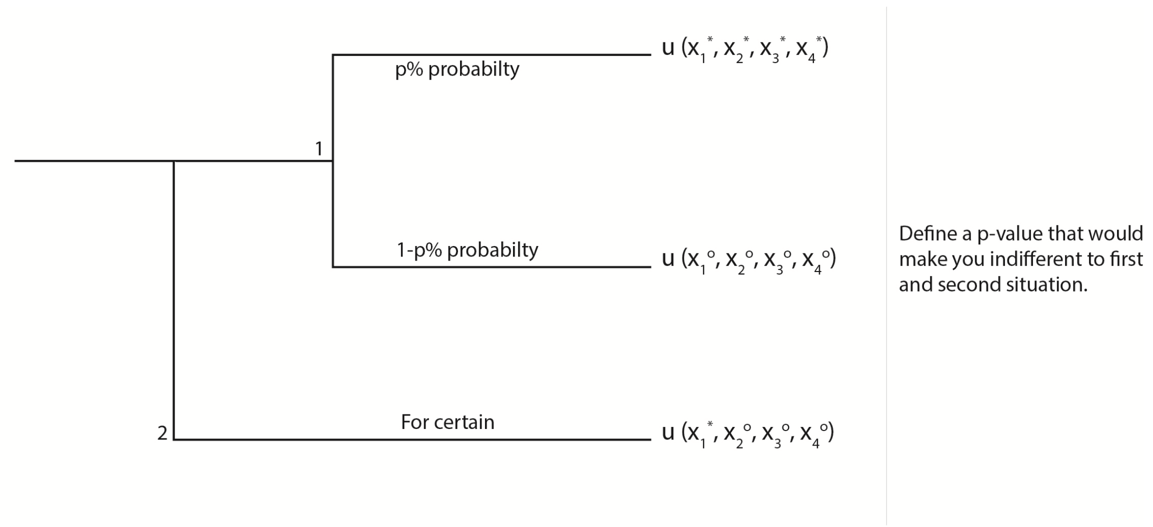
$$U = \sum_{i=1}^{n} k_i u_i \tag{3.7}$$

For the multiplicative utility function, multi attribute utility function is aggregated from the single utility function with the Equation (3.8),

$$\begin{aligned} U = &\sum_{i=1}^{n} k_i u_i + k \sum_{i=1}^{n} k_i k_j u_i u_j + k^2 \sum_{i=1}^{n} k_i k_j k_k u_i u_j u_k \\ &+ \ldots + k^{n-1} k_i k_j \ldots k_n u_i u_j \ldots u_n \end{aligned} \tag{3.8}$$

where $j > i$ and $j > k$, and k is calculated with Equation (3.9):

$$k + 1 = \prod_{i=1}^{n} \left[k \left(k_i u_i \right) \right] + 1 \tag{3.9}$$



Note: x*,represents the best utility value for the attribute x and x° represents the worst attribute value for the attribute x.

Figure 3.3. Gamble question to determine P-value.

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

3.5. Questionnaire

Twenty bridges from Western Turkey are need in repair with constraints such as limited budget, available network and safety. Those bridges will be analyzed to be put in a prioritization order as the first priority needs the utmost maintenance rank and the last one needs the less. It is worth mentioning that bridges have relatively high truck ratio as the bridges are in the industrially developed provinces of Turkey and nearly all the bridges are located in rural freeways.

Attributes are defined listed as:

(i) Importance Factor: 25000 AADT will give maximum utility as there are a lot of users of the bridge and we would like to maintain a bridge that is used by many people throughout the day. 1000 AADT will give minimum utility as that bridge is not preferred by many users so, we would not want to rush maintaining a bridge that was not used frequently.

(ii) Bridge Condition Rating: Bridge condition rating in Turkey ranges from 1 to 4. 1 represents the excellent condition and 4 represents the worst condition. The bridges chosen for this research are generally in good condition so, the range is determined as 1.7 to 1.1. Bridge condition rating of 1 is the excellent condition and 1.1 is near excellent so, it is not logical to maintain a bridge that is in near excellent condition so, we would get the minimum utility. Whereas a bridge with a bridge condition rating 1.7 needs maintenance as users might experience inconvenience while traversing the bridge. Therefore, maintaining a bridge with a worse condition would give us a better utility.

(iii) Cost-Effectiveness Factor: Cost is an important factor, as budget is a major constraint in lots of projects. We will not get much utility if we pay an enormous amount of money. If we can get a lot of work done with a small amount of money, we would be happy. Therefore, if we pay \$1 for each m2 of maintenance, we will get the maximum utility and if we pay \$15 for each m2, we would get the minimum utility.

(iv) Work-zone Safety Factor: Work-zone safety factor is calculated by the ratio of the desired roadway and shoulder length to design roadway and shoulder length. For the ratio >1, we have more than enough space to accommodate workers to work safely. As the ratio goes down to 0.65 which is the minimum acceptable design according to AASTHO Roadway Design, we need to take extra precautions maybe stop the traffic to let the work done without the risk of accident and that means additional cost and workhours for the maintenance project. Therefore, WSF <0.65 will give us minimum utility as we don't want to make additional cost to ensure the work-zone safety and we don't want any accident risk and WSF>1 will give us the maximum utility as the design is sufficient according to AASTHO Guidelines.

Where importance factor measures the relative importance of the bridge in the overall highway network based on AADT, bridge condition rating measures the overall physical condition based on the condition of the individual elements. Cost effectiveness factor measures the cost effectiveness of the maintenance work.

The objectives of the application of MAUT are:

(i) Maximize Importance Factor
(ii) Maximize Bridge Condition Rating
(iii) Minimize Cost-Effectiveness Factor
(iv) Maximize Work-zone Safety Factor

To create the utility function for the attributes, mid-value splitting method and gamble method is used together to represent the decision maker's risk preferences better. Utility weights such as X-25, X-50, X-75 will be determined where X-50 represents a value such that the decision maker is equally delighted with the improvement from 0 to X-50 and the improvement from X-50 to X-max.

For example, let us imagine a situation where we would like to buy a house and we would like to live somewhere near a good school where our child goes. The available range of distance of the house we would consider is from 0.5 km to 50 km. Naturally, we would like to live somewhere close to the school if it is the only attribute and that would give us the maximum utility. No one would like to reside 50 km away from the school if that is the only attribute and that would give the minimum utility. In order to determine the X_{50} that is the 50 utility on a range of 0-100, we would ask the decision maker to make a gamble where,

Situation 1: You will select the housing with that certain value of km away from the school Situation 2: or you will play the lottery of the:

50%, you will live in a house 0.5 km away from the school
50%, you will live in a house 50 km away from the school
Question: How many kilometers away from the school are you willing to reside for not taking the gamble?

We ask this question to determine the risk preference of the decision maker. A risk-taking decision maker might answer this question as 10 kilometers because residing 0.5 km away from the school is very attractive for the decision maker. He/she does not accept 15 or 20 km away from the school because he/she thinks, "I would like to live in a house 0.5 km away from the school so much that I'm willing to take the risk". On the contrary, a risk avoiding decision maker might answer this question as 40 kilometers because residing 50 km away from the school is repulsive for the decision maker. He/she does not accept 30 or 35 km away from the school because he/she thinks, "I do have the fear of losing the gamble and residing 50km away from the school so much that I would not want to take this gamble".

Additional questions will be asked to determine the X_{25} and X_{75} values.

We determined the utility functions from the previous section, but there is a problem. Not all attributes have the same importance. It must be distinguished that difference to determine the priorities. For example, let us add price and area attributes to the previous example. A person might say the distance from the school is important as price is not important and another person might say area is the most important as he/she always dreamed living in a house spacious and distance to school is not very important. To assess the importance of the attributes, analytical hierarchy process is used. Decision makers are asked to some questionnaire questions to compare the criteria verbally to assess the pair-wise importance. The decision makers may clarify the level of importance with nine unique responses such as extremely more important, strongly more important, moderately more important, slightly more important and equally more important. They can also specify lesser importance with the same scale of importance. After that, the pair-wise comparisons are plotted to construct a matrix to calculate the relative weights.

Those responses are specified as:

(i) extremely more important
(ii) strongly more important
(iii) moderately more important
(iv) slightly more important
(v) equally important
(vi) slightly less important than
(vii) moderately less important
(viii) strongly less important
(ix) extremely less important

A question will be asked to determine if the utility function is additive or multiplicative and if it is multiplicative what is the k-scaling constant value. The unidimensional utility of the worst potential value for each attribute will set to zero, and the utility of the best possible value will be set to one. The following gamble will be proposed to the decision maker to determine a value of p that makes his or her decision indifferent between the two alternatives. Let us imagine three attributes such as price, area and distance to school just like the previous examples. We can set a gamble with two situations such as;

Situation 1: You will select a maximum utility value for distance and minimum utility values for area and price for guarantee.

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

p%, best utility values for distance, area and price

1-p%, worst utility values for distance, area and price

Question: Specify a value for p that would make you indifferent between situations 1 and 2.

With the response of this question, the overall scaling constant K could be determined so that the utility function values were bounded by 0 and 1.

4. CASE STUDY

Multi-Attribute Utility Theory (MAUT) approach was implemented to the bridge network maintenance problem to prioritize the bridge inventory. Data was obtained from a research made by Masoumi in 2014 (Masoumi, 2014). Masoumi made research on development of a bridge management system and an inventory of 20 bridges in Western Turkey was questioned (Masoumi, 2014). Bridge data such as name and location of the bridge, bridge traffic, bridge condition, physical bridge properties and cost properties was obtained from that research and factors used in our research are quantified from the data mentioned.

Network-level bridge maintenance problem can be questioned by different engineering fields such as transportation, management and structural engineering. The questionnaire was conducted with 5 experts in academics, 2 in traffic, 2 in structural and 1 in engineering management field. The experts from different fields made the decision-making process more inclusive rather than enquiring the problem in a single point of view. In addition, 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 (Keeney and Raiffa, 1993). The first three topics create the scope of the bridge management problem by defining problems, objectives and attributes. In addition, 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 the relative weights that quantifies the importance of the attributes on a scale of 0 to 1. 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. Detailed discussion that clarifies the topics are outlined in the following sections.

4.1. Problem Definition

Bridges provide passage over obstacles for millions of vehicles daily, bridges are crucial infrastructure elements of a country and infrastructure is an important part of the developed world, the lack of the infrastructure is a major limitation to achieve the full economic growth of a developing country. Since the budget of the developing and low-income countries is limited, decision makers should use the public fund wisely. Infrastructure objects, such as bridges, should be used to a management system to have a better organization and controlling mechanism. These systems let the decision making easier and let the decision makers to spend the limited public fund better. If an inventory of some bridges could be listed according to the priority, the decision-makers could decide which bridges to repair with a limited budget.

The data of 20 bridges in Western Turkey, and those bridges need some maintenance with a limited budget are used in this study. The problem is to determine which bridges to maintain with a limited budget is unknown because not all the bridges can be maintained because of the budget constraints. Therefore, a selection must be made between those 20 bridges, but the decision is difficult to make because there are many parameters. It is not possible to prioritize those 20 bridges without an analysis. Those bridges will be analyzed to be put in a prioritization order as the first rank of the prioritization needs the utmost maintenance and the last one needs the less.

4.2. Definition of Objectives

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. The aim of these sub-objectives is achieving 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 are set according to achieve the "overall utility" and they are representative for 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.

It is natural that the objectives conflict with each other because there is not a single solution that optimize all the objectives. Therefore, the objectives are selected according to NCHRP generic objectives for bridge management problems. (Thompson *et al.*, 2006)

4.2.1. Definition of Attributes

It is important to define attributes for each objective that represents all the aspects of the problem. Subjective quantitative scales for attributes are defined to 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 is 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, it is considered that selecting the scale locally would be better because of the small and closely scattered data. Keeney propose four desirable properties to define a set of attributes for the objectives (Keeney and Raiffa, 1993).

- Complete: Attributes must be complete, covering all parts of the problem.
- Operational: Attributes must be defined unambiguously so that decision makers can make a clear judgement between the alternatives.
- Non-redundant: Attributes must be kept non-redundant in order not to have

multiple attributes representing the same objective.

- Minimal: Dimension of the attributes must be kept minimal, as the number of attributes increase; the problem becomes more complex and difficult than intended.

Therefore, the attributes for the objectives of the case study are defined according to those four desirable properties.

- 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

4.2.2. Importance Factor

VDOT recommends importance factor based on average annual daily traffic (AADT) to represent the relative importance of the bridge to the overall highway network. (Moruza *et al.*, 2017) 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 that is used by many daily users so that more people can benefit from the maintenance work and we would achieve the maximum utility. The user impact would be minimum with a bridge by maintaining a bridge with small AADT; therefore, it has a lesser importance on the overall highway network. Importance factor is described in Equation (4.1).

$$IF = AADT \tag{4.1}$$

VDOT defines other parameters to enhance the importance factor (Moruza *et al.*, 2017) but in this research, only AADT is used since only the daily users of a bridge is representative to determine the importance of the bridge to the overall network.

4.2.3. Bridge Condition Factor

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 of Masoumi (Masoumi, 2014) calculated the bridge condition ratings with Equation (4.2):

$$BCR = \sum_{i=1}^{3} CSI_i \ x \ w_i \tag{4.2}$$

where BCR= Bridge condition rating, CSI= Condition state index for element i, w_i= Weighted score of the element i.

There are three major elements for assessing the condition state: superstructure, substructure, and accessories. Therefore, the physical conditions of that three elements are quantified with visual inspection and non-destructive testing methods (Masoumi, 2014) and condition state indexes are weighted and aggregated to a bridge condition rating. The bridges chosen for this research were in pleasant 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 has not an urgent repair. Maintaining bridges with worse physical condition would give the maximum utility since inconveniences because of the physical condition is noticeable and fixing a bridge that produces inconvenience would cause maximum utility.

4.2.4. 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 are 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 elements that need immediate action 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 (4.3).

$$CEF = 1 - \frac{optimal\ repair\ cost}{rehabilitation\ cost} \tag{4.3}$$

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, CEF value of 1 means that highest effectiveness can be obtained from that maintenance work since all the rehabilitation is optimal and that situation would provide the maximum utility. A low CEF value means non-optimal maintenance work that would not offer much utility.

4.2.5. 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 road and closing down the bridge to traffic for difficult maintenance situations are estimated and 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 Equation (4.4), (4.5) and (4.5).

$$WSF = \frac{design\ width}{desired\ width} \tag{4.4}$$

$$design\ width = (2\ x\ design\ shoulder\ width) \\ + (no.of\ \ lanes\ x\ design\ lane\ width) \tag{4.5}$$

$$desired\ width = (2\ x\ design\ shoulder\ width) \\ + (no.of\ \ lanes\ x\ desired\ lane\ width) \tag{4.6}$$

Desired shoulder width and desired lane width values were selected from the AASTHO Highway Design Manual according to the percentage of trucks, road type and other parameters (AASTHO and Caltrans, 2017).

The range of the WSF is selected as 0.88-1 that the maximum value of WSF would give the maximum utility, and the minimum value of WSF would cause minimum utility. For instance, WSF value of 1 means that the road design is proper according to AASTHO highway design manual so, 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 and therefore additional costs must minimize the accident risk due to the road deficiency.

4.3. Creating Single Utility Functions

In this thesis, a questionnaire was prepared for the decision-makers to calculate the single utility functions, to determine the relative weight of the attributes and to determine the additive utility independence. Decision-makers were informed with the background information of the network-level bridge maintenance problem, and attributes were listed and defined. Three gamble method questions were asked for each attribute to construct the single utility functions as the process is explained in Section 3.2.1. Creating single utility functions for each attribute is discussed in following sections.

4.3.1. Single Utility Function of Importance Factor

Figure 4.1 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 X_{25}, X_{50} and X_{75} values are marked on the plot.

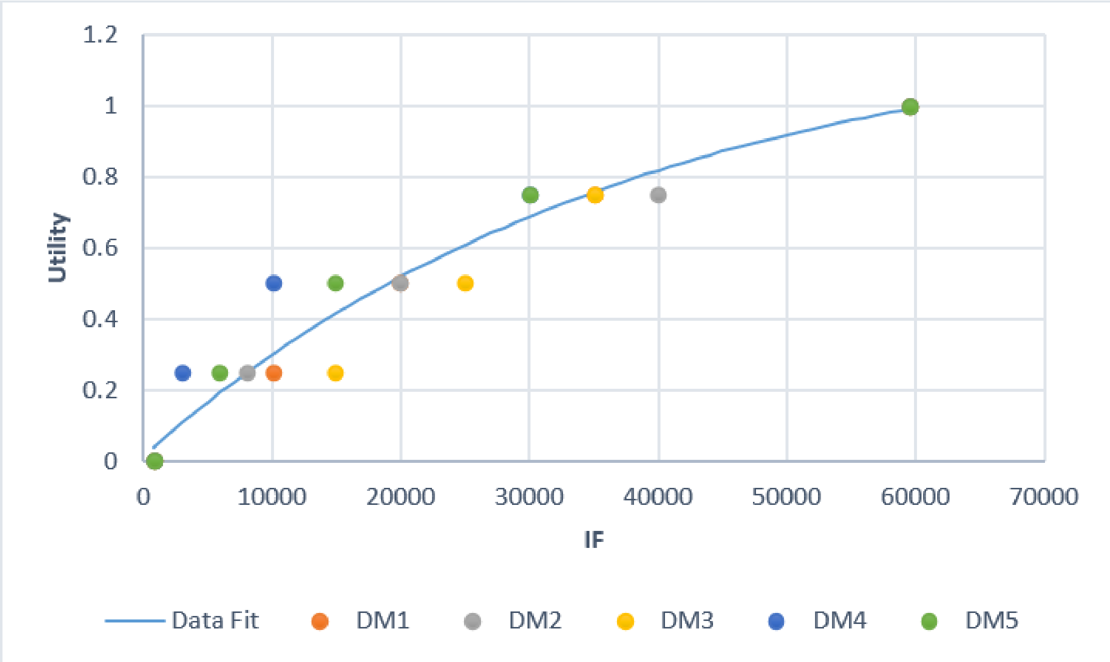


Figure 4.1. Single utility function of the Importance Factor.

The definition of importance factor was given in Section 4.3.1. Higher value of IF index signifies a more important bridge on the overall highway network. Hence, the objective is set as achieving maximum user impact by maximizing IF. The range of importance factor is specified as 850-59500 which is on the Table 4.2. As explained in Section 4.3.1, gamble method is implemented to determine X25, X50 and X75 values for the IF. The setting of gamble method to determine X50 is presented in Figure 4.1. A certain X50 value is asked to give up the 50%-50% gamble of having the best and the worst IF values. Similarly, X_{25} and X_{75} values are gathered with the same method by comparing maximum and $X50$, minimum and X_{50}. The Expected Value (EV) is noted which indicates the risk-neutral behavior. Five decision-makers from different domains were asked to follow this procedure individually. Negative exponential growth model mentioned in Section 3.2.3 is fitted to the obtained utility data. Therefore, single attribute utility function for IF is presented in Equation (4.7):

$$u_1\left(x_1\right) = 1.250 - 1.237xe^{-x_1/2.628x10^{-5}} \tag{4.7}$$

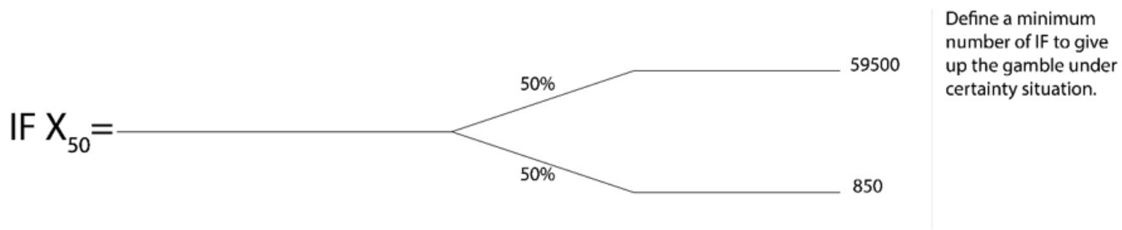


Figure 4.2. Importance Factor gamble question.

4.3.2. Single Utility Function of Bridge Condition Factor

As explained in Section 4.3.2, the objective is preserving the physical condition with maximizing the bridge condition factor (BCF). Maximum utility is achieved with maintaining bridges with worse physical condition. The range of BCR is set to (Table 4.2) 1.05-1.68. Gamble method is applied to determine X25, X50 and X75 values by applying the gamble method for the BCR shown in Figure 4.3.

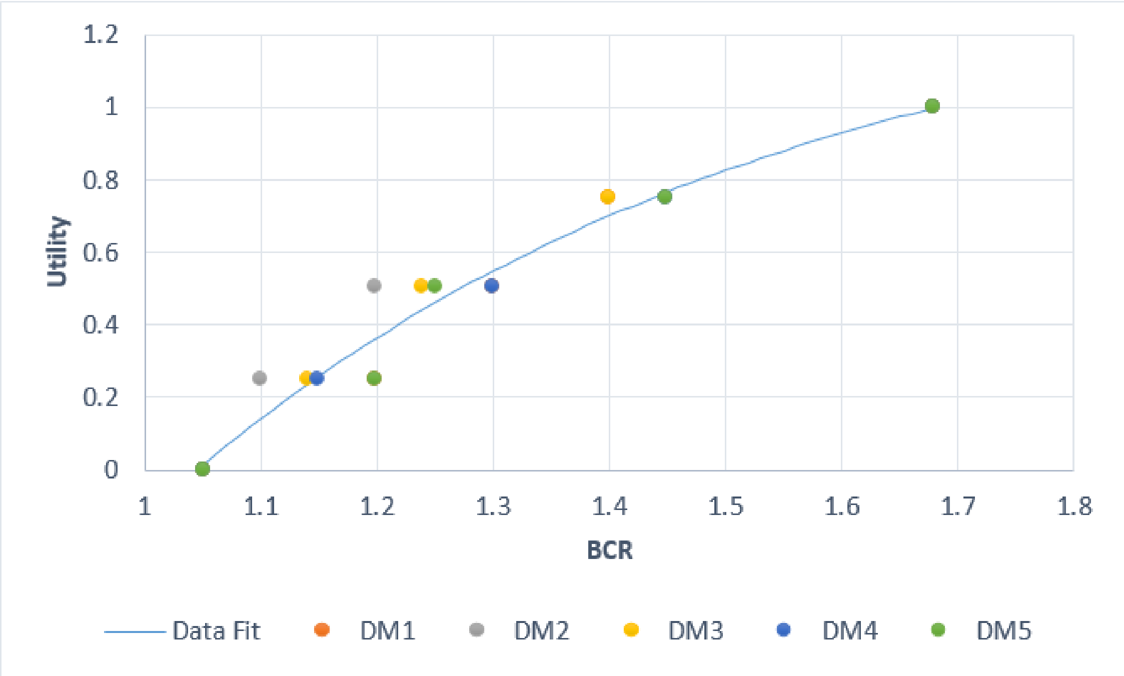


Figure 4.3. Single utility function of the Bridge Condition Rating.

Decision-makers are asked a gamble of obtaining 1.68 and 1.05 BCR with a 50% probability. They were asked a certain value of BCR to give up this gamble. BCR values for X_{25}, X_{50} and X_{75} utilities are plotted for five decision-makers. Finally, single utility function is constructed by fitting a negative exponential growth model to the obtained data. Therefore, the single utility function for BCR is shown in Equation (4.8):

$$u_2\left(x_2\right) = 1.416 - 10.65xe^{-x_2/1.930} \tag{4.8}$$

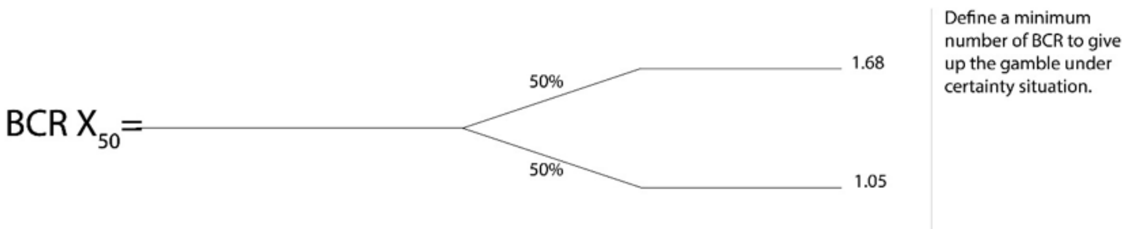


Figure 4.4. Bridge Condition Rating gamble question.

4.3.3. Single Utility Function of Cost-Effectiveness Factor

The calculation of CEF mentioned in Section 4.3.3 is applied to the twenty bridges. CEF ranges from 1 to 0.43 (Table 4.2) is used as a base to construct a gamble (Figure 4.6) that presents 50% probability of getting 1 CEF and 50% probability of getting 0.43 CEF. Decision-makers are asked a certain value to give up that gamble.

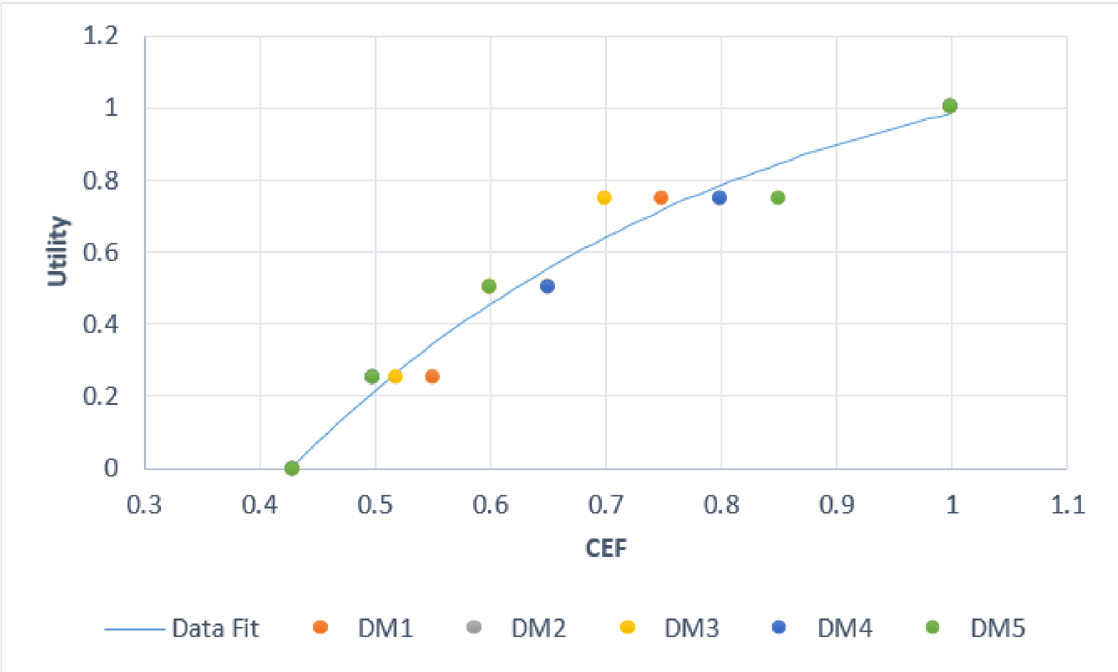


Figure 4.5. Single utility function of the Cost-Effectiveness Factor.

The result of that gamble provided the X_{50} value and X_{25} and X_{75} values are calculated with the same method by comparing 1 to X_{50} and 0.43 to X_{50} for five decision-makers. CEF values obtained from the decision-makers are plotted (Figure 4.5) and a single utility function for CEF is fitted with a negative exponential growth model as shown in Equation (4.9):

$$u_3\left(x_3\right) = 1.287 - 3.809xe^{-x_3/2.538} \tag{4.9}$$

Figure 4.5 also shows that the risk preference of decision-makers indicate risk avoiding behavior due to concave shape of the function.

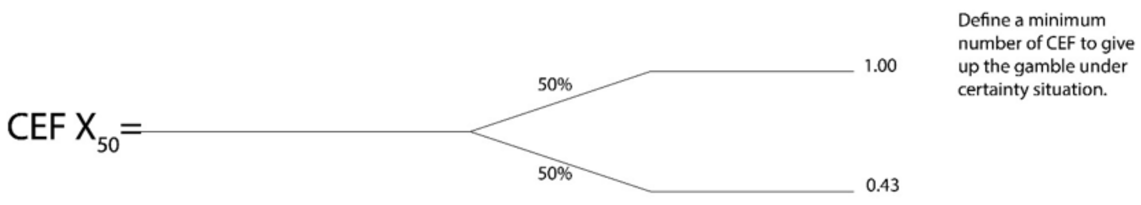


Figure 4.6. Cost-Effectiveness Factor gamble question.

4.3.4. Single Utility Function of Work-Zone Safety Factor

WSF attribute is calculated for twenty bridges with Equations (4.4), (4.5) and (4.6), and it ranges from 1 to 0.88 that we can argue that the interval is small compared to other attributes due to generally sufficient road widths of the bridge inventory. A gamble of getting 1 WSF for 50% and getting 0.88 for 50% is proposed to decision-makers shown in Figure 4.6.

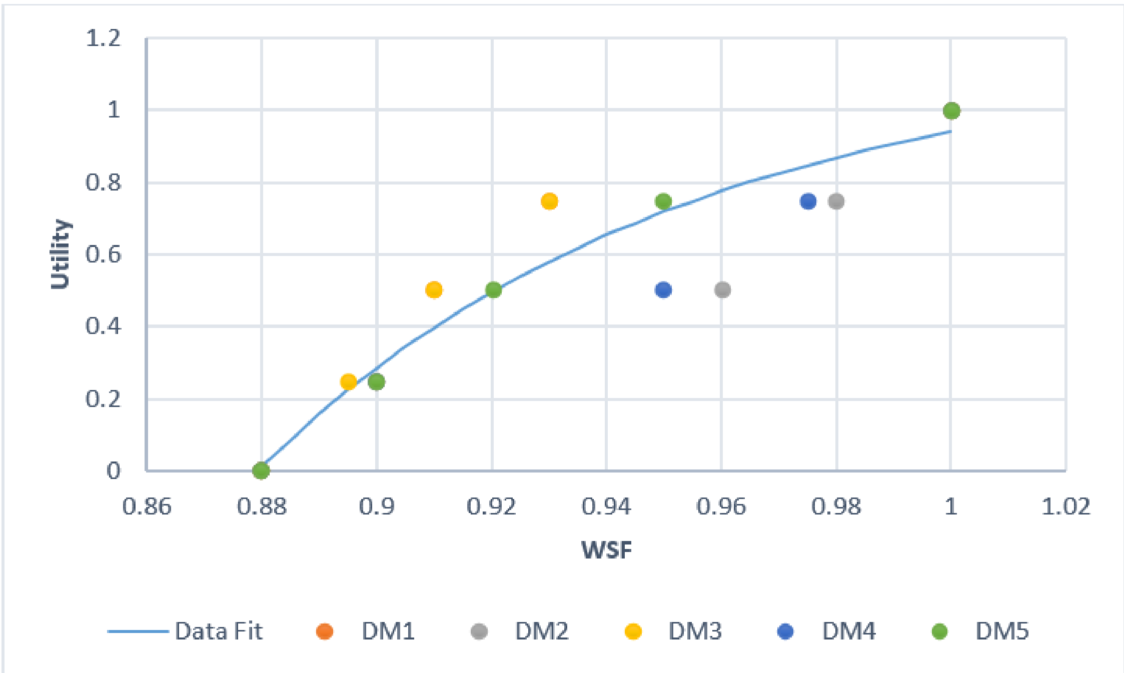


Figure 4.7. Single utility function of the Work-zone Safety Factor.

A minimum value is demanded from the decision-makers to give up that gamble. That value is labeled as X_{50} value. The same procedure is applied to calculate X_{25}

and X_{75} values by constructing the gamble of X_{50} value - 1 and X_{50} value - 0.88. All the utility value - WSF data is plotted for five decision-makers and the negative exponential growth model is fitted to that data shown in Figure 4.7.

Finally, the single utility function for WSF is shown in Equation (4.10):

$$u_2(x_2) = 1.166 - 173003xe^{-x_2/13.54} \tag{4.10}$$

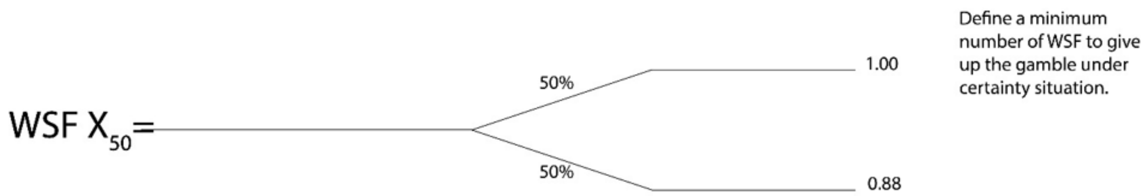


Figure 4.8. Work-zone Safety Factor gamble question.

4.4. Performing Value Trade-off among the Attributes

As specified, in the four objectives for the bridge maintenance problem, certain 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. (Thompson *et al.*, 2006) Analytical hierarchy process is employed in this study as we discussed in Section 3.3.

Five different decision-makers from different expertise were asked six questions that compares the importance among the attributes pair wisely. Decision-makers made their judgements on importance of two attributes according to the scale shown in Table 3.1. The weights of four attributes are calculated with the process mentioned in Section 3.3 and the results are shown in Figure 4.5, each attribute was a given a weight on a scale of 0-1. Importance factor was chosen the most important attribute as the bridge inventory had a good physical condition. Thus, bridge condition rating was in second place. Decision-makers placed cost-effectiveness factor in third place following the BCR. Finally, word-zone safety factor was in less place since decision-makers judged the cost of taking extra safety precautions because of road deficiency as a minor importance in bridge maintenance planning.

Table 4.1. Weights of the 4 Attributes with Analytical Hierarchy Process.

Initial Matrix		IF CR-1	BCR CR-2	CEF CR-3	WSF CR-4
IF	CR-1	1.00	2.46	2.63	6.00
BCR	CR-2	0.41	1.00	3.27	6.00
CEF	CR-3	0.38	0.31	1.00	4.60
WSF	CR-4	0.15	0.17	0.22	1.00
	SUM	1.93	3.94	7.11	18.40
Normalized Matrix		IF CR-1	BCR CR-2	CEF CR-3	WSF CR-4
IF	CR-1	0.52	0.63	0.37	0.37
BCR	CR-2	0.21	0.25	0.46	0.33
CEF	CR-3	0.20	0.08	0.14	0.25
WSF	CR-4	0.08	0.04	0.03	0.05
	SUM	1.00	1.00	1.00	1.00
Weights and the other indicators				λ_{max}	4.26
				CI=	0.09
		Weights	Multiplicative	RI=	0.90
IF	CR-1	0.47	0.43	C.R.=	0.10
BCR	CR-2	0.31	0.28		
CEF	CR-3	0.17	0.15		
WSF	CR-4	0.05	0.05		

Consistency factor that defines the reliability of the pair-wise decisions was calculated just below 10%, which is favorable, by Saaty's research. (Saaty, 1987) Therefore, pair-wise comparisons are consistent within the overall importance ranking.

4.5. Creating Multi-Criteria Utility Function

Single utility functions and the weights are calculated in the previous steps, and the data of twenty bridges on the single utility functions is shown in Figure 4.9. Therefore, the last step is aggregating those single utility functions into a multi-attribute utility function as discussed in Section 3.4, a gamble question was asked to decision-makers to determine if the function is additive or multiplicative that tests the additive independence. For this test, the decision-makers are asked a gamble (Figure 4.6) of two situations. The first situation is getting the maximum utility for the most important attribute and the minimum utility values for all the other attributes for certain and the second situation is taking the 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 a minimum value of p to give up the Situation 1 for taking the gamble in Situation 2. Calculating k values are explained in Section 3.4, multi-attribute utility function is resolved as multiplicative. Therefore, the overall function to calculate the global utility value for prioritizing the twenty bridges are shown in Equation (4.11) and the k-value is calculated from Equation (4.12) where k_1 is the result of p-value of the AI test and k_2, k_3, k_4 are derived from the ratio of k_1 from their respective weights.

$$\begin{aligned}
&u\left(x_1, x_2, x_3, x_4\right) \\
&\quad = k_1 u_1\left(x_1\right) + k_2 u_2\left(x_2\right) + k_3 u_3\left(x_3\right) + k_4 u_4\left(x_4\right) + k k_1 k_2 u_1\left(x_1\right) u_2\left(x_2\right) \\
&\quad + k k_1 k_3 u_1\left(x_1\right) u_3\left(x_3\right) + k k_1 k_4 u_1\left(x_1\right) u_4\left(x_4\right) + k k_2 k_3 u_2\left(x_2\right) u_3\left(x_3\right) \\
&\quad + k k_2 k_4 u_2\left(x_2\right) u_4\left(x_4\right) + k k_3 k_4 u_3\left(x_3\right) u_4\left(x_4\right) \\
&\quad + k^2 k_1 k_2 k_3 u_1\left(x_1\right) u_2\left(x_2\right) u_3\left(x_3\right) + k^2 k_1 k_2 k_4 u_1\left(x_1\right) u_2\left(x_2\right) u_4\left(x_4\right) \\
&\quad + k^2 k_2 k_3 k_4 u_2\left(x_2\right) u_3\left(x_3\right) u_4\left(x_4\right) + k^2 k_1 k_3 k_4 u_1\left(x_1\right) u_3\left(x_3\right) u_4\left(x_4\right) \\
&\quad + k^3 k_1 k_2 k_3 k_4 u_1\left(x_1\right) u_2\left(x_2\right) u_3\left(x_3\right) u_4\left(x_4\right)
\end{aligned} \tag{4.11}$$

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 global utility values of twenty bridges is discussed in the next section.

4.6. Results and Conclusions

The single-utility values of the 20 bridges on four different attributes is shown in Figure 4.9. It could be observed that for the importance factor, bridges do have less than 60% utility except two bridges. Since the relative weight of the importance factor is significant, those two bridges ranked higher than their alternatives. Bridge condition rating is distributed on the graph rather evenly. Two bridges have utility score almost 100% but they are distributed between 40%-60%. The single-utility scores of cost effectiveness factor are high; they are distributed between 75% to 100% except for three bridges. Finally, for the work-zone safety factor, half of the bridges have the perfect or almost-perfect utility score of 100% and the other ten bridges are dispersed on the graph.

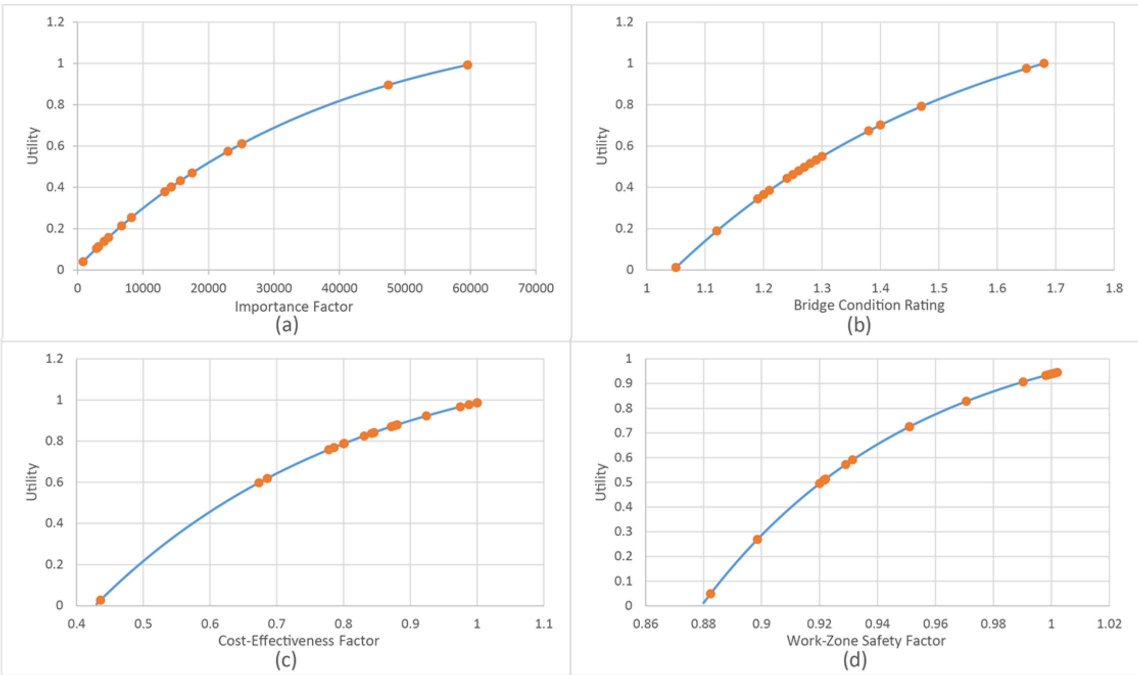


Figure 4.9. Attribute data of the 20 bridges over the single utility functions.

Utility values for respective attribute values are shown in Table 4.1. Also, single utility values for each attribute is specified and the global utility values are aggregated with relative weights and multiplicative aggregation. The results of global utility values of twenty bridges are also shown in Table 4.1. The bridges are ranked from maximum to minimum aggregated utility scores and the results are compared to the research Masoumi which prioritized the same bridge inventory. (Masoumi, 2014) The priority order changed significantly however, first and second order resulted the same. It is not a surprise that bridge A came out first in priority because of its high IF which has the highest 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 of their also have relatively high IF and despite its low IF, Bridge I and G came out in rank 7-8 with very high BCR. The other rankings can be observed from the Table 4.2. The results show that IF have a crucial role in prioritizing bridge maintenance planning since the 8 out of 10 most prioritized bridges in the data set have high IF. It highlights the decision makers' desire to maximize the user impact. From this result, it is also clear that WSF does not have a critical role in prioritizing as WSF's total contribution to the total utility ranges from 0 to 5%. It is also noticeable 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.

Table 4.2. 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	1.20	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	0.5	7	9
G	14321	1.3	0.83	0.90	0.40	0.55	0.82	0.27	0.5	8	7
K	13329	1.19	1.00	0.92	0.38	0.34	0.99	0.51	0.5	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

By comparing results from Masoumi's research, we demonstrate the change of priority order of the same set of bridges. (Masoumi, 2014) This change displays the effect of using 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 different expertise, presented more democratic and more agreeable results compared to Masoumi's research (Masoumi, 2014). Another contribution is that additive utility independence is not assumed contrary to the studies (Jeon, 2010; Allah Bukhsh *et al.*, 2019) which argues that assuming additive independence can generate suboptimal solutions for transportation asset problems (Kalan, Kurkcu and Ozbay, 2019).

Work-zone safety factor is added as a fourth attribute as a contribution to the study. (Masoumi, 2014) Despite of its small part in overall utility, we believe that it is important 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 characterizes the IF is AADT because of the limited data about the characteristics of 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 is particularly important when investigating a bridge maintenance problem.

This study presents a detailed application of MAUT on a bridge maintenance problem. AHP is used to determine the trade-offs among the attributes, and the additive independence of the utility function is intrigued. Dataset was selected among 20 bridges in Western Turkey to apply MAUT that maximizes selected objectives 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 (Velasquez and Hester, 2013). 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, and a comparison is made with the study of Masoumi that used the same set of bridges. (Masoumi, 2014).

For the future studies:

- With a larger and comprehensive dataset, a more detailed criteria hierarchy can be constructed.
- With a detailed maintenance information, prioritization decisions can be given in terms of different maintenance strategies.
- An optimization model can be integrated to prioritization model with limited budget scenarios for a certain period of years.

4.7. Sensitivity Analysis

In this study, objectives are defined, criteria are quantified, weights are attained to the criteria and the alternatives are ranked according to the utility functions and their respective weights. An implementation of sensitivity analysis is needed understand the weight-alternative relationship of the research better. Decision-makers could make a better choice if they know how sensitive the alternative of the 20 bridges in a situation of a change in the weights. Also, the decision-makers' judgement would be better in a situation where the criticality of each criterion is clear so that they would know how a change in the criterion would affect the outcome.

As methodology, the sensitivity analysis approach of Triantaphyllou is used in this research. (Triantaphyllou, 1997) This paper provides a methodology that shows an approach to a sensitivity analysis on the weights of the criteria and three methods of decision methods are presented as weighted sum model, weighted product model and analytical hierarchy process. (Triantaphyllou, 1997) Where, weighted sum model is the simplest addition model, which assumes additive independence utility. It aggregates the criteria and its weights additively. Weighted product model is also an addition model but it aggregates the criteria and its weights multiplicatively. Therefore, it does not assume the additive utility independence and it uses multiplicative aggregation method, which is pointed out in Section 3.4. The aim of this sensitivity research is to determine the amount of change of the determined criteria to alter the ranking of the alternatives.

Three-step approach is implemented for the numerical analysis of the data as pointed on in the research. (Triantaphyllou, 1997).

The first step is determining the relevant criteria and alternatives. The criteria is selected as Importance Factor, Bridge Condition Rating, Cost-Effectiveness Factor and Work-zone Safety Factor to represent the objective of the bridge maintenance problem that is discussed in Section 4.3. Those criteria are denoted as C1, C2, C3 and C4 respectively. In this research, we have an inventory of 20 bridges in Western Turkey that needs to be put in a ranking for bridge maintenance. In addition, the bridge inventory is denoted with letters from A to O alphabetically.

The second step is determining the ranking of the criteria. In this research, Analytical Hierarchy Process (AHP) is implemented to calculate the weights of the criteria. Since there were four criteria, six questions are asked to five decision makers to compare the importance of the criteria pair-wisely. The weights are calculated with the AHP matrix and the consistency rating, which determines the consistency of the responses of the decision-makers, is found out to be less than 10%. Finally, the weights of the criteria are represented with Wi, which represents the C_i.

The final step is the process of the weights and criteria to the bridge inventory to have a ranking. Additive utility independence is intrigued and the case is found out to be multiplicative by an additive utility independence test. Therefore, the criteria are aggregated multiplicatively, the global utility scores are calculated according to the multiplicative amalgamation, and the ranking of the bridge inventory is shown in Table 4.2. The preference of the ranking is denoted with P_i where i=1 represents the first in priority.

Two scenarios with two different assumptions could be intrigued. In the first scenario, additive utility assumption will be assumed and the total utility of the alternatives will be aggregated through additive method. Then, the weighted sum model of the sensitivity analysis will be applied shown in Equation (4.12) (Fishburn, 1967):

$$P_i = \sum_{j=1}^{N} a_{ij} W_j,\ for\ i = 1,\ 2,\ ...,\ M \tag{4.12}$$

For i=1, 2, 3, ... , M

The sensitivity analysis will be applied to understand the weight-alternative relationship of the five most prioritized bridges out of twenty bridges according to the total utility value. In the second scenario, additive utility independence will not be assumed. Therefore, the utility score of the alternatives will be calculated multiplicatively and the sensitivity analysis will be conducted with the weighted sum model however k-values will also be calculated to make sure that the system is always multiplicative. Every alternative is compared with the other alternatives with multiplying with a ratio and Equation (4.13) will be used to ensure the k-values and finally to compare alternatives such as A_1 and A_2 (Triantaphyllou, 1997).

$$k + 1 = \prod_{i=1}^{n} \left[k\left(k_i u_i\right)\right] + 1 \tag{4.13}$$

In addition, we need to define a constraint that should satisfy to prevent infeasible solutions. Since the reduction or increase, more than 100% is infeasible; we can define a constraint shown in Equation (4.14):

$$K_{ij} \leq 100 \tag{4.14}$$

In the sensitivity analysis, the most critical criterion will be intrigued. Normally, the criterion with the highest value would be thought to be the most critical criterion however, this may not be the case all times. According to the Triantaphyllou's research, the most important criterion is determined with two definitions. (Triantaphyllou, 1997) For the first definition, the most important criterion specifies if it can change the best alternative or not. In addition to that, for the second definition, the most important criterion decides if it can change any alternative. Changes on the weights might be absolute or relative where absolute change specifies a number and relative change specifies the percent in change. In this research, relative change is used as it could represent the situation better because a change with a specific number might not give much clue but the percentage always tell something. For example, a change of 0.10 might be extremely significant if the original value is 0.20 however if the original value is 0.90, a change of 0.10 would not be that significant. Therefore, working with percentages would result in better grasp of the situation. Finally, with those changes' determination of the most critical criterion and the most critical performance measure is aimed.

Before going on the sensitivity analysis definitions and denotations are given.
δ_{kij} is the minimum change of the weight Wk so that the preference rank of i and j would change.
$\delta_{kij'}$ is the minimum percent change of the weight Wk so that the preference rank of i and j would change.

The relationship between those definitions is shown in Equation (4.15):

$$\delta_{kij'} = \delta_{kij} \frac{100}{W_k} \tag{4.15}$$

For determining the most important criterion, we can define some descriptions: Percent Top (PT) is the minimum value of $|\delta_{kij'}|$ which changes the best alternative. Percent Any (PA) is the minimum value of $|\delta_{kij'}|$ which changes any alternative. D_k' is the criticality degree which defines the smallest change in percentage in order to have a change in the ranking of the alternatives for the weight Wk. It is defined with Equation (4.16):

$$D_k' = \min\left\{|{\delta_{kij}}'|\right\}, for\ all\ alternatives \tag{4.16}$$

$sens(C_k)$ is the sensitivity coefficient which inversion of the criticality degree which shows some information such as in the case of infeasible criticality degree, the 0 values of sensitivity coefficient shows that there could not be any changes in the alternatives. Sensitivity coefficient can be calculated with Equation (4.17):

$$sens\left(C_k\right) = \frac{1}{D_k'} \tag{4.17}$$

4.7.1. Implementation of the Sensitivity Analysis

In this research, sensitivity analysis will be applied to the first five rank of the alternatives according to the global utility scores shown in Table 4.3. In the first case, the additive independence is assumed and the weighted sum method (WSM) will be applied as stated in the methodology. Only five alternatives out of twenty alternatives are chosen since, for determining the Percent Top (PT), we do not need to analyze all of the alternatives since we are looking for the change in criteria that would change the ranking order of the first rank and the first five rank is enough to find out that change. For the Percent Any (PA), it is not very important to see a change in all 20 bridges since there are a lot of close global utility values and for example a change between rank 16 and 17 would not be significant. In addition, analyzing 20 bridges would compare 190 combinations, which would be an unnecessary task.

Table 4.3. Ranking of the Total Utility of Five Bridges.

Bridge ID	' Total Utility	Ranking
A	0.82	1
B	0.59	2
F	0.57	3
D	0.56	4
C	0.55	5

For this problem, we are considering five alternatives $(A_1, A_2, A_3, A_4, A_5)$ and four criteria (C_1, C_2, C_3, C_4). The multiplicative utility values of the alternatives are shown in the decision matrix in Table 4.4.

Table 4.4. Decision Matrix of the WPM Approach.

	C1	C2	C3	C4
Alternative	0.47	0.31	0.16	0.05
A1	0.99	0.52	0.97	0.94
A2	0.90	0.01	0.79	0.91
A3	0.61	0.48	0.88	0.56
A4	0.61	0.37	0.87	0.51
A5	0.57	0.39	0.99	0.51

WSM approach will be applied to the alternatives pair-wisely with to determine the new weights of the criterion in order to make a change in ranking pair wisely, which means in this new weight of criterion, the global utility of the two alternatives will be swapped. Also, since the addition of the criterion values is equal to 1 in additive approach, the values of the other criteria are normalized. The results are shown in Table 4.5.

Table 4.5. New Weights of the Pairwise Alternatives.

Pair of Alternatives	Criterion CR1	CR2	CR3	CR4
A-B	NF	NF	NF	NF
A-F	NF	NF	NF	NF
A-D	NF	NF	0.94	NF
A-C	NF	NF	NF	NF
B-F	0.488	0.298	0.066	0.077
B-D	NF	NF	0.357	NF
B-C	NF	NF	NF	NF
F-D	0.432	0.350	0.248	NF
F-C	0.408	0.367	0.388	NF
D-C	0.569	NF	0.102	NF

Therefore, the D-values that will show the critical percentage that the criterion needs to be changed in order to affect the ranking order can be determined. The D-values are calculated with Equation (4.15), Equation (4.16) and the results are shown in Table 4.6.

Table 4.6. D-values of the Five Bridges in Percentage.

Pair of Alternatives	Criterion CR1	CR2	CR3	CR4
A-B	NF	NF	NF	NF
A-F	NF	NF	NF	NF
A-D	NF	NF	465,3	NF
A-C	NF	NF	NF	NF
B-F	3.780	-4.758	-60.10	51.83
B-D	NF	NF	114,7	NF
B-C	NF	NF	NF	NF
F-D	-8.182	12.15	49.40	NF
F-C	-13.33	17.33	133.6	NF
D-C	20.96	NF	-38.95	NF

From the Table 4.6, we can see that the lowest percentage is 3.780% for the first five bridges in the ranking. Therefore, Percent Any (PA) is 3.780% that means the minimum percentage value of criterion that we need to change in order to change any preference ranking (in this case order 2 to order 3). The sensitivity coefficients are calculated with Equation (4.17) and shown in Table 4.7. Finally, we can conclude that the most sensitive decision criterion for changing the ranking of Bridge B with Bridge F is C_1 followed by C_2, C_4 and C_3.

Table 4.7. Sensitivity Values of the Pair of Alternatives.

Pair of Alternatives	Criterion			
	CR1	CR2	CR3	CR4
A-B	NF	NF	NF	NF
A-F	NF	NF	NF	NF
A-D	NF	NF	0.002	NF
A-C	NF	NF	NF	NF
B-F	0.265	0.210	0.017	0.019
B-D	NF	NF	0,009	NF
B-C	NF	NF	NF	NF
F-D	0.122	0.082	0.020	NF
F-C	0.075	0.058	0.007	NF
D-C	0.048	NF	0.026	NF

In addition, from the results we can see that there are only one feasible solution for the Percent Top (PT) that means there is only one criterion that changes the preference order by for the five bridges and that criterion is C_3 for bridges A and D. If we increase the C_3 by 465%, Bridge D would be the first in ranking. Therefore the Percent Top (PT) value is 465%.

4.7.2. Implementation of the Sensitivity Analysis for the Alternative Situation

In the first part, the percentage of change in the criteria in order to change ranking order was found with assuming additive independence. In the second part, the change in the performance measure of an alternative in order to change the priority order when there is no assumption of additive independence will be calculated.

The decision matrix shown in Table 4.4 is used for the analysis. Just like the first part, there are five alternatives and four criteria. We would use the same WSM approach of the previous part; therefore, the alternatives pair-wisely with Equation (4.12) to determine the new weights in order to have a change in the rating. By using the Solver function in Microsoft Excel, the k-values that are used to calculate multiplicative weights are calculated.

Table 4.8. New Weights of the Pairwise Alternatives in Multiplicative Case.

Pair of Alternatives	Criterion			
	CR1	CR2	CR3	CR4
A-B	NF	NF	NF	NF
A-F	NF	NF	NF	NF
A-D	NF	NF	NF	NF
A-C	NF	NF	NF	NF
B-F	0.508	0.281	NF	0.103
B-D	NF	NF	0.376	NF
B-C	NF	NF	NF	NF
F-D	0.45	0.332	0.213	NF
F-C	0.426	0.349	0.343	NF
D-C	0.582	NF	0.094	NF

The new weights of Table 4.8 show the amount of criterion weight in order to have a change in the ranking order. For instance, the priority ranking of Bridge B and Bridge F would change if the weight of the Criterion 1 was 0.508. Table 4.9 is calculated by comparing the values in Table 4.8 with the original criterion weights that percentage change of the selected weight in order to have a change in the ranking.

Table 4.9. D-values of the Five Bridges in Percentage in Multiplicative Case.

Pair of Alternatives	Criterion CR1	CR2	CR3	CR4
A-B	NF	NF	NF	NF
A-F	NF	NF	NF	NF
A-D	NF	NF	NF	NF
A-C	NF	NF	NF	NF
B-F	8.05	-9.91	NF	101.69
B-D	NF	NF	126.02	NF
B-C	NF	NF	NF	NF
F-D	-4.40	6.35	28.08	NF
F-C	-9.37	11.84	106.35	NF
D-C	23.77	NF	-43.49	NF

Therefore, from Table 4.9, we can conclude that the most critical criterion is C1 which if we reduce the C1 by 4.40%, the ranking order will be change and the alternative 3 will be in 5th order in priority ranking. Minus sign indicates if there would be a reduction or increase in order to change the alternative. The sensitivity coefficient of the most critical alternative could also be calculated with Equation (4.17) as shown in Table 4.10.

Table 4.10. Sensitivity Values of the Pair of Alternatives in Multiplicative Case.

Pair of Alternatives	Criterion CR1	CR2	CR3	CR4
A-B	NF	NF	NF	NF
A-F	NF	NF	NF	NF
A-D	NF	NF	NF	NF
A-C	NF	NF	NF	NF
B-F	0.124	0.101	NF	0.010
B-D	NF	NF	0.008	NF
B-C	NF	NF	NF	NF
F-D	0.227	0.157	0.036	NF
F-C	0.107	0.084	0.009	NF
D-C	0.042	NF	0.023	NF

If we compare the results of the sensitivity values of Table 4.7 and Table 4.10, we can observe that Criterion 1 is the most sensitive criterion that changes the ranking. Since there is a great gap of global utility between the Bridge A and other alternatives, there is only one criterion change that swaps the ranking order for the bridge A and it is quite high with change in Criterion 3 with 465% that means the rank of the Bridge A is resilient to a change. We can also observe that the results of the intriguing the additive independence as the sensitivity values are changed. In the additive case the most sensitive change was between the bridges B and F; however, in the multiplicative case the most sensitive change was between the bridges F and D.

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APPENDIX A: TRAFFIC EXPERT-ACADEMICIAN

Questionnaire Form 1

Name: X

Title: Traffic Expert-Academician

Date: 21/07/2020

Part 1 Utility Values

Importance Factor:

X50: 20000

X25:10000

X75: 35000

Bridge Condition Rating:

X50: 1.3

X25: 1.2

X75: 1.4

Cost Effectiveness Factor:

X50: 0.65

X25: 0.55

X75: 0.75

Work-zone Safety Factor:

X50: 0.91

X25: 0.90

X75: 0.93

Part 2 Weighting the Attributes

Table A.1. Weighting the Attributes 1.

AHP	IF	BCR	CEF	WSF
IF	1	4	2	7
BCR	0.25	1	1	4
CEF	0.5	1	1	3
WSF	0.143	0.25	0.333	1

Part 3 Additive Utility Independence

p%: 0.60

Questionnaire Form 2

Name: Y

Title: Engineering Management Expert

Date: 21/07/2020

Part 1 Utility Values

Importance Factor:

X50: 20000

X25: 7500

X75: 40000

Bridge Condition Rating:

X50: 1.2

X25: 1.1

X75: 1.45

Cost Effectiveness Factor:

X50: 0.6

X25: 0.5

X75: 0.8

Work-zone Safety Factor:

X50: 0.96

X25: 0.90

X75: 0.98

Part 2 Weighting the Attributes

Table A.2. Weighting the Attributes 2.

AHP	IF	BCR	CEF	WSF
IF	1	0.2	0.142857	5
BCR	5	1	1	7
CEF	7.000007	1	1	5
WSF	0.200	0.142857	0.200	1

Part 3 Additive Utility Independence

p%: 0.18

Questionnaire Form 3

Name: Z

Title: Structural Expert

Date: 22/07/2020

Part 1 Utility Values

Importance Factor:

X50: 25000

X25: 15000

X75: 35000

Bridge Condition Rating:

X50: 1.24

X25: 1.14

X75: 1.40

Cost Effectiveness Factor:

X50: 0.60

X25: 0.52

X75: 0.70

Work-zone Safety Factor:

X50: 0.910

X25: 0.895

X75: 0.930

Part 2 Weighting the Attributes

Table A.3. Part 2 Weighting the Attributes 3.

AHP	IF	BCR	CEF	WSF
IF	1	5	1	7
BCR	0.2	1	0.333	5
CEF	1	3.003003	1	7
WSF	0.143	0.2	0.143	1

Part 3 Additive Utility Independence

p%: 0.65

Questionnaire Form 4

Name: Q

Title: Structural Expert

Date: 22/07/2020

Part 1 Utility Values

Importance Factor:

X50: 10000

X25: 3000

X75: 30000

Bridge Condition Rating:

X50: 1.30

X25: 1.15

X75: 1.45

Cost Effectiveness Factor:

X50: 0.65

X25: 0.50

X75: 0.80

Work-zone Safety Factor:

X50: 0.950

X25: 0.900

X75: 0.975

Part 2 Weighting the Attributes

Table A.4. Weighting the Attributes 4.

AHP	IF	BCR	CEF	WSF
IF	1	0.11111	5	7
BCR	9.00009	1	9	9
CEF	0.2	0.111111	1	7
WSF	0.143	0.111111	0.143	1

Part 3 Additive Utility Independence

p%: 0.20

Questionnaire Form 5

Name: R

Title: Traffic Expert

Date: 23/07/2020

Part 1 Utility Values

Importance Factor:

X50: 15000

X25: 6000

X75: 30000

Bridge Condition Rating:

X50: 1.25

X25: 1.20

X75: 1.45

Cost Effectiveness Factor:

X50: 0.60

X25: 0.50

X75: 0.85

Work-zone Safety Factor:

X50: 0.92

X25: 0.90

X75: 0.95

Part 2 Weighting the Attributes

Table A.5. Weighting the Attributes 5.

AHP	IF	BCR	CEF	WSF
IF	1	3	5	8
BCR	0.333333	1	5	5
CEF	0.2	0.2	1	1
WSF	0.125	0.2	1	1

Part 3 Additive Utility Independence

p%: 0.50