

*OPTIMIZATION -BASED SIMULATION MODEL FOR ALLOCATING
CONSTRAINED BUDGET FOR BRIDGE MAINTENANCE IN KSA*

By

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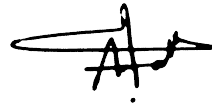
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2020



IN THE NAME OF ALLAH THE BENEFICENT THE MERCIFUL

*To my **parents, family, wife**
and **baby Nada***

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All praise be to Allah the almighty for blessing me with the health of body and strength of mind to complete this thesis.

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LIST OF ABBREVIATIONS

AADT	:	Average Annual Daily Traffic
ADT	:	Average Daily Traffic
AHP	:	Analytic Hierarchy Process
BMS	:	Bridge Management System
CI	:	Consistency Index
CR	:	Consistency Ratio
KSA	:	Kingdom of Saudi Arabia
MAUT	:	Multi-Attribute Utility Theory
MCDM	:	Multi-Criteria Decision Making
MOMRA	:	Ministry of Municipal and Rural Affairs
N	:	Bridges Numbers
RI	:	Random Index
SAR	:	Saudi Arabian Riyals

ABSTRACT

Full Name : [AMIN SALAM ABU SAA]

Thesis Title : [OPTIMIZATION -BASED SIMULATION MODEL FOR
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Bridges constitute a major component in any road and transportation network. Their main function is to connect road intersections to enhance the thru traffic while reducing the traffic congestion and travel time delay. Bridges as any other infrastructure facility require periodic maintenance in order to keep the operation of bridge road at an acceptable level of service hence avoiding traffic interruption and bridge and road networks blockage. Bridges owner and maintenance directorates usually have an internal bridge management system where all information of bridges in their concerned area is stored. In addition to that, there are models attached to that system assist the owners in making decisions related to bridges maintenance and reconstruction. Based on the condition of the bridge the maintenance cost can be calculated. Usually bridge owners have major constrain on their budget for maintenance and the available budget does not cover the maintenance of whole bridges in a certain area. The aim of this research is to develop a model to assist bridge owners in identifying their priority for bridge maintenance and accordingly allocate the available budget effectively. The methodology followed in this research utilizes a MCDM tools like AHP and MAUT. The first step is identifying the prioritization factors of bridge for maintenance in network level thru an extensive literature review and local experts' interview and determine their

weights using AHP. Second, establishing the MAUT utility curves for each factor. Third, identify the maintenance strategies followed locally and their preferences. Fourth, optimization-based simulation model development including model description, workflow and model objective function and constraints. The model output is a list of prioritized components along with their priority and maintenance cost. The uncertainties in the model were examined and found to be mainly from the subjectivity nature of the problem and the bridges data which come from the condition assessment and visual inspection which is reflected in the priority of the bridge. Based on these assessments the maintenance cost is estimated which results in an uncertainty in the maintenance cost, as well. The uncertainty results in a risk in making decisions related to optimal solutions. More attractive solutions may become more desirable since they accommodate the budget overrun and unexpected events since the optimal solution mostly consumes the budget without preserving contingency. Results were shared with the local experts and they agreed with the model outputs and the sources of uncertainty in the model. They suggest to further the research in this area with detailed model for each component. |

ملخص الرسالة

الاسم الكامل: امين سلام أبو صاع

عنوان الرسالة: نموذج محاكاة قائم على الحل الأمثل لتخصيص ميزانه محدودة لصيانة الجسور في المملكة العربية السعودية

التخصص: هندسة وإدارة التشييد

تاريخ الدرجة العلمية: أبريل - ٢٠٢٠

تشكل الجسور مكوناً أساسياً في أي شبكة طرق ونقل. وظيفة هذه الجسور هي بشكل رئيسي ربط التقاطعات لتسهيل حركة المرور المباشر في حين تقليل الازدحام المروري وتقليل تأخير زمن الرحلات. الجسور كأى منشأة بنية تحتية تحتاج للصيانة الدورية من أجل المحافظة على مستوى خدمة التشغيل عند حد مقبول وبذلك يتم تفادي تعطل المرور واغلاق الجسور وشبكات الطرق. ان مالِك هذه الجسور وإدارات الصيانة التي تتبع لها تلك الجسور لديهم نظام إدارة الجسور الذي يحتوي على قاعدة بيانات تخزين فيها معلومات تلك الجسور الواقعة في منطقة معينة. بالإضافة إلى ذلك، يوجد بعض النماذج المرفقة بالنظام التي تساعد مالِك الجسور في صنع قرارات تتعلق بصيانة الجسور واستبدالها. بالاعتماد على حالة الجسر يتم تقدير تكلفة الصيانة له. عادة ما يواجه مالِك هذه الجسور محددات للميزانية المخصصة لصيانة تلك الجسور وفي اغلب الأحيان لا تكفي هذه الميزانية لصيانة جميع الجسور في منطقة معينة. الهدف المنشود من هذه الدراسة هو بناء نموذج يساعد مالِك هذه الجسور على تحديد أولويات الصيانة للجسور وتخصيص الميزانية المتاحة تبعاً لذلك بشكلٍ فعال. ان منهجية هذا البحث تقوم على أساس استخدام أدوات صناعة القرارات ذات السمات المتعددة مثل نظرية التحليل الهرمي ونظرية المنفعة متعددة السمات. الخطوة الأولى في هذا البحث هي إيجاد عوامل تحديد الأولويات لصيانة الجسور في منطقة الدراسة من خلال مراجعة ادبية مكثفة وواسعة النطاق في الأبحاث السابقة والمثابرة ومن ثم مقابلة الخبراء المحليين لإيجاد العوامل الملائمة لمنطقة الدراسة ومن ثم إيجاد وزن كل عامل باستخدام نظرية التحليل الهرمي. الخطوة التالية هي انشاء منحنيات المنفعة لكل عامل. الخطوة الثالثة هي تحديد استراتيجيات الصيانة وافضلياتها. الخطوة الرابعة هي تكوين نموذج المحاكاة القائم على الحل الأمثل حيث يتم وصف النموذج وتحديد سير عمل النموذج ووضع دالة الهدف والمحددات. ان مخرجات هذا النموذج هي عبارة عن قائمة بالمكونات المراد صيانتها مع أولوية كل مكون وتكلفة صيانتها. تم اختبار الشك في هذا النموذج ووجد ان مصدر هذه الشك هو الطبيعة الذاتية للمشكلة وكذلك بيانات الجسور

التي تعتمد بشكل أساسي على تقييم حالة المنشأ والفحص العيني والتي تنعكس على أولوية الجسور للصيانة. أيضاً، اعتماداً على هذه التقييمات يتم تقدير تكلفة الصيانة للجسور مما يجعل التكلفة مصدراً آخر للشك. الشك في عملية صناعة القرارات هو مخاطرة خاصة إذا كان القرار متعلق بالحل الأمثل. نتيجة لذلك، يوجد حلول أكثر جاذبية مرغوبة حيث ان تلك الحلول تستوعب عجز الميزانية والاحداث غير المتوقعة حيث ان الحل الأمثل يستهلك اغلب الميزانية مع عدم إبقاء أي احتياطي. تم مشاركة نتائج الدراسة مع الخبراء المحليين حيث أبدوا توافقه مع نتائج النموذج ومصادر الشك كذلك. اقترح الخبراء توسيع البحث في هذا المجال بعمل نموذج لكل مكون للجسر.

CHAPTER 1

INTRODUCTION

This chapter presents the problem of the research and states the research objectives along with the significance and limitations of the study. The study mainly focuses on developing a model assisting the owners of the bridges allocating a constrained budget for bridge maintenance efficiently. This chapter states the significance of the study, as well.

1.1 Background

Bridges constitute a critical component in any transportation network. Their main function is to connect intersections while reducing traffic congestion. Maintenance, repair and replacement (MR&R) actions are needed once the condition of a bridge element becomes deteriorated (Abu Dabous & Alkass, 2008). The deterioration affects the bridge's performance and safety. Since the budgets of transportation agencies are becoming more stringent and MR&R projects account for a considerable amount of their capital investment, it becomes increasingly important to allocate the constrained budget as efficiently as possible (Rashidi, Samali, & Sharafi, 2016a). Allocating a constraint budget is a complex task in which the decision makers should consider multiple conflicting factors such as the cost of the maintenance to increase the lifespan of the bridge, the bridge's daily traffic, reducing the environmental impact etc. (Frangopol & Liu, 2007). As a result, decision support systems are required to provide rational justifications for the high cost commitments associated with bridge management.

1.2 Statement of the Problem

Allocating a constrained budget to maintain a set of bridges in a certain network, considering maximization of the number of bridges to be maintained is a challenging task and is the focus of this research.

Developing a work program to maintain a set of bridges in a certain network is a challenging task, specially under a constrained budget. It requires, first the development of a database of all bridges in the network where all information is stored for later use, specially the bridges under study. It requires the identification of the factors that reflect the importance of each bridge (in the study area) which represent the priority of bridges to undergo a maintenance action, in other words to be included in the proposed maintenance work program. As a result, a decision support system that can assist decision makers for allocating available budgets to bridge maintenance work program is the main concern of this research.

There are two main scenarios in case of limited available budget. First scenario is that the budget is covering all the bridges in the network considering minimal maintenance actions (low level maintenance). Second scenario is that the budget is spent on the top priority bridges including all maintenance action required, thus, other bridges are deferred and have no maintenance actions.

The focus of this study is on the bridges which belong to MOMRA in Saudi Arabia in Eastern Province. MOMRA has issue a manual for bridges and tunnels maintenance and management system. The manual suggests a methodology for bridge prioritization for maintenance and it is discussed further in sections 2.4 and 2.6.5. This methodology, as stated in the manual, requires further judgment of expert engineer for bridges priorities as it can't consider all constraints which

means that the final decision for the selected bridges for maintenance depends on the subjective evaluation of the engineer and this results in an uncertainty in the selected bridges as these bridges may not urgently require maintenance while other bridges are in urgent need for maintenance. In addition, the methodology depends mainly on the database of the bridge management system in which a lot of uncertainties are associated with it as there are no mentioned details for the content of the database. Moreover, the manual did not state the definitions of the factors identified in the methodology.

Therefore, an optimization-based simulation model is developed in this study to provide the best maintenance work plan that aims to maximize the number of beneficial bridges and the level of maintenance for each bridge taking on consideration the importance of the bridge while meeting the constrained budget and also works as a decision support tool to the current methodology to overcome its shortcomings.

1.3 Objectives of the Study

The main objective of this thesis is:

1. To develop an optimization-based simulation module for constrained budget allocation for identified bridges in a certain network.

This goal can be reached by achieving the following:

2. To identify the criteria attributed to bridges' criticality for prioritizing bridges in a network under consideration.
3. To develop a bridge ranking model based on bridge criticality score and condition assessment.

1.4 Significance of the Study

The model developed in this research can be used by municipalities, owners/managers of bridges in urban areas of Eastern Province, to improve the decision-making process for bridge management for effective use of the available budget in an efficient and cost-effective manner. Furthermore, current industry practice in the kingdom assigns budgets based on urgency of the maintenance project alone which is a single criterion. This study recommends improvements to optimize budget allocation for a network of bridges considering multiple criteria and to align the industry with the best international practices that eliminate the subjectivity of the inspector. The model considers the inputs from the owner for the constrained budget and the concerned bridges conditions and then the results of the model is the allocation for each bridge with the recommended maintenance plan.

This study is intended to develop an MCDM model which can assist in the following:

1. Avoiding subjective decision making in measuring the importance of existing bridge for the purpose of maintenance.
2. Providing consistent weight of criteria involved in process of selecting bridges for maintenance.
3. Providing decision-makers with a tool that makes the selection process easier and more effective.

1.5 Scope and Limitations of the Study

1. Only bridges composed mainly of reinforced concrete is considered since most bridges which belong to MOMRA are typically conventional bridges made of reinforced concrete as recognized by the local experts.
2. Deterioration modelling is not be considered as part of the study
3. The condition assessment data for validating and testing the model is gathered from the Municipality of Eastern Province or assumed due to lack of expertise and data.
4. This study focusses on the bridges which belong to Municipality of Dammam since it would facilitate the flow of work, ease the justification of results and save time and cost as the collected data is related only to municipality and thus, they can justify the results at the end.
5. Only bridges of road intersections in urban areas is considered in the study. Other types of bridges such as railway, pedestrian, pipeline and cable bridges are not included as part of the study since all bridges which belong to Dammam Municipality are located in urban areas and the other types of bridges have different consideration for maintenance and these types of bridges can't follow common methodology for maintenance as recognized by the local experts.
6. Only budget constrain is considered in the optimization module

CHAPTER 2

LITERATURE REVIEW

This chapter goes thru the literature and summarizes the previous works done in the same topic of the study. Also, it summarizes the local current practices for bridge management system.

2.1 Bridge Condition Assessment

Transportation infrastructure plays a critical role in the urban development of every metropolitan city. Whether it is for providing safe and reliable commuting methods for the populace or for enhancing the movement of goods which supports economic activity, civil infrastructure is required. Bridges are an important component of the transportation system. In order to ensure the longevity of this asset it is important to maintain it in an effective manner. Imposed loads caused by traffic and environmental on bridges result in physical damage to structural elements which leads to its deterioration (Ryall, 2010). Bridge condition assessments aid maintenance activities by providing a concise description of the current state of the bridge in terms of the internal and external damage that might impact safety or performance of the structure (M. Alsharqawi, Zayed, & Abu Dabous, 2017). Characterizing the current state of a bridge is a challenging task for two main reasons (Rashidi & Gibson, 2011):

1. Many bridge rating systems depend on subjective data which reduces the accuracy of the condition assessment.
2. If the assessment of the bridge's condition was conservative unnecessary costs are likely to incur as a result of the subsequent maintenance activities. In contrast, neglecting actual

deterioration on the bridge could massively shorten its lifespan and increase repair costs in the future.

Bridge Inspection

Bridge management systems commonly employ a methodological procedure to streamline consistency (Ryall, 2010). This procedure follows the four sequential steps that are illustrated graphically in Figure 1 (Rashidi & Gibson, 2011):

1. The external condition of the bridge is examined by a professional inspector.
2. If there is apparent physical damage additional inspection is conducted to determine the actual extent of the deterioration.
3. Inspection data is utilized to match each defect with a score that represents its degree of significance, which is based on a predefined scale with specific weighing criteria.
4. Based on the information contained in the inspection reports and the ensuing analysis of the data for each element, the bridge as a whole is rated. This rate can be used to determine the health of the bridge and can also enable comparing it with other bridges within the transportation network to decide which bridge requires urgent repair.

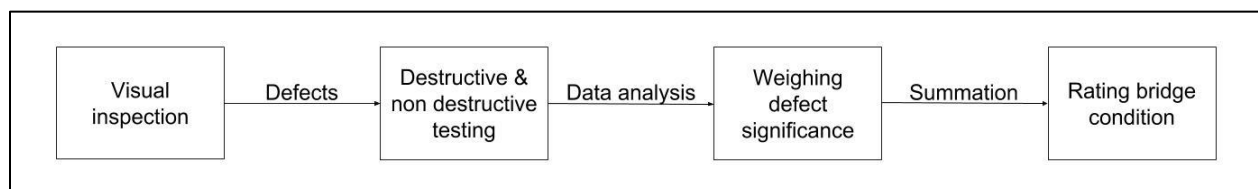


Figure 1 Condition assessment process

Source: (Rashidi & Gibson, 2011)

The process of inspecting a bridge consists of utilizing various methods and tools such as visual inspection, destructive testing and non-destructive testing methods. The following sections describe these methods in detail.

Visual inspection

The process of visual inspection utilizes several human senses, but vision is the primary sense used for bridges. Its purpose is to acquire data from physical objects which can then be used to control quality (Ryall, 2010). This method of inspection is relatively simple and inexpensive due to the fact that it does not require sophisticated equipment or material. In addition, it can be done during operation of the bridge, it does not damage the tested elements and it is effective in detecting surface defects like cracks. Nevertheless, there are two main issues that impose limitations on visual inspection. Firstly, only surface damage can be detected by visual inspection. This means that deterioration such as the corrosion of steel reinforcement and delamination is not be detected by this method (M. Alsharqawi et al., 2017). Secondly, the results of visual inspection are subjective because they rely on the personal judgement of the inspector. Consequently, the accuracy and precision of the output is decreased (Graybeal, Phares, Rolander, Moore, & Washer, 2002).

Destructive testing

Destructive testing is the process of collecting actual samples from an object and then testing their mechanical properties, such as compressive and shear strengths by imposing loads that cause their failure (Bungey, Millard, & Grantham, 2006). The results of these tests are highly accurate since they neither extract data indirectly from interpolation nor depend on subjective input from inspectors (M. Alsharqawi et al., 2017). The downside to destructive testing is that it requires

coring the structural element which is expensive, and it is likely to require stopping traffic or rerouting the road while the tests are conducted (White, 1992).

For the purpose of bridge condition assessment, the most commonly used method for destructive testing is conducted by taking a core sample from a bridge component. It could be from the bridge deck, superstructure or substructure. The void of the displaced concrete is be replaced with a stronger material that possess high adhesive strength leaving the area with excess capacity (Mohammed Alsharqawi, Zayed, & Abu Dabous, 2017). Table 1 provides a list of the common destructive testing methods.

Non-destructive testing

The evaluation of material properties without impacting its performance or dimensions is defined as non-destructive testing (Ryall, 2010). This can be achieved through various techniques such as acoustical, electrical and electromagnetic signals (Mohammed Alsharqawi et al., 2017). Non-destructive testing of bridges is highly beneficial since it can extract accurate data without damaging any component of the bridge. Furthermore, it can be conducted while a facility is being operated. However, non-destructive inspection requires highly trained professionals to use sophisticated equipment, analyze data and translate it into a concise description of the current state of the object being inspected (Abu Dabous, Yaghi, Alkass, & Moselhi, 2017). Table 2 summarizes common non-destructive methods used for bridge condition assessment.

Table 1 List of destructive testing methods

Method	Brief description	References
Static testing	Static testing can be applied on bridge structural elements either by taking a core sample and testing it in a lab or in-situ tests. These methods are used to provide evidence that the bridge can withstand the assigned load rating.	(Bungey et al., 2006; Faber, Val, & Stewart, 2000)
Dynamic testing	Vibration testing can be induced on a full-scale bridge in order to obtain data regarding the dynamic response, induced excitation and modal parameters which simulate the loads imposed by traffic.	(Douglas & Reid, 1982; Salawu & Williams, 1995)
Durability tests	Durability testing methods are applied to bridges that are suspected to have structural integrity and reliability issues. These tests are conducted on site and detect deterioration that can't be detected visually such as, localized corrosion, asphalt deterioration and measure the amount contaminating materials present in the bridge.	(Park, Choi, Lee, & Hwang, 2009; VASSIE, 1984)

Table 2 Summary of non-destructive methods

Method	Brief description	References
Hammer sounding	Detects delamination in bridge deck by hitting the surface with a hammer. A clear ringing sound indicates the absence of defects.	(Graybeal et al., 2002; Rens & Kim, 2007; Watanabe, Even, Morales, & Ishi, 2015)
Chain dragging	Identifies moderate to severe delamination in horizontal surfaces by dragging a chain. Once the sound dampens delamination is indicated.	(Almond, 2003; M. Alsharqawi et al., 2017; Graybeal et al., 2002)
Half-cell potential	Detects corrosion in steel reinforcement by measuring the difference of potential between two points.	(Elsener, 2001; Elsener, Raupach, Gulikers, Andrade, & Polder, 2006; Estes & Frangopol, 2001)
Infrared thermography	Measure the energy radiation emitted from concrete to identify delamination	(Abu Dabous et al., 2017; Kee, Popovics, Oh, Arndt, & Zhu, 2011; Omar, Nehdi, & Zayed, 2018)
Ultrasonic pulse-echo	Ultrasonic waves are propagates with specific frequencies to detect flaws in material	(M. Alsharqawi et al., 2017; Gaafar, Afifi, & Mekawy, 2009; Kohl & Streicher, 2006)
Impact echo	Acoustical method that transmits soundwaves to identify defects such as cracks, deboning and honeycombs	(Kee et al., 2011; Maher, Slabaugh, Fang, Wang, & Gucunski, 2008; Zhu & Popovics, 2007)
Ground penetrating radar	Images subsurface condition by utilizing radar pulse to detect corrosion	(Abu Dabous et al., 2017; Jol, 2008; Maierhofer, 2003)

2.2 Bridge Maintenance Planning

Maintaining civil infrastructure is a challenging task that is important to keep bridges in a safe and serviceable condition in cost effective manner. Periodic civil infrastructure maintenance is critical need for a safe and competent transportation system. (Ng, Lin, & Waller, 2009) Nowadays municipalities and transportation agencies have started to utilize Geographic Information System (GIS) to keep records of their bridge assets (She, Aouad, & Sarshar, 1999). The purpose of this activity is to have sufficient information on a network of bridges to aid in inspection and maintenance planning so that any deterioration is detected early, repair defects impacting bridge performance and extend the lifespan of the bridge for as long as possible. Figure 2 illustrates the bridge lifecycle stages (Ryall, 2010).

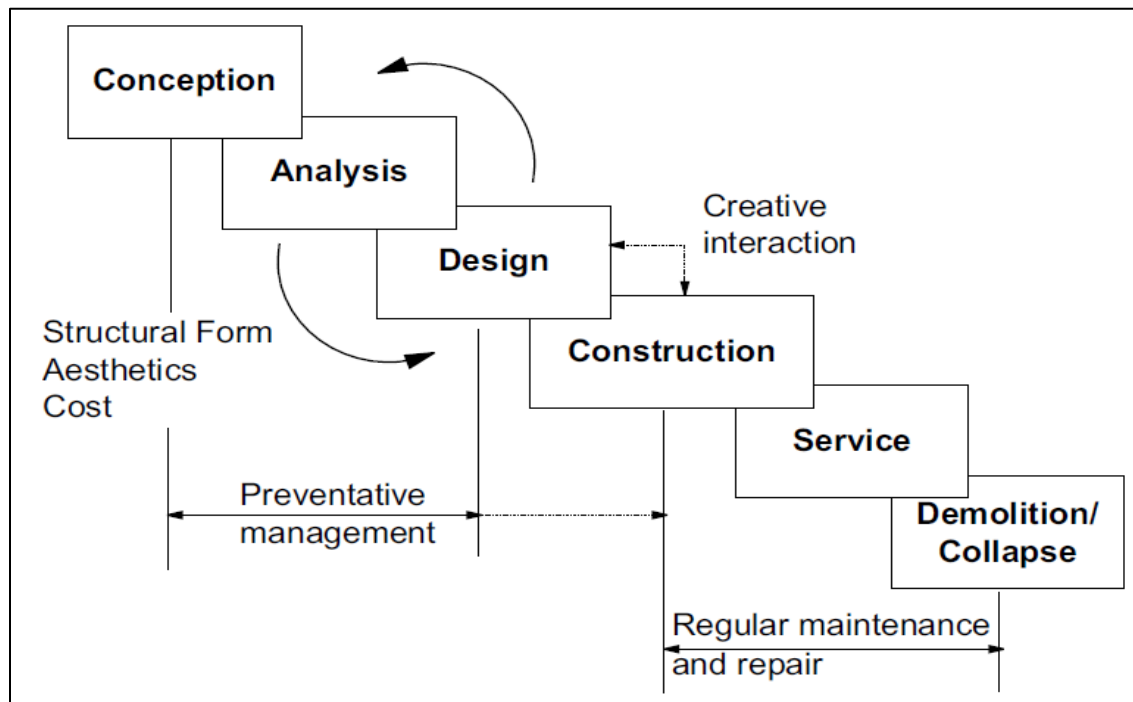


Figure 2 Bridge lifecycle

Source: (Ryall, 2010)

Additionally, this record possesses valuable information such as traffic volume, peak traffic time, inspection and maintenance history and the design of the asphalt and the structural components. All this data is utilized to determine the criticality of the bridge, which in turn can be used for bridge management decision making purposes. For example, a critical bridge with a deteriorated condition is prioritized over a less critical one.

2.3 Bridge Management Systems (BMS)

2.3.1. BMS Definition

BMS can be defined as any necessary actions taken to manage bridge network (Gattulli & Chiaramonte, 2005). BMS consists of a database in which all information related to each bridge in the concerned transportation network are available. These data are like bridge design, construction, inspection and testing reports, recent maintenance, and identified damages which helps in prioritization of bridge for maintenance. Having proper BMS locally helps in selecting optimal strategic plans for bridge maintenance (Bleiziffer & Tkalc, 2005).

CBR-DSS (Bridge Remediation Decision Support System), kind of Bridge Management System, has been developed and comprised of two stages, project ranking and remediation planning (Rashidi et al., 2016a). American Pontis bridge management system is a system used in different countries like Hungary after experiencing several systems (MOLNÁR & BAKÓ, 1995). In Croatia the implemented system named HRMOS in which it is based on Danish BMS called DANBRO and also applied in Mexico, Columbia, Malaysia and Saudi Arabia (LARSEN & HOLST, 1999).

2.3.2. Goals of BMS

Goals of BMS are enhancing the existing network and ensuring high level of serviceability (Bleiziffer & Tkalc, 2005; Ryall, 2010), also assists the bridge owners in effectively addressing

the bridge needs (MOLNÁR & BAKÓ, 1995). In addition, BMS is used to achieve economic optimal solutions for repair, considering the economic interests of society into account and maintain safety for the road users, and management and administration of information in the data base (LARSEN & HOLST, 1999).

Bridge management can be thought of as a management tool of resources needed to be spent on inspection, maintenance, repair and replacement of bridges in a certain network (Amini, Nikraz, & Fathizadeh, 2016). BMS takes care about bridges since the time of construction till end of their life expectancy (Ryall, 2010).

2.3.3. Functions of BMS

Functions of any bridge management systems can be as follows (Ryall, 2010):

1. Data collection of basic information of the bridges (Date of construction, physical dimensions, etc.).
2. Periodic inspection of bridges.
3. Condition assessment.
4. Proposing alternatives for repair, strengthening or replacing the bridges.
5. Prioritizing bridges for available budget.

2.3.4. BMS Outline

Figure 3 illustrates the BMS outline (Amini et al., 2016).



Figure 3 BMS Outline

Source: (Amini et al., 2016)

Data flow into the BMS from the bridge administration, directory of transportation agency. The BMS has the ability to update the database and analyze the input data. The results of the analysis are then reported to the decision maker (HUDSON, Carmichael III, Moser, Hudson, & Wilkes, 1987). One example of a conceptual framework for a BMS is presented in Figure 4.

The most important part of BMS is the database in which the bridge information is stored, Table 3 summarize the elements of BMS (Ryall, 2010):

Table 3 Elements of BMS

Source: (Ryall, 2010)

Bridge location	Bridge age	Bridge designer
Bridge contractors	Bridge dimensions	Bridge structure type
Bridge functionality	Bridge importance degree in the transportation network	Bridge condition based on performed inspections
Information related to the repairs and maintenance and bridge history		

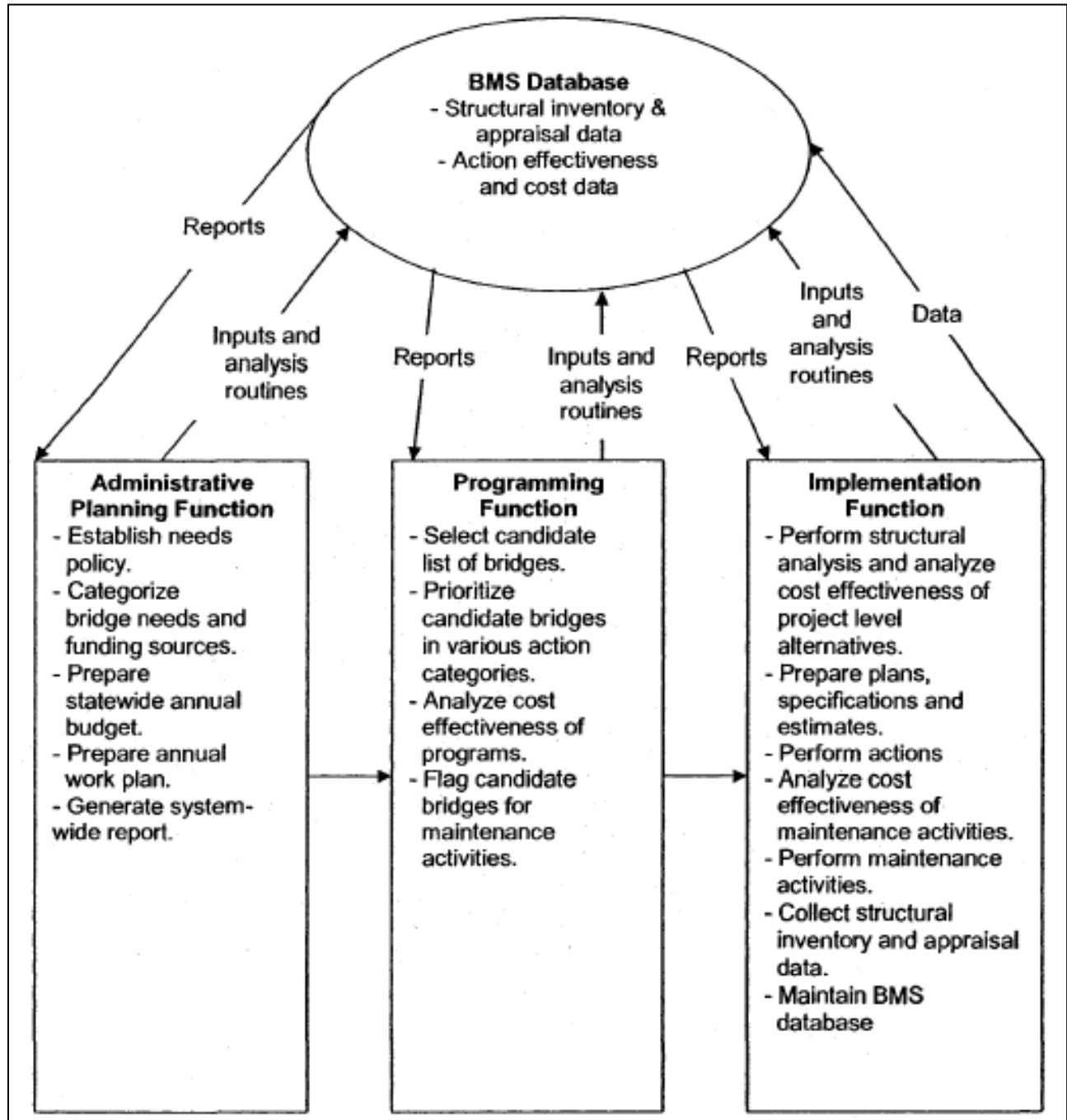


Figure 4 Conceptual Framework for a BMS

Source: (S A Dabous, 2008)

2.4 Bridge Management System in Saudi Arabia

The area of concern in this study is the bridges owned by Municipality of Dammam which belong to Ministry of Municipal and Rural Affairs (MOMRA). All municipalities wide the kingdom report to MOMRA and follow their manuals, standards and specs. MOMRA has issued a manual for bridge and tunnels maintenance called “Bridge and Tunnels Maintenance Manual” and comprised of three parts as below:

1. Part 1: Bridge and Tunnels Maintenance Manual
2. Part 2: Bridge and Tunnels Maintenance Manual – The Contract and Bill of Quantities
3. Part 3: Bridge and Tunnels Maintenance Manual – Bridges, Tunnels and Culverts Management System

The management system mentioned above contain guides about the following: inspection, performance evaluation, reform, documentation, reporting, priorities of maintenance and cost estimates for maintenance.

The manual suggests that the strategies of maintenance can be determined after conducting the general and detailed inspection where needed.

The prioritization procedure recommended by the manual is of three stages. The first stage is to sort bridges based on the condition evaluation according to the given scale. If the available budget covers the total cost then this stage is enough. Otherwise, the next stage is to consider the RA factor to prioritize the shortlisted bridges from the first stage. The RA factor depends on the bridge case, bridge safety, remained age of service and the effect of the bridge on the roads network. If

the budget is still not covering the total cost then the third stage is to rank the bridges shortlisted from the second stage to achieve the optimal maintenance strategy of each bridge considering the cost of each strategy. The guide refers to an optimal strategy of maintenance of the bridge during certain period of time in which the excess money due to deferring the maintenance work in the current year is relatively high compared with the maintenance cost in case of postponing maintenance to longer period of time due to the additional degradation during this period. This method requires calculation of cost to benefit ratio for each bridge according to the equation
$$\frac{\text{(surplus resulted from delaying maintenance works)}}{\text{(age cost + cost resulted from additional degradation)}} = R$$
, lower ratio means high priorities of maintenance.

It can be notice that the first and second stages are used to prioritize a group of bridges for maintenance in which each bridge obtain a rank to be maintained first. The first stage looks easier to apply and has an advantage of considering the overall life of the bridge. The second stage is intended to be used in specific period, thus there is a difficulty in determining the cost due to the additional degradation.

Figure 5 shows the three stages of prioritizing bridges for maintenance.

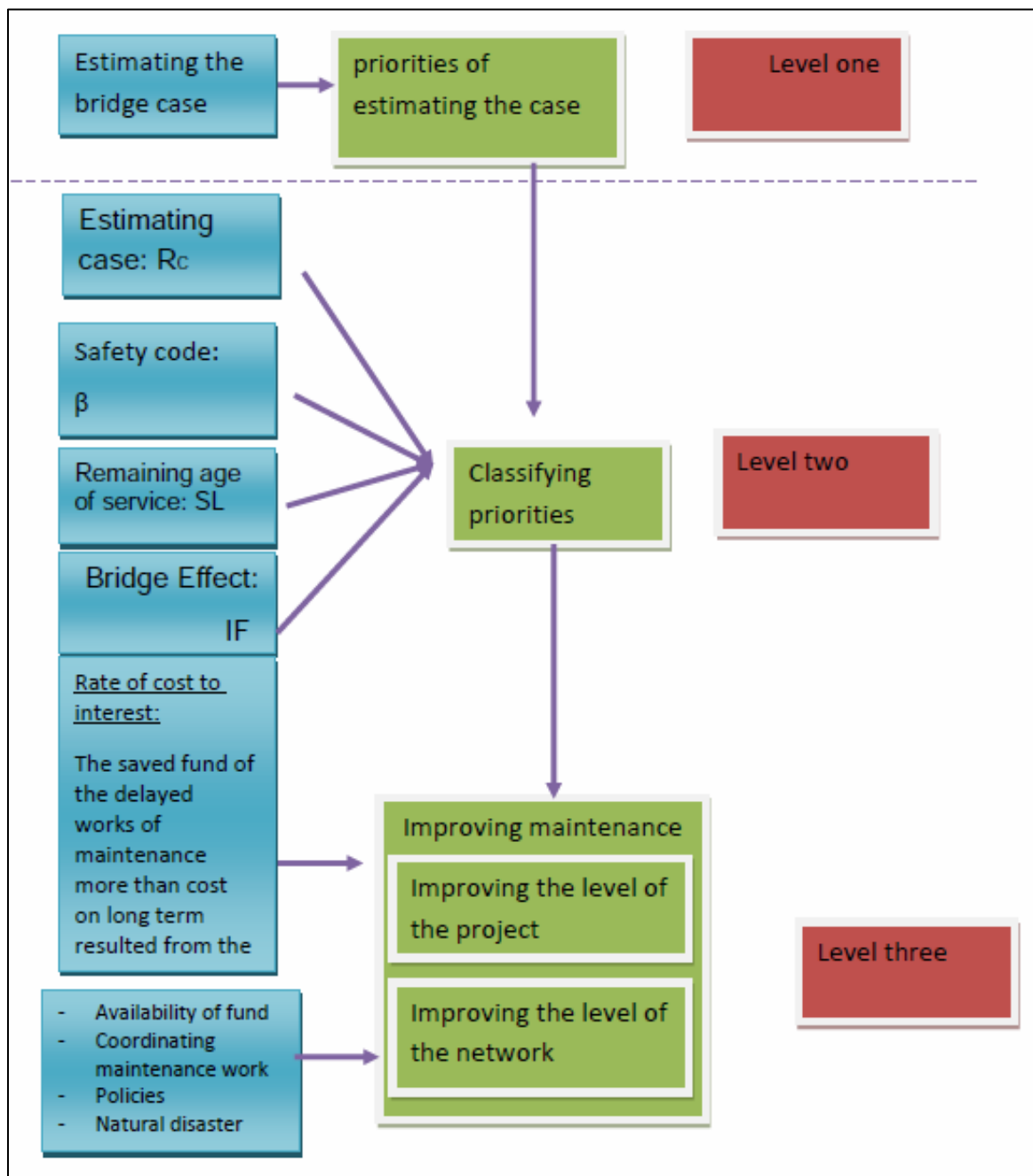


Figure 5 Methodology of maintenance and reform priorities for bridges and tunnels

Source: (Bridge and Tunnels Maintenance Manual - MOMRA 2014)

2.5 Bridge Ranking & Prioritization

One key element of BMS is the prioritization of bridges for maintenance eligibility. Usually, bridges owners, i.e. governments, allocate certain amount of money to do maintenance (Amini et al., 2016). Prioritization model involves setting evaluation factors and rate each bridge in terms of these factors to end up with a total score for each bridge compared with other bridges in the study. Then, the bridges with higher score is more eligible for maintenance than other bridges under the same study (Ryall, 2010). Such factors can be classified into two groups, first group factors that are related to the overall network like location of the bridge, traffic volume, owner assessment. Second group, factor that are related to the bridges itself like the structural conditions. The bridges are compared with each other and then the budget allocated for each bridge is further distributed according the strategies evaluation for each bridge, Figure 6 shows a proposed model for budget allocation (Saleh Abu Dabous & Alkass, 2012).

Bridge management systems take into consideration two levels of decision making, Project (bridge) level and Network level. First, at project-level bridge management which emphasize each bridge individually and is mainly concerned with the maintenance actions each bridge. Project level bridge management handle each bridge accounting for inspection, maintenance, repair, and rehabilitation needs. Second, at network level the main concern here is to handle the evaluate the comment factors among the whole bridges under study in a certain network, factors that represent the real status and conditions of the bridge (S A Dabous, 2008).

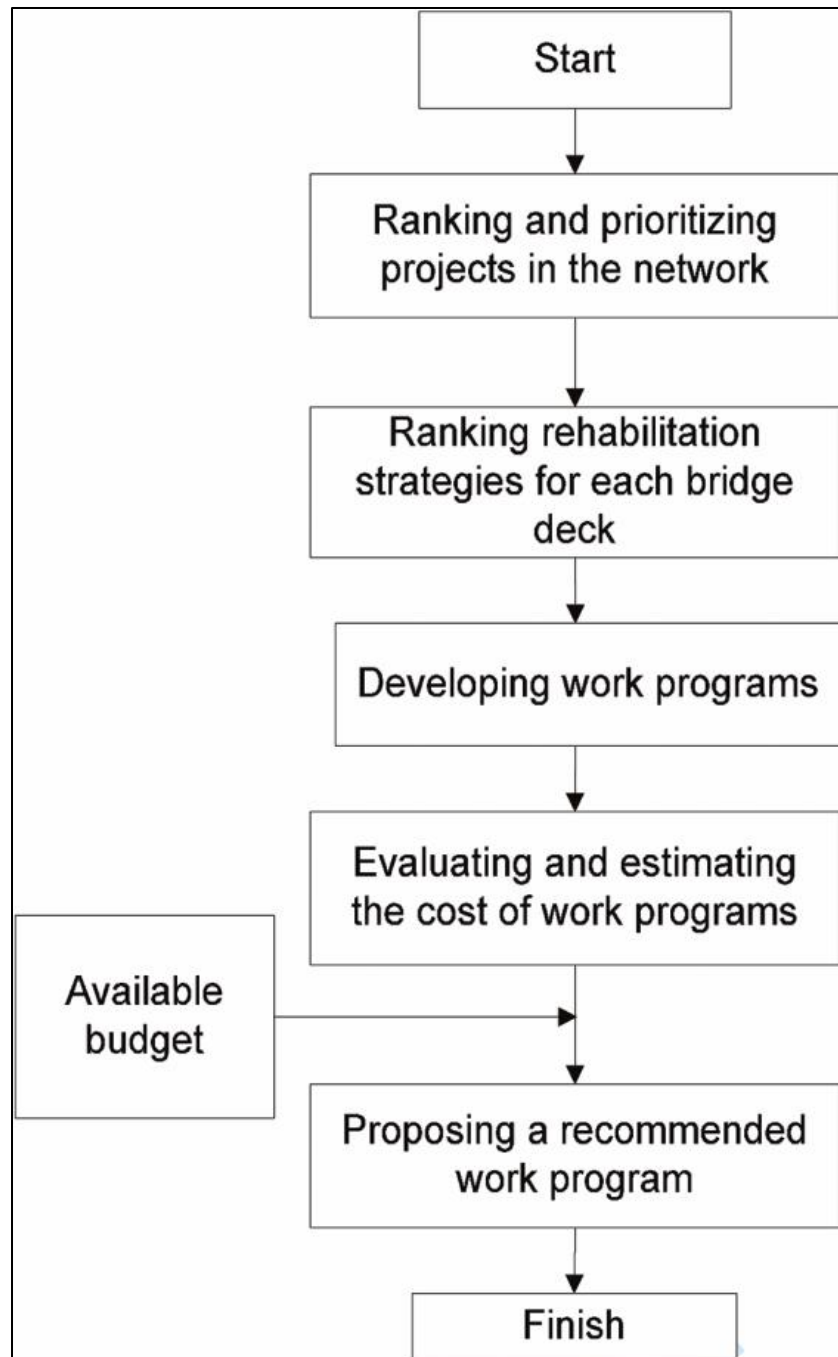


Figure 6 Proposed Workflow for Budget Allocation Model

Source: (Saleh Abu Dabous & Alkass, 2012)

2.5.1. Network-level Ranking

A transportation network consists of large number of bridges that requires first to rank and prioritize its bridges in order to allocate a certain sum from the available budget to each bridge based on pre-determined factors. Figure 9 shows a model work flow for a ranking methods (Saleh Abu Dabous & Alkass, 2012). The model utilizes the MAUT to reflects the experience of bridge managers, or owners. Figure 8 illustrates the hierarchy of ranking goal breakdown (S A Dabous, 2008).

2.5.2. Project-level Ranking

There are several strategies available for maintenance of a bridge. These strategies are like major rehabilitation, minor rehabilitation or increased routine maintenance. These strategies are evaluated based on the following criteria: agency cost, user cost, bridge safety, bridge deck useful life, and environmental impact, Figure 7 depicts a AHP hierarchy structure of choosing rehabilitation strategies. (Saleh Abu Dabous & Alkass, 2012).

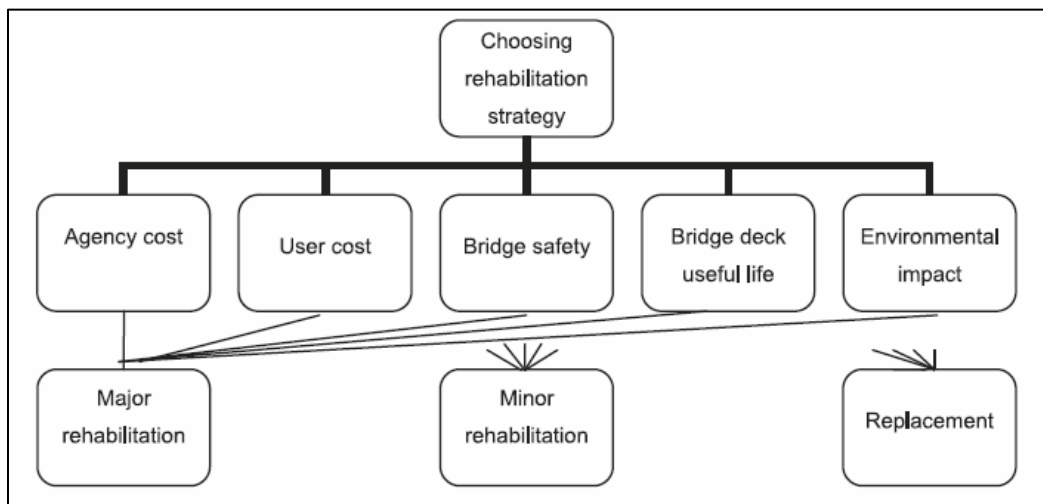


Figure 7 AHP Hierarchy Structure of Choosing Rehabilitation Strategies

Source: (Saleh Abu Dabous & Alkass, 2012)

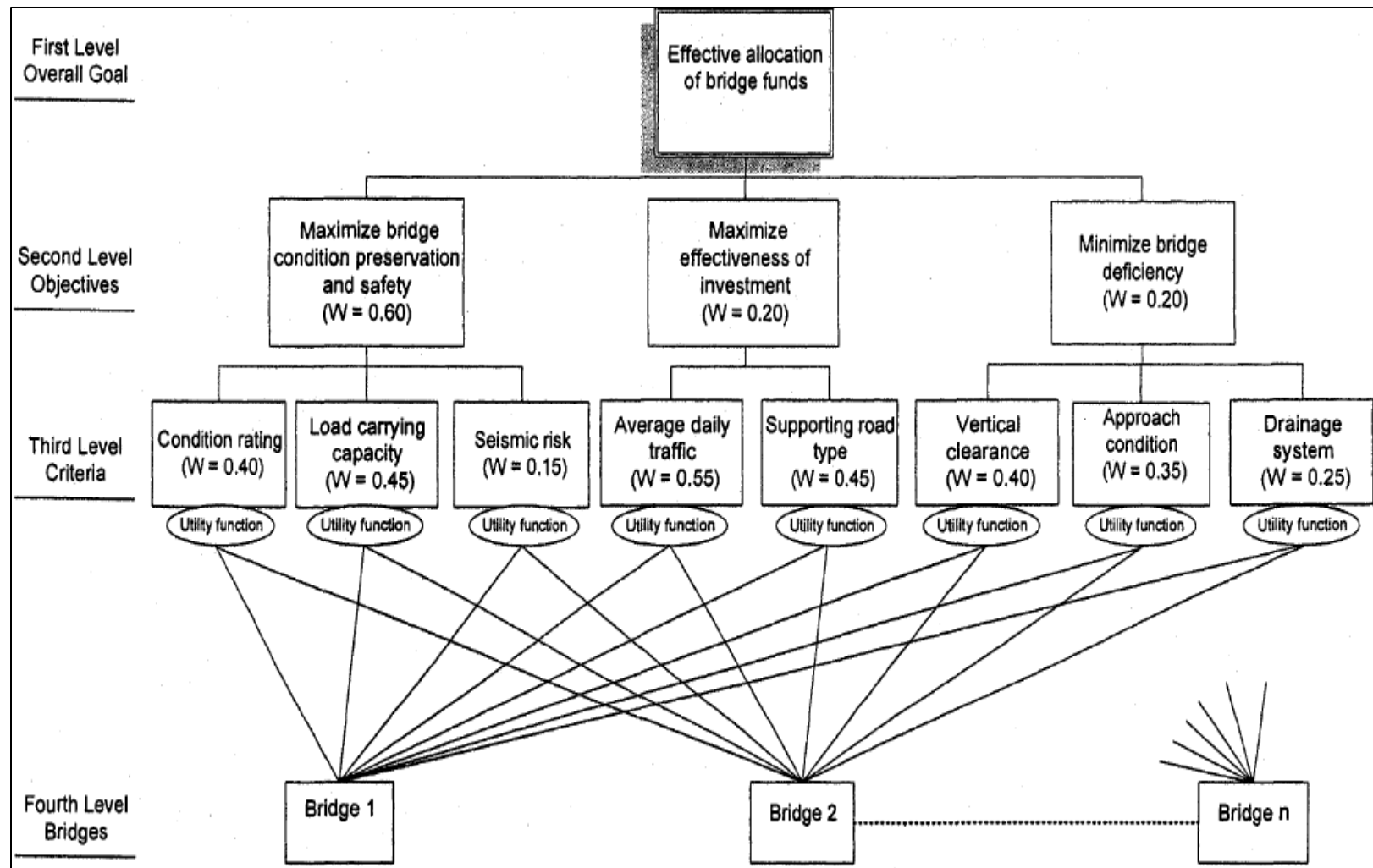


Figure 8 Hierarchy Illustrates the Ranking Goal Breakdown

Source: (S A Dabous, 2008)

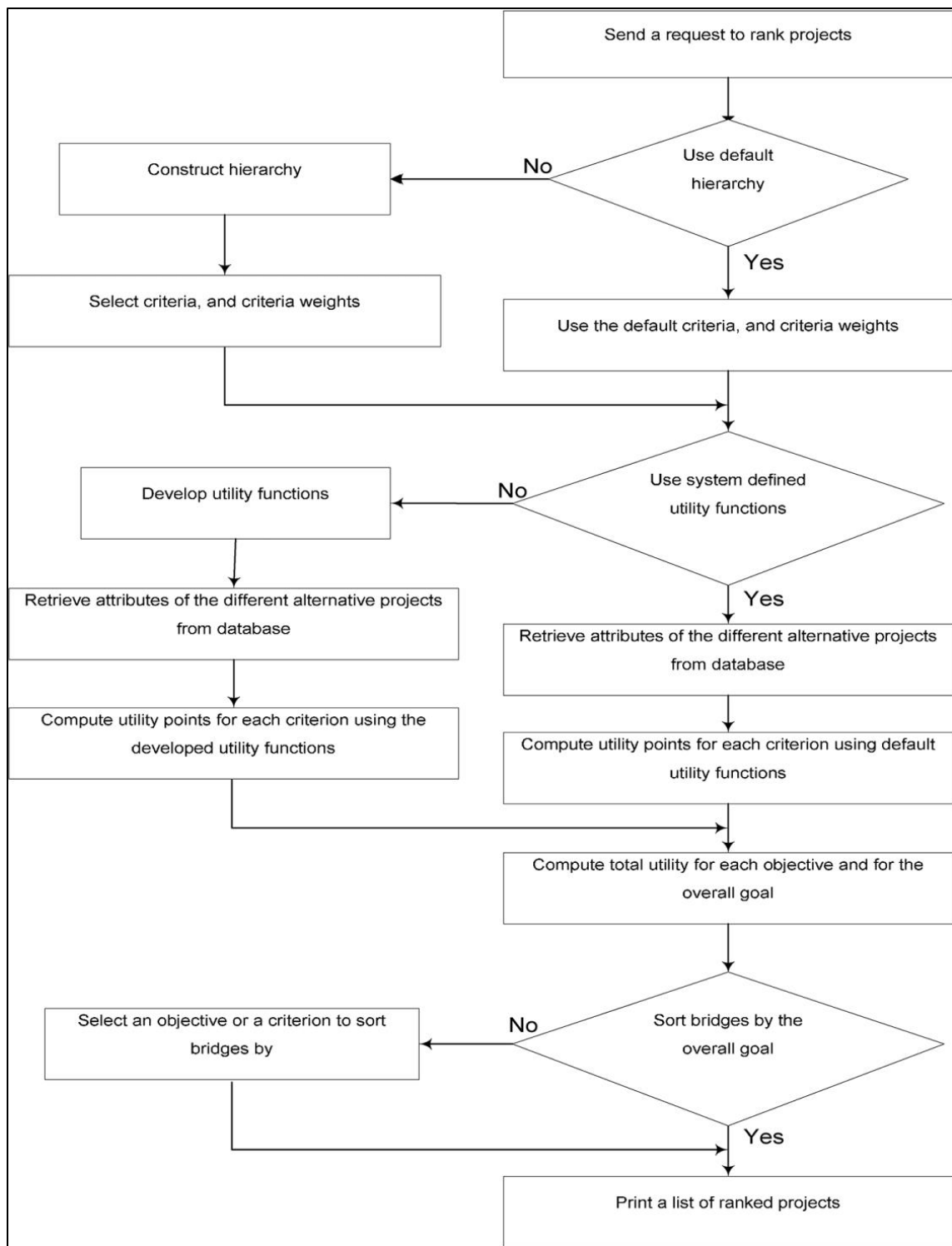


Figure 9 Model Work Flow for a Ranking Methods

Source: (Saleh Abu Dabous & Alkass, 2012)

2.5.3. Criteria for Prioritization

Literature reveals that, several studies spent efforts to resolve the issue of prioritizing bridges within certain transportation network. This requires the design of a database model to process these data based on several parameters. Depending upon the accuracy required and the power of the model the complexity is determined. Based on the previous researches which were conducted in different geographic locations Table 4 summarize the factors of these studies (Amini et al., 2016). These factors were classified into four main categories as described in Table 5. The whole factor may not be applied in all geographic location. Accordingly, in order to properly reflect the real need of bridge maintenance, an interview with bridges maintenance departments in Municipality shall be conducted to sort out the factors that really affects the priority of bridges in the area of study.

Table 4 Summary of Factors of Prioritization

Source: (Amini et al., 2016)

No	Country	Parameter
1	UK (Ryall 2001)	1-Bridge condition factor, 2-Bridge location factor, 3-Bridge route factor
2	Australia (Rashidi et al. October 2013)	1-Structural significance, 2-Material vulnerability, 3-Age, 4-Environmental aggressive factor, 5-Road class, 6-Inspection quality, 7-Load-bearing capacity, 8-Vertical clearance, 9-Width, 10-Bridge barrier, 11-Drainage system, 12-Socioeconomic, 13-Political, 14-Historical
3	Chile (Valenzuela et al. 2010)	1-Strategic importance, 2-Hydraulic vulnerability, 3-Seismic risk, 4-Bridge condition
4	Thailand (Rashid and Herabat 2008)	1-Traffic speed, 2-Traffic volume, 3-Bridge condition, 4-Bridge load-bearing capacity 5-Remaining service life, 6-Bridge structure inventory and condition appraisal 7-The clear deck width in metres, 8-Number of accidents per year, 9-Agency cost, 10-Vehicle operating cost, 11-Travel time savings after maintenance in minutes, 12-Visibility distance in metres, 13-Savings in accident costs after maintenance
5	Vietnam (Hai 2008)	1-Bridge location, 2-Volume of traffic passing over the bridge, 3-Bridge load-bearing capacity
6	Belgium (Woodward et al. 2001)	1-Bridge maintenance history, 2-Geotechnical conditions at Bridge site, 3-Danger due to bridge collapse
7	Germany (Woodward et al. 2001)	1-Type, severity, size and extent of the bridge components destruction 2-Type of path which bridge is located on, 3-Traffic safety passing through the bridge 4-Availability of personnel, machinery and materials required for maintenance, 5-Bridge free deck space
8	France (Woodward et al. 2001)	1-Bridge condition, 2-Type of path which bridge is located on, 3-Maintenance division facilities, 4-Minimum budget allocated for maintenance division, 5-Bridge political importance
9	Norway (Woodward et al. 2001)	1-Type, severity, size and extent of the bridge components destruction, 2-Comparison between the cost of repairing and replacing the bridge
10	Finland (Woodward et al. 2001)	1-Type, severity, size and extent of the bridge components destruction
11	Slovenia (Woodward et al. 2001)	1-Volume of traffic passing over the bridge, 2-Type, severity, size and extent of the bridge components destruction, 3-Type of path which bridge is located on
12	Portugal (Woodward et al. 2001)	1-Type, severity, size and extent of the bridge components destruction, 2-Traffic safety passing over the bridge
13	Sweden (Woodward et al. 2001)	1-Bridge efficiency enhancement after repair
14	Greece (Chassiakos, Vagiotas, and Theodorakopoulos 2005)	1-Type, severity, size and extent of the bridge components destruction, 2-Volume of traffic passing over the bridge, 3-Type of path which bridge is located on, 4-Bridge structure type, 5-Bridge age
15	Netherland (Klatter, van Noortwijk, and Vrisou van Eck 2002)	1-Traffic safety passing through the bridge, 2-Bridge aesthetics, 3-Bridge load-bearing capacity, 4-Construction quality 5-Passing convenience
16	BRIME (Woodward 2001)	1-Bridge condition, 2-Traffic safety passing over the bridge, 3-Costs due to traffic delay, 4-Type, severity, size and extent of the bridge components destruction 5-Bridge construction quality, 6-Bridge age, 7-Bridge historical importance, 8-Bridge aesthetics, 9-Taffic volume passing over the bridge, 10-Deterioration prediction based on bridge initial designing
17	Canada (Elbehairy 2007)	1-Disruption of public services due to repair operations, 2-Volume of traffic passing over the bridge, 3-Type of path which bridge is located on, 4-Bridge structure type 5-Bridge free deck space
18	USA (Maryland and Wisconsin states) (Pesti et al. 2003)	1-Bridge structure type, 2-Weather information, 3-Volume of traffic passing over the bridge, 4-Bridge accident history
19	USA (Texas State) (Zhang 2002)	1-Bridge age, 2-Bridge condition, 3-Volume of traffic passing over the bridge
20	Iran (Alikhani 2009)	1-Bridge seismology position, 2-Air pollution rate, 3-Environment humidity, 4-Temperature changes at bridge site, 5-Filling of expansion joints over time and their dysfunctionality, 6-Blockage of drainage channels and insulators destruction, 7-Oil and chemical material pouring from vehicles on the bridge, 8-Use sand or salt to prevent vehicles from sliding, 9-Bump creation because of pavement destruction and damage to bridge caused by vehicles crossing the bridge, 10-Vibrations affect the bridge because of it is located on underground excavation or transportation routes, 11-Vibrations on the bridge because of it is located next to urban development projects, 12-Soil Erosion at bridge foot by the surface and sub-surface water, 13-Fatigue (bridge loading cycle during the day), 14-Bridge importance in time of crisis, 15-The annual rate of increase or decrease in traffic, 16-Availability of personnel, machinery and materials required for maintenance, 17-Cost of bridge repair, 18-Volume of traffic passing under the bridge, 19-Volume of traffic passing over the bridge, 20-Bridge free height, 21-Bridge military importance, 22-Bridge structure type, 23-Bridge design and construction code, 24-Low quality of bridge construction, 25-Geotechnical conditions at bridge site, 26-Condition and maintenance history, 27-Bridge appearance, 28-Type of path which bridge is located on, 29-Maximum and average speed of vehicles passing over the bridge

Table 5 Factors Categorized in Four Groups

Source: (Amini et al., 2016)

No	Main factor	Sub-factor
1	Destruction and environmental	Environment humidity
2		Air pollution rate
3		Bridge hazardous seismology position
4		High temperature variations at bridge site
5		Risky geotechnical conditions at bridge site
6		Blockage of drainage channels and insulators destruction
7		Failure of expansion joints because of filling by dirt and debris
8		High average of annual rainfall and rainfall continuation
9		Oil and chemical material pouring over the bridge by passing vehicles
10		Sand or salt usage to prevent vehicles from sliding
11		Bump creation because of pavement destruction and damage caused by passing vehicles
12		Effects of vibrations because underground excavation or transportation
13		Effects of vibrations because of nearness to urban development projects
14		Soil erosion at bridge foot because of surface and sub-surface water
15		Maximum and average speed of vehicles passing the bridge
16		Fatigue (bridge loading cycle during the Day)
17		Bridge design errors
18	Destruction losses	Bridge accidents history (previous damages caused by accidents)
19		Maintenance history (poor or incomplete maintenance)
20		Low construction quality
21		Bridge load-bearing capacity reduction
22		Life and financial damages due to bridge collapse
23	Funds, logistic and information	Costs arising from traffic delays
24		The annual rate of increase or decrease in traffic
25		Disruption of public services due to repair operations
26		Accessibility to weather information
27		The fuel consumption rate of vehicles passing the bridge if they pass a longer detour during the repair operations
28	Strategic and condition	The amount of funds allocated for repairs
29		Cost of bridge repairs
30		Difference between repairing cost and replacing cost of the bridge
31		Bridge efficiency enhancement after repair
32		Availability of personnel, machinery, technology and materials required for maintenance
33		Type, severity, size and extent of the bridge components destruction (joints, structure ...)
34		Volume of traffic passing over the bridge
35		Volume of traffic passing under the bridge
36		Traffic safety passing the bridge
37		Bridge importance in crisis or disaster time (like earthquake)
38		Type of path which bridge is located on (highway, the main route or shortcut route)
39		Bridge structure type (concrete, steel, pre-stressed concrete) in terms of ease of operation and maintenance
40		Bridge political and symbolic importance
41		Bridge military importance
42		Bridge appearance
43		Bridge free height
44		Bridge historical value
45		Bridge age

2.6 Maintenance actions

Each bridge has a number of maintenance alternatives based on its condition, these are mainly major rehabilitation, minor rehabilitation or additional routine maintenance. The rehabilitation options range from do-nothing to complete replacement. (Saleh Abu Dabous & Alkass, 2012).

Analyzing each bridge project individually to select the appropriate Maintenance, Repair and Replace (MR&R) strategy is normally referred to as the project level decision making. Actions taken by MR&R could be either routine maintenance, minor repair, major repair, and replacement. (S A Dabous, 2008).

CBR-DSS, a kind of BMS, consists of two key stages that are project ranking and remediation planning. In remediation planning, it is proposed for better strategy selection. It comprised of the following elements. Determining the possible courses of action, main constraints, and selection of the best decision analysis tool. Figure 10 illustrates CBR-DSS model (Rashidi, Samali, & Sharafi, 2016b).

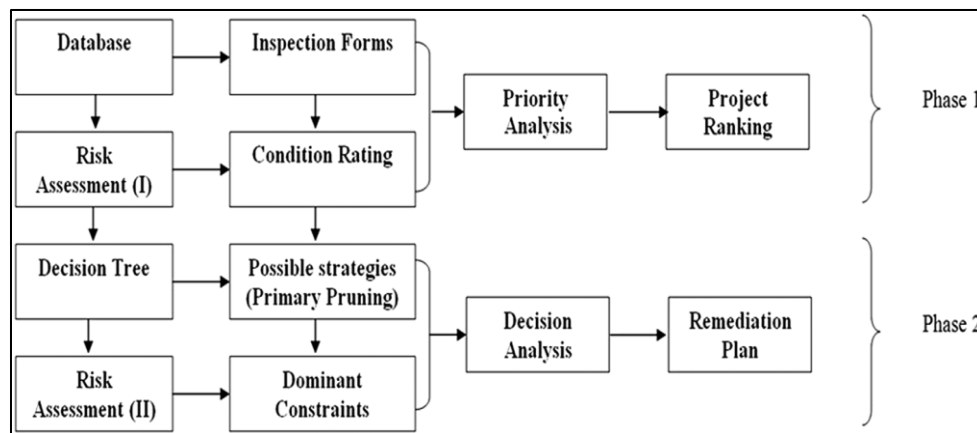


Figure 10 CBR-DSS Model

Source: (Rashidi et al., 2016a)

Further in this model, the decision tree, in phase 2 in remediation plan, is a tool for sorting all possible alternatives for bridge maintenance. It is depicted in Figure 11. It is observed that it consists of three levels. The first two level major potential strategies and the third level represent the minor ones, examples (Rashidi & Lemass, 2011).

Maintenance can be further classified as preventive maintenance and essential maintenance. Preventive maintenance is conducted to keep the structure of the bridge in a safe condition and if neglected then eventually costs more in late stages. Whereas the essential maintenance is required to keep the structure safe. The preventive maintenance is further divided into proactive and reactive. Proactive is applied before any weakening. Reactive is applied only after some weakening appear (Noortwijk & Frangopol, 2004).

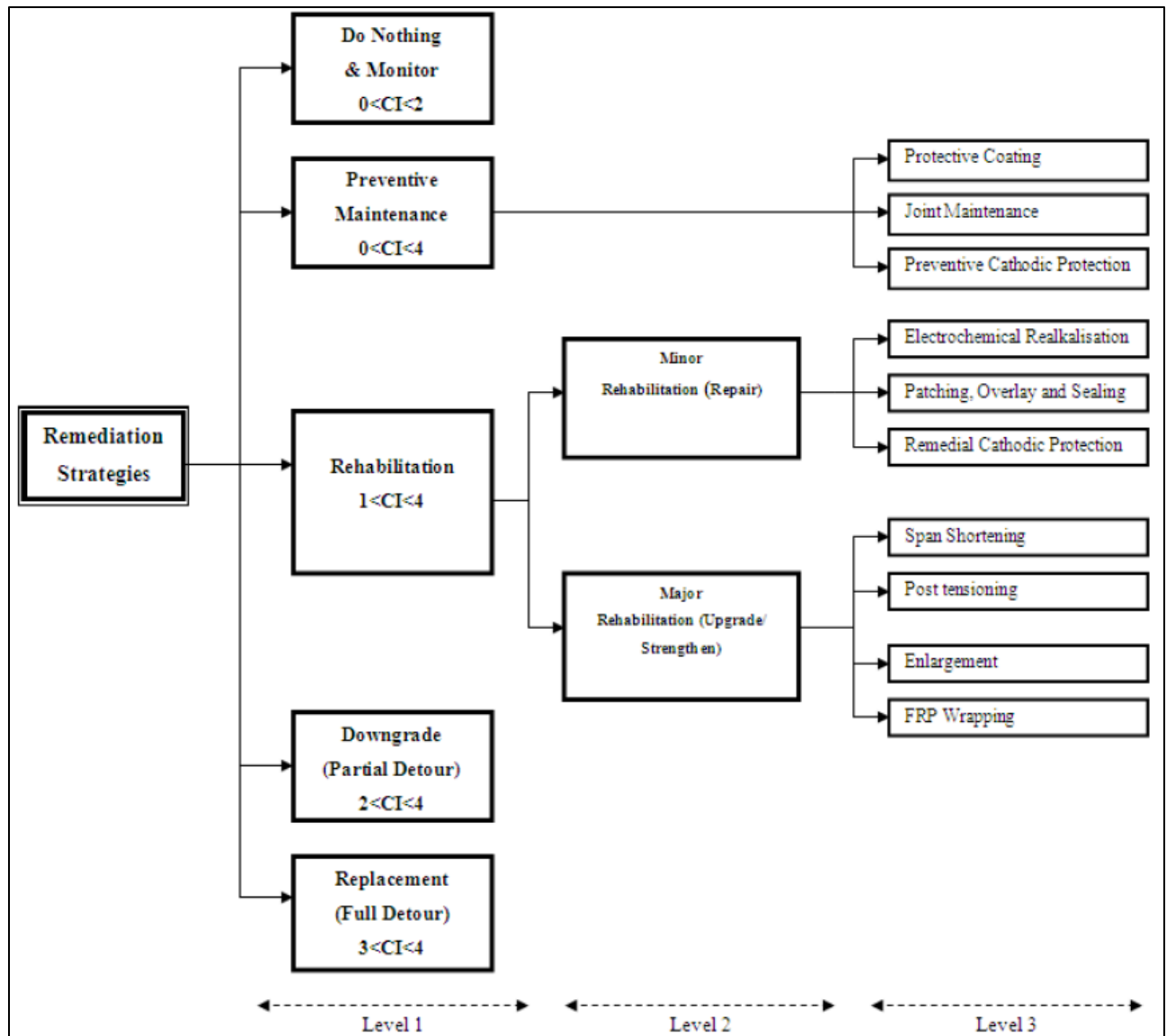


Figure 11 Proposed Remediation Plan

Source: (Rashidi & Lemass, 2011)

In making decisions related to whether to replace, repair or maintenance of bridges another concept is introduced here which is the condition states. It is subjective assessment consists of five ratings that are 'excellent', 'good', 'fair', 'poor' and 'critical'. Their definition is described in Table 6. It suggests a maintenance strategy based on the condition state of a bridge (Wakchaure & Jha, 2012).

Table 6 Condition States

Source: (Wakchaure & Jha, 2012)

Condition state	Description
I (Excellent)	Sound structural condition; components do not individually or as a whole impair the strength, stability, traffic safety, durability and serviceability of the structure; only constructional deficiencies may be present. Extent of deficiencies is nil or insignificant; severity of deficiencies is very low; no need of repair except routine maintenance. Functionality of bridge is more than adequate.
II (Good)	More than satisfactory structural condition; components do not individually or as a whole impair strength/stability; traffic safety, durability and/or serviceability of the structure might be impaired slightly in the long term. Extent of deficiencies is minor; severity of deficiencies is low; no urgent action needed except low cost regular maintenance works; specialized maintenance and repairs may be needed at convenience. Functionality of bridge is adequate.
III (Fair)	Satisfactory structural condition; strength, stability and traffic safety of the components/structure are assured; however, considerable reduction is possible in the long term; serviceability and durability of the affected component are reduced and durability of the structure might be impaired considerably in the long term. Extent of deficiencies is major; severity of deficiencies is medium; specialized maintenance and repairs needed soon; some damage needs monitoring. Functionality of bridge is just adequate.
IV (Poor)	Structurally deficient bridge; strength/stability/traffic safety no longer assured; durability may be affected in short term; monitoring is required; restriction of use of the bridge may be needed. Extent of deficiencies is large; severity of deficiencies is high; rehabilitation/replacement on programme basis is needed; measures for reconstruction or warning signs for upholding traffic safety might be necessary in the short term; detailed investigations and economic analysis are required for justification of funds. Functionality of bridge is less than adequate.
V (Critical)	Weak structural condition; partial failure or risk of total failure of the component or as a whole; durability of the structure is no longer ensured; immediate propping of the structure and closing may be required. Extent of deficiencies is very large/expensive; severity of deficiencies is very high; repair/rehabilitation/replacement is required immediately; design strength, expected serviceability and desired remaining service life of a component/bridge can no longer be achieved with economic costs. Functionality of bridge is inadequate.

Four classes of MR&R strategies are available for the decision makers (S A Dabous, 2008):

2.6.1. Replacement of the component:

This strategy is recommended when the component is in a poor condition. Replacing this component improves its condition to excellent rating. It also increases the life of the overall structure. On the other hand, this strategy is costly and when compared with other strategies it is the costliest.

2.6.2. Major Rehabilitation:

This strategy is recommended when the component is in a fair or poor condition and the budget is not sufficient to replace it. Major Rehabilitation of this component significantly improve its condition thus if this component in poor condition then it is improved to good condition.

2.6.3. Minor Rehabilitation:

This strategy is recommended when the component is in a fair condition but required to be improved to good condition. Minor Rehabilitation of this component marginally improves its condition thus the condition may improve from fair to good or poor to fair.

2.6.4. Do Nothing:

This strategy is recommended always. The actions associated with this strategy are routine cleaning of major components like deck slab and drainage system. Also, it is associated with monitoring the condition of each component till the need for major repair or the requirement of complete replacement.

Figure 12 presents three levels of hierarchy generally required to rank the above four MR&R strategies according to the preidentified criteria.

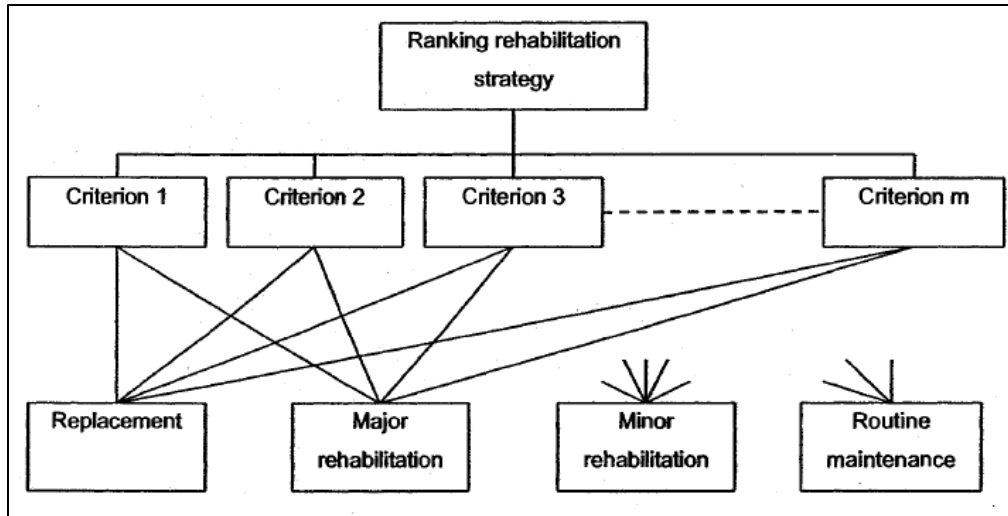


Figure 12 Three Levels of Hierarchy for MR&R

Source: (S A Dabous, 2008)

2.6.5. MOMRA Maintenance Strategies

The manual of MOMRA suggest the following maintenance strategies:

1. Preventive maintenance: prevents the occurrence of damage in the structural components.
2. Remedial/Curative maintenance: intended to ensure the functionality of the structural components within acceptable design and safety requirement.
3. Rehabilitation: restoring the structural components to their original design state after being subjected to several damages that have reduced the design condition or structural capacity of these components.
4. Replacement and Reconstruction: reconstruction of components that have been subjected to several defects which caused damages to these components that reduced the original design state or structural capacity of these components and rendered it unserviceable.

MOMRA has set thresholds for selecting the proper maintenance strategies based on the overall condition of the bridge. Table 7 shows the condition state and the corresponding recommended maintenance strategy. Note that MOMRA as mentioned earlier have a scale of 7-condition states to evaluation bridge condition.

Table 7 Recommended Maintenance

Source: (MOMRA, 2014)

Recommended Maintenances	Preventive	Remedial/Curative	Rehabilitation	Replacement
Condition State	More than 5	5-4	4-3	Less than 3

2.7 Budget Allocation

A suggested work program, as a result of the previous step of ranking bridges in network-level, propose a group of bridges to distribute the available budget to them. Moreover, it also recommends what action of maintenance to be implemented for each bridge. One of the most challenging work of decision makers and bridge managers is to distribute the available budget to bridges in a certain network considering the proper maintenance action for them (Saleh Abu Dabous & Alkass, 2012). Directories of bridge management usually base their decisions on quantitative reports and subjective finding of bridge engineers (Kulkarni, Miller, Ingram, Wong, & Lorenz, 2004). The objective of this work is to distribute the available budget from the bridges owner to bridges that require maintenance taking into consideration the proper maintenance activity for each bridge according to their conditions and factors prioritizing these bridges for maintenance. This process involves a considerable part of subjective judgment and engineers

handling bridges monitoring should be rational about their decisions and they also should utilize the proper decision support tools.

Life Cycle Cost based concept has been evolved to consider the initial and future cost called Life-Cycle Cost Analysis (LCCA). The aim of this concept is to evaluate each alternative in terms of its cost in the long run. The preferred alternative is the alternative that would cost less in the long run. Although this method maybe very useful but applying it could face difficulties in practice when budget available is more or less than the minimum LCC (Saleh Abu Dabous & Alkass, 2012). The recommended work program is developed by assessing several combinations of the different bridges and the available maintenance actions for each bridge. The problem under consideration is difficult to carry out the analysis manually since many possible combinations can be developed and included for consideration.

Due to uncertainties associated with the maintenance cost, optimization-based simulation model can be used to develop and evaluate the various possible work programs. That offers the decision makers with an effective tool to carry out if-then analysis to evaluate different scenarios with high level of confidence

(Saleh Abu Dabous & Alkass, 2012) have developed a model for allocating a bridge maintenance budget that considers the weight of the maintenance actions. The model starts with the first bridge with the highest priority and consider the highest maintenance action. Then the second iteration considers the bridges with highest priority and develop the work program combination. The simulation keeps adding the bridges till reach to a point the simulation generates combinations that produce cost more than the budget available, the combination with the highest score which can

produce the greatest improvement to the sub- network is selected as the best alternative. refer to the work flow in Figure 13.

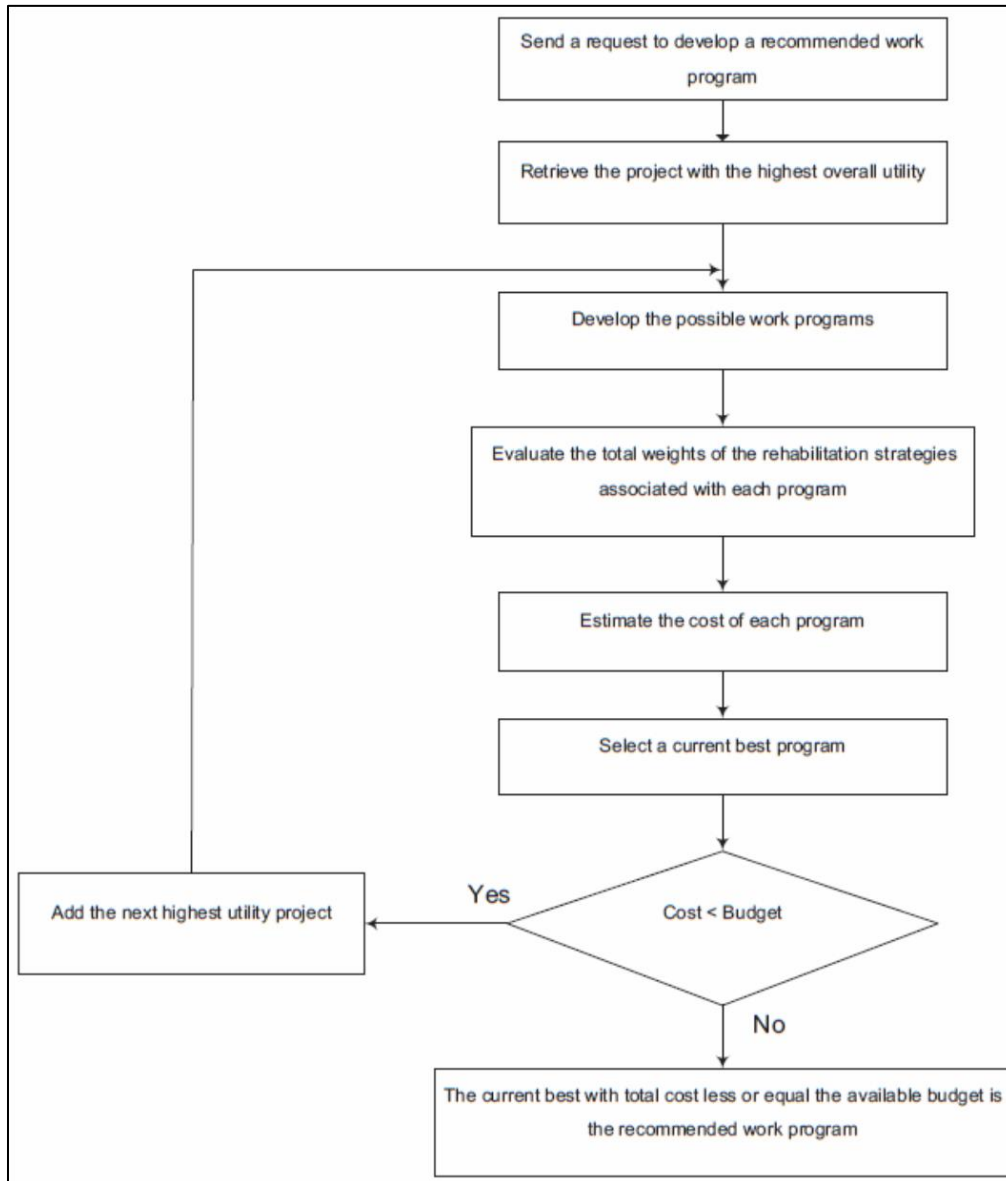


Figure 13 Work Flow of Proposed Simulation Model

Source: (Saleh Abu Dabous & Alkass, 2012)

2.8 Previous work models

The literature reveals that several works on bridge prioritization and for maintenance has been developed in order to solve the budget constrain issue. Researches looked at the subject from different point of views. They all agree on performance goals to be achieved during maintenance. Based on location and condition of the study, other factors may have been considered to represent the current situation to yield better results from the model.

(Bukhsh et al., 2019) have used the MAUT for bridge maintenance planning in Netherlands road network and considered a case study from there. The performance indicators considered in this study are Condition index, Owner cost, User delay cost and Environmental cost. The study has established a single utility function for each of these indicators. Then, each of these indicators have a given weight out of 100. For each bridge given for each of these attributes a score then the score is multiplied by the weight of the same indicator. After that, the scores times the weights are aggregated to come up with the utility value which represent the rank of the bridges.

(Wakchaure & Jha, 2012) have utilized the AHP in order to come up with a weight for every each and single components and their subcomponents. They have utilized a 5-scale condition state to represent the condition of each component. Then, the overall bridge health index can be calculated knowing AHP weights and condition states for each component. As the bridge health index approaches to 100 it means that the bridge is in good health and requires no maintenance.

(Rashid & Herabat, 2008) have developed a prioritization framework for maintenance operations of road facilities. They have utilized MAUT to assists in decision-making process to road facility maintenance. To do so, they identify the prioritization attributes for bridges and other road

elements like roadside elements and traffic control devices and weighted them with the help of local experts in Thailand. The bridge with higher utility value is more prioritized. They have identified 6 objectives and total of 14 performance indicators. The objectives are service, condition, safety, cost, Socioeconomic and energy. The performance indicators are sub factors from the objectives and they are traffic volume and speed under services, load capacity, remaining service life and deterioration under condition, load capacity, clear deck width and occurrences of accidents under safety, agency and user costs under cost, travel time savings, visual quality and saving in accident costs under socioeconomic and fuel consumption under energy.

(Chassiakos et al., 2005) in Greece have developed a knowledge-based system for bridge maintenance. The system has 3 functions that are setting maintenance priority, evaluation of feasible treatment and maintenance planning. Priority is determined by weighted parameters that are defect type, traffic load, riverbed, environmental conditions, bridge age, foundation and superstructure types. Each of these factors have sub-factors and corresponding weights. Then, from these weights the priority index is determined using model score equation. Then, each possible treatment is evaluated by lifetime to cost ratio. Finally, the maintenance plan is evaluated by the cost and effectiveness of the selected treatment and the number of cases treated using model equations developed by the authors.

(Zhang & Wang, 2017) have developed a decision model that assists in determining maintenance prioritization for a set of bridges with constrained budget. They utilized the following techniques: network analysis, structural reliability and meta-heuristic optimization algorithms. they identified certain parameters in order to integrate hem with the mentioned techniques to determine the overall network performance and maintenance cost. The network performance is measured in terms of

travel time between all possible origin and destination. They also introduce two priority indices which are static and dynamic priority index. The static represents the deference between block running and smooth running. The dynamic represents the likelihood of a bridge being selected for maintenance.

(S A Dabous, 2008) worked on a decision support methodology for rehabilitation management bridge decks. In the context of the methodology he presented a mean to rank bridges using the approach of MAUT. The attributes considered are condition rating, load carrying capacity, seismic risk, average daily traffic, support road type, vertical clearance, approach condition and drainage system. With the help of Monte Carlo Simulation and modified AHP a method is discussed to evaluate different rehabilitation strategies for each bridge in the study area. The considered strategies are Routine maintenance, minor rehabilitation, major rehabilitation and replacement. The criteria to evaluate each strategy are agency cost, user cost, bridge safety, useful life and environmental impact.

(Saleh Abu Dabous & Alkass, 2012) this work is further the previous model of Dabous 2008. In this work, for each bridge the owner ranks the rehabilitation strategies and on that basis the model develops a set of combinations of strategies for each of the bridges creating a work program. The work program is then having rank which is the sum of the priority of each strategy comprising that program. The program which costs more than the budget is eliminated. The remaining programs are considered and the one with highest weight is considered.

(Rashidi et al., 2016a, 2016b) have developed a BMS known as CBR-DSS (which stands for Concrete Bridge Remediation Decision Support System). The said BMS comprised of two phases

that are project ranking and remediation planning. In the first phase the follow factors are used to rank the bridges in the network level: structural efficiency (SE), functional efficiency (FE) and client impact factor (CIF). There are subfactors for each of these factors. The weight of each of these factors and subfactors are determined by the AHP. The value of each factor is given either by an equation or a table of states based on the actual or physical measurement of the bridge. Then, the Priority Index (PI) is calculated for each bridge representing the priority of each bridge for maintenance. The second phase of the mentioned BMS is the remediation planning. This phase is depicted as a tree call decision tree which is useful tool for classification of all the possible alternatives of maintenance strategies. It has two levels of decision the first level contains the following strategies: Do Nothing and Monitor, Preventive Maintenance, Rehabilitation and Replacement. The Rehabilitation is further broken into Minor and Major: Repair and Strengthening respectively.

The best remediation plan can be selected by evaluating the following criteria for each strategy these criteria are service life, safety, cost, environmental impact, traffic disruption and legal/political. After conducting the AHP between these criteria the weight of each of them is identified. A score for each of the strategies for each bridge is obtained by prioritize each of them in terms of the above criteria. After that, for each of the bridges shortlisted from the first phase have 3 different strategies for maintenance. These strategies are to be combined to generate alternative maintenance plans. The sum of the scores of each set of strategies gives the score of this alternative maintenance plan. The alternatives which meet the budget is considered as a priority. The higher score of them is the best maintenance plan.

Table 8 Summarize the mentioned work in terms of the techniques they have utilized in their work.

Table 8 Summary of Previous Models

Researcher	Location	AHP	MAUT	Other	Techniques Used
(Bukhsh et al., 2019)	Netherlands		✓		
(Wakchaure & Jha, 2012)	Indian	✓			AHP – Component Weight
(Rashid & Herabat, 2008)	Thailand		✓		Attributes Weights by Experts
(Chassiakos et al., 2005)	Greece			✓	Knowledge-based System
(Zhang & Wang, 2017)	USA			✓	Network Analysis Methods
(S A Dabous, 2008)	Canada	✓	✓		
(Saleh Abu Dabous & Alkass, 2012)	Canada	✓	✓		
(Rashidi, Samali, & Sharafi, 2016c; Rashidi et al., 2016b)	Australia	✓			AHP – Weights of Factors, Factors are being Calculated

The main setback of the previous stated models and systems individually or collectively is that the main consideration is to prioritize the bridges in the network level for maintenance, while the budget allocation of the maintenance strategies is considered for each bridge. Based on the priority of that strategy, the constrained budget and the overall weight of the program, from the weights of the strategies forming that program, the best maintenance program is determined. This shows a lack of link between the considerations of prioritizing the bridges in the network level and the main goal of the study which is allocating the constrained budget for a set of bridges. Also, the proposed

model required a lot of iterative comparisons between the maintenance strategies as an input to the model. Whereas, there is no comprehensive model in which moderate number of inputs is required versus the targeted accuracy of the model. Also, the previous stated models do not consider the uncertainties associated with the maintenance cost and the subjectivities associated with users input values related to the criteria scores. This would make those models not practice and even may mislead the users with maintenance plan that hard to achieve. In the present research, the main setback if the previous models are to be overcome by developing optimization-based simulation model as explained in chapter 4 and 5.

2.9 Summary

This chapter went thru the literature and covered a background about the bridge maintenance practices and bridge management systems in different location. Also, this chapter listed the most common prioritization factors for prioritizing bridges for maintenance and the factors related to Saudi Arabia were identified. In addition, maintenance strategies were discussed. Moreover, models for bridge maintenance planning and budget allocation were discussed and the area of improvement in the previous work is determined. The current practices for bridge management system in Saudi Arabia were also presented and discussed.

CHAPTER 3

RESEARCH METHODOLOGY

In order to achieve the stated objectives of this research, several activities have been identified. Firstly, the criteria for characterizing bridge criticality must be determined. These criteria have a major impact on the planning of maintenance activities. Multicriteria decision making methods are adopted to rank the criteria to prioritize bridges based on the criticality score of each bridge. Secondly, an optimization-based simulation model is developed to allocate a defined budget on a bridge network.

The criteria are obtained from two sources. First source is the literature where a comprehensive review of literature was carried out to come with a complete list of criterions. The second source is local experts in the Saudi bridge maintenance industry. The expert reviews the identified criteria and modify them based on their judgement and experience to suit Saudi Arabian need. Afterwards, AHP is utilized to conduct pairwise comparisons against the criteria to rank them. The prevalence of each criteria is scored against all the bridges in the network by using MAUT. Figure 13 illustrates the aforementioned research methodology. As it can be seen form the figure, the methodology consists of nine main steps as follow:

Step 1: conducting the literature review to identify the factors of prioritization from previous research and in different locations. Also, current practices of Bridge Management Systems (BMS) could be identified from the literature.

Steps 2&3: Review the extracted factors with local experts in Saudi and short-list them to suit the requirement in Saudi Arabia. Local experts' engineers working in Municipality in Bridge and Tunnels Management were able to judge these factors.

Steps 4&5: The factors from Step 3 is the concern of our study. These factors should be ranked and their relative weight contributes to the main objective of the study, that is ranking the bridges in terms of their criticality for maintenance, should be identified. This can be done through conducting AHP analysis on these factors and then establish the MAUT curves for each factor. The required data in AHP is the pairwise comparison between each set of factors. The data required to establish the MAUT curves is the best and worst values and the intermediate values between them, 25%, 50%, 75%. This is done through structured interview. After gathering this data, it is tested for the consistency. If it does not match the required level of consistency the interview is to be repeated. Through the interview of local experts and owners also the local current practices of bridge management can be identified.

Step 6: the data collected and verified is now our analysis parameters to figure out the relative weights of each factor. In addition, the utility curves for each factor are established from the values of best and worst. The equation of the line is determined.

Step 7: Using the established curves, each factor in each bridge is assigned a score according to the bridge condition. The overall score for each bridge is calculated by aggregation of individual factors of a bridge. The score for each bridge represents the bridge priority for maintenance.

Steps 8&9: In this step the constrained budget is distributed according to priority. And then the budget allocated for each bridge is further distributed to each structural element. The model input are the bridges conditions, bridges scores, constrained budget, bridges elements. The model output is the allocated budget for each bridge and for each element of the bridge according to the constraints applied that are the budget, number of bridges and level of maintenance required. Model results were share with local experts looking for their feedback or any additional information which might be helpful in improving the model. Figure 14 shows the model parameters.

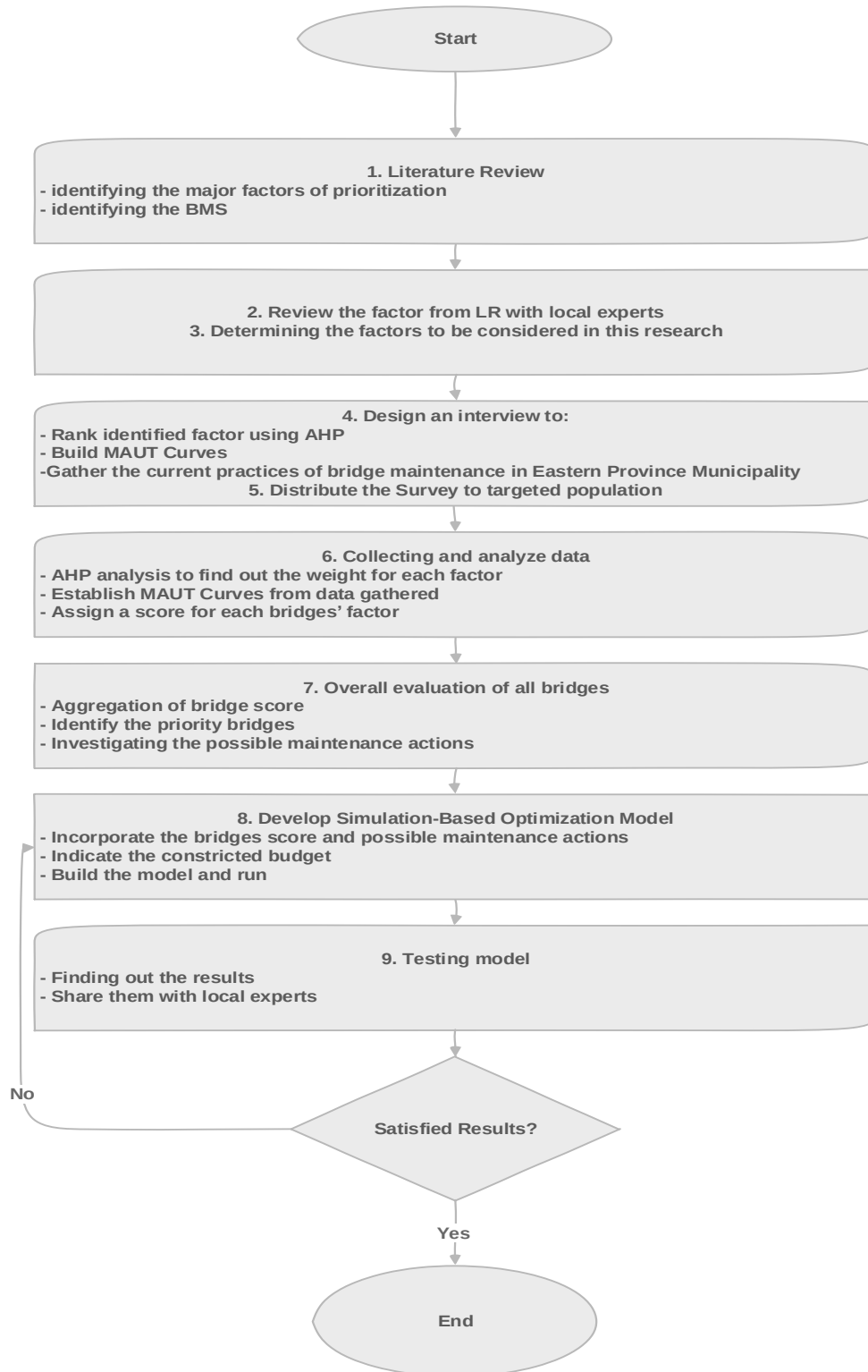


Figure 14 Research methodology

3.1 Multi-Criteria Decision Making Methods

3.1.1. Analytical Hierarchy Process

3.1.1.1. AHP Approach

AHP was first introduced by Saaty (1980). AHP is an approach developed to handle complex problems that have a lot of uncertainties. Also, it assists decision makers to evaluate problems that have a lot of interrelated trading-off factors. The main concept of AHP is to identify the relative importance of these factors contributing to main objective of the problems to enable the trading-off between them. AHP helps problem solvers to systematically handle problems with great number of trading-off factors. These factors might be tangible, intangible, objective and subjective. For instance, the factors considered are bridge condition, age, location, etc., these factors have different contribution for prioritizing bridges for maintenance. The aim here is to identify the amount of contribution of each factor for prioritizing each bridge for maintenance.

3.1.1.2. Hierarchy Construction

The first step in the application of AHP is to decompose the problem and depict it in a hierarchy-type structure. In the first level of the hierarchy the main objective of the problem is set. Factors contributing to achieve the main objective are set in the same hierarchy one level below. These factors are called also attributes. These factors may be further broken down into other factors to achieve them. If the resulted factors have no further subfactors then they are called decision factors or leaf attributes. At the lowest level, leaf attributes, there are all possible alternatives and they all must be linked to leaf attributes possibly affecting their evaluation. The resulted hierarchy structure

must show the interrelationships between the decision factors. Figure 15 show a typical AHP hierarchy.

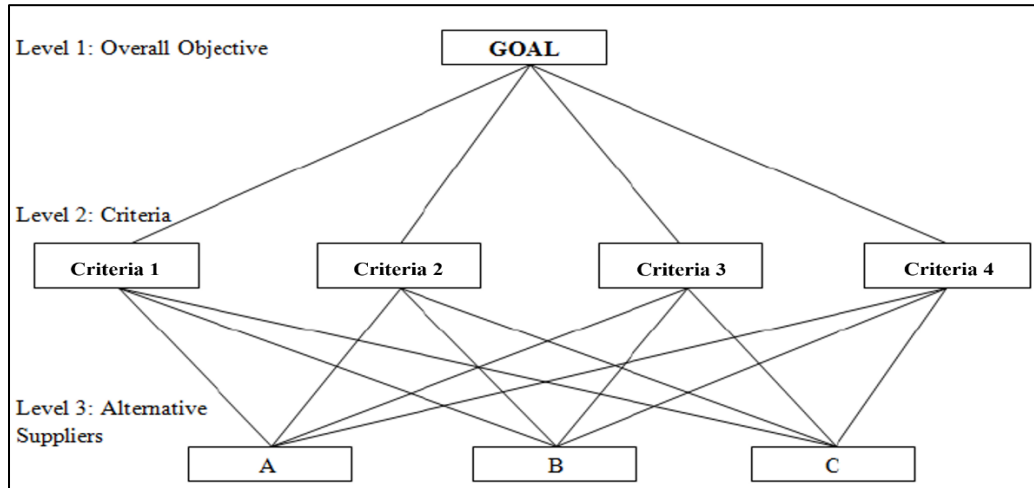


Figure 15 Typical AHP hierarchy

Source: (Shapira, Asce, & Goldenberg, 2006)

For instance, in our case the hierarchy as show in Figure 16

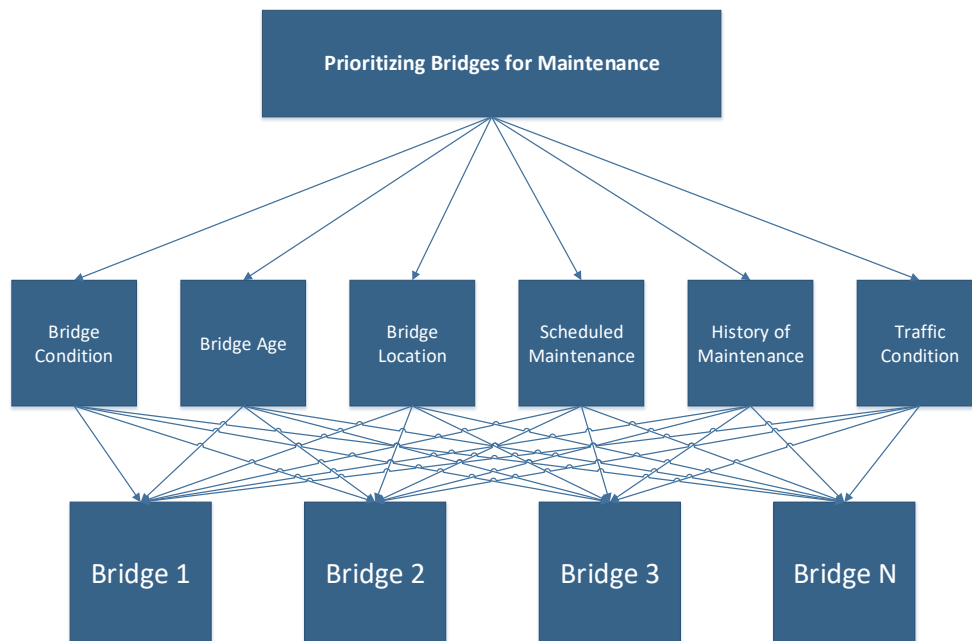


Figure 16 Research Hierarchy

3.1.1.3. Pairwise Comparisons

Second step in the application of AHP is to identify the relative weight of each decision factor by conducting a pairwise comparison. This step is needed to determine which factor have more impact to achieve the main objective. Also, the intensity of this importance is recognized as well. The intensity is according to given scale in the Table 9. This step is done thru conducting a comparison between two factors till covering all possible combinations of factors. The factors are presented in a matrix called decision matrix. This step considered to be the key step in AHP analysis as it determines the intensities of the factors contributing to achieve the main objective of the problem. This step is conducted with local experts thru an interview asking then the two important questions, which factor has more effect or contribution to prioritize bridges for maintenance and what is the amount if impact that has over the other factor. Matrix in Table 10 shows the research matrix. The shaded cells are filled automatically by the reciprocal of the same comparison happen first.

Table 9 Scale of Relative Importance

Source: (Saaty 1980)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over the another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	the evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Table 10 Research Matrix

Bridges Priority Factors	Condition	Age	Location	History of Maintenance	Scheduled maintenance	Traffic Condition
Condition	1	A				
Age	1/A	1				
Location			1			
History of Maintenance				1		
Scheduled maintenance					1	
Traffic Condition						1

3.1.1.4. Relative-Weight Calculation

The eigenvector for the same decision matrix is to be established. It is a priority vector of the factors compared earlier. it represents the relative weights of the factors contributing to the main problem objective. It can be calculated using different approximation methods. Average Normalization Column (ANC) method is one approximation method to establish the eigenvector. According to Saaty, it is the most accurate approximation method. Equation 1 is used to form the eigenvector for a decision matrix of size n x n as follow:

$$w_i = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \quad (3.1)$$

where a_{ij} =element located in row i and column j of the decision matrix.

The matrix in our case is 6 x 6 as we have 6 factors taken into consideration in this research.

3.1.1.5. Aggregation of Relative Weights

The results from the previous step identifies the local relative weight for each factor. Then, in order to find out the feasible alternative these weights are to be converted to global weight by multiplying the local weight for each leaf attribute by the weight of the main factor one level above it till reach the main objective of the problem. The summation of all leaf attribute global weights shall be 1. After that, the overall score of each alternative can be calculated. Hence, by multiplying the corresponding global weight for each leaf attribute by the weight for each alternative the overall score is calculated by summing the products. Thus, this score represents the preference for each alternative which allows to compare between all alternative.

3.1.1.6. Consistency Ratio

Last step in AHP analysis is to determine the consistency of the results form pairwise comparison. AHP allows the subjective assessment of alternatives for best selection thus absolute consistency should not be predicted. Absolute consistency means that if there are three factors X, Y and Z where Y is more important than X by 5 factors and Z is more important than Y by 2 factors then factor Z is more important than X by 10 factors. The formula (3.2) developed by Saaty to calculate and control the inconsistency to a certain desired level. Based on several empirical studies Saaty proposed that the tolerable inconsistency, CR, should not exceed 0.10 regardless of the nature of the problem. In case if the CR goes higher than 0.10 then a revision of pairwise comparison shall be repeated. It does imply to have good results if the CR is below 0.10 rather it means that no random prioritization happens and no intolerable conflict in the comparisons made. The consistency is directly checked after getting the pairwise in order to repeat the comparison again if the consistency does not match according to Equation 3.2:

$$C.R. = \frac{C.I.}{R.I.} \quad (3.2)$$

Where

C.R. is the Consistency Ratio

R.I. is the Random Consistency Index, and is given by Table 11

Table 11 Random Consistency

Source: (Saaty, 2001)

# of Element	3	4	5	6	7	8	9	10	11
RI	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.51

C.I. is the Consistency Index

The deviation from consistent results of pairwise comparison is called consistency index and is given by Equation 3.3:

$$C.I. = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (3.3)$$

Where

n is the number of criteria

λ_{max} is the largest eigenvalue

3.1.2. Multi-Attribute Utility Theory (MAUT)

MAUT is an evaluation technique used to help in complex decisions that have many attributes and multiple criteria. The base for this technique is a quantitative comparison method. It can be used with various criteria like time, cost, safety, and benefits, which have different measuring units along with different contributors and different preferences, and turns these into high-level, collective preferences. Utility functions are the base of MAUT, it converts different factors to one incorporated measurement scale known as the multi-attribute utility. For instance, the utility functions convert different dimensioned scores of attributes (value of the factor) such as Riyals, Kg, Meter, M^3 per minute, etc. to a dimensionless score that ranges between 0 and 1. Once utility functions are built, the raw data of alternatives, can either be subjective or objective, can be transformed to unified scores. The factors considered for a study are weighted based on their importance. Each decision factor has a utility function built for it which can be established based on collected data for each factor. The utility scores are weighted by multiplication of the utility score by the weight of the decision factor, this reflects the decision maker values and the expert opinion and is summed for each alternative. The preferred alternative is the one that sums up the highest score (Baker, 2001).

3.1.2.1. Attribute Utility Function

This method is applied when there is a quantitative information about the factors available and can be determined. This represents a reliable measure and predefined and uniform evaluation of each factor. The values of utility function set out a quantitative value of the factor weight and measure the risk as well. Building such curve is a key step in performing the MAUT analysis. It can be also depicted graphically. The utility function can be calculated from the following Equation 3.4:

$$u(X_1, X_2, X_3, \dots, X_n) = f(u_1(X_1), u_2(X_2), \dots, u_n(X_n)) \quad (3.4)$$

where : $u(x)$ single attribut utility function

3.1.2.2. Value Function

The value function can be obtained using several methods one method commonly used is bisection method. The notion of this method is to set the best and worst values of the factor assigning 1 for the best and 0 for the worst. Then midpoints (utility scores) 25%, 50% and 75% are identified by the experts. After that, when all five points are set the curve can be drawn accordingly (Goodwin, 2004).

3.1.2.3. Attribute Utility Graphs

The opinion of experts and decision makers is important in deciding the shape of the curve. The shape could be linear (simple case), zigzag, fluctuating, convex or concave. This shape depends upon the nature of the factor. Figure 17 shows examples of utility curves drawn from the literature.

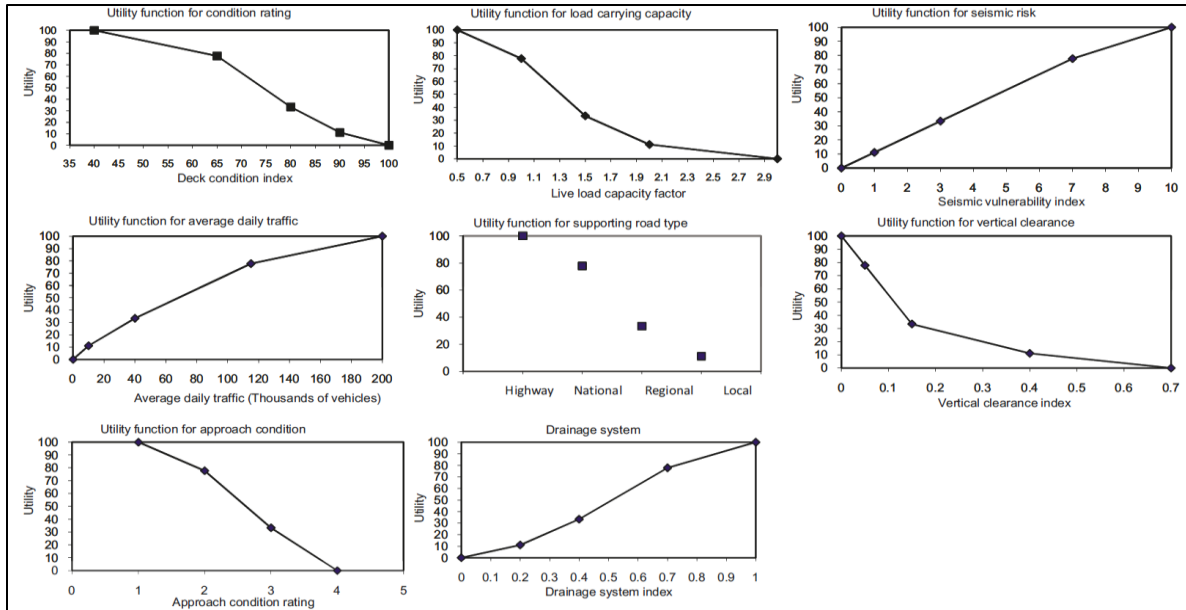


Figure 17 Examples of Utility Curves

Source: (Saleh Abu Dabous & Alkass, 2012)

3.2 Pilot study

The pilot study is conducted to make sure that the subject of the main study is feasible and easy to be understood by the targeted population from which the sample is collected. Also, it can be used to measure the time required to complete the interview and whether it is reasonable or not. In addition, it can be applied to gather the expert's opinion about certain aspects of the study.

In this research, the pilot study was conducted in the following steps:

1. Conducted with bridge maintenance engineer/manager in Municipality to review the factors from the literature review affecting bridge prioritization in network-level in the area of Eastern province, Dammam, Saudi Arabia. Experts should tell which factors are applicable in the concerned area and whether additional factors are there not listed in literature.

2. Conducted after structuring the interview of AHP and MAUT which are utilized to rank the factors in terms of their relative importance for AHP and to find the utility curves for MAUT. practitioners should tell about the flow of the interview, language, duration, addition, omission, terminologies used, etc.

The pilot study is an important tool to enhance the quality and efficiency of the interview before conducting a larger size interview. Four experts from the field participated in this study.

The study revealed that the factors affecting the prioritization of the bridges in network-level are Condition factor, Age factor, Location factor, History of maintenance factor, Scheduled maintenance factor and Traffic condition factor.

3.3 Data Collection

The data needed in this research are described below:

3.3.1. Factors affecting bridge ranking in network-level

Factors that were collected from the literature review needs to be reviewed by experts in the same fields and area. Additions and omission from these factors are possible since these factors were collected from different geographic locations, regulations, standards, policies and so on. This kind of information is subjective.

3.3.2. Gathering the local current practices of BMS

In this step the system been followed by municipality to manage their bridges and the way the maintenance is been conducted is gathered thru the interview. This can help forming an

integrated model that can fulfill their requirement as well. The local experts were presented with the BMS in other countries and this may help them improve their system.

3.3.3. Ranking of factors affecting bridge ranking in network-level

The above shortlisted factors are then required to be ranked and their level of importance and contribution to the main objective is to be determined thru application of AHP. The experts are presented with the tables to fill decision matrix of AHP by conducting the pairwise comparison between the factors asking the following questions, which factors have more impact on the bridge ranking in network level and what intensity of importance of this factor have over the other factor. This kind of data is objective.

3.3.4. Gathering information to construct utility curves

These factors are now having a weight form AHP step and every attribute of these bridges now should be scored according to predefined, unified base which is in this research utility curves of MAUT. As mentioned earlier in section 3.1.2, one method of building these curves are by gathering the best and worst value of the attributes and bisects them by gathering the value of 25%, 50% and 75%. These kinds of data are objective.

3.3.5. Maintenance Work Program (MWP)

The available maintenance actions that Municipality offer are gathered and the preferences is determined. If required, AHP model is to be established to achieve this purpose. Average Cost of each MWP is to be gathered from history which may be linked with age and size of the bridge so as to identify the cost and preference of each MWP which are utilized in the simulation model.

This kind of data is objective. The combination of each recommended maintenance action for each bridge is call maintenance work program.

3.4 Population and Sampling

The targeted population in this research are as presented in Table 12:

Table 12 Targeted Population

Bridge engineers	Owners/Contractors/Consultants Municipality
Maintenance engineers	
Structural Engineers	
Head of Bridges/Tunnel Directory	
Head of Maintenance Directory	

In order to apply the AHP with acceptable results first the consistency of each response shall be less than the prespecified limit as described in section 3.1.1.2.5. Second, regarding the sample size, the existent literature of applications of AHP in construction management revealed that there no restriction on the minimum sample size. Some researchers used sample sizes from 4 to 9 (Zhang and Zou 2007; Hyun et al. 2008; Lam et al. 2008; Pan 2008; Dalal et al. 2010; Zou and Li 2010; Li and Zou 2011; Pan et al. 2012; Akadiri et al. 2013; Chou et al. 2013). Only a rare researchers used sample sizes greater than 30 (Ali and Al Nsairat 2009; El-Sayegh 2009) (Darko et al., 2019).

Accordingly, in this research, only 9 consistent responses are considered as a sample size. Getting 9 consistent responses from interview was hard work as the results may be inconsistent and every time there is inconsistency the interview was repeated again. Also, the population of bridges

engineers and managers is very limited as they are available in either MOT or Municipality office. Also, one engineer may serve a group of bridges and there is only one directory in MOT and another one in municipality.

3.5 Data Analysis

The data gathered from section 3.3 is then required to be analyzed as follows:

3.5.1. AHP analysis

After AHP data gathering, the resulted matrixes are averaged and then the eigenvector is calculated after doing normalization of all columns. Every response is evaluated thru the consistency ration and the overall matrix as well. The procedure as described in section 3.1.1.

3.5.2. Establishing MAUT Curve

Data collected for each attribute (best, Worst, 25%, 50%, and 75%) is averaged from all responses for the same attribute. Then for each attribute the curve is drawn considering the shape of the curve. The procedure as described in section 3.1.2.

3.5.3. Scoring attributes of bridge

The weight for each attribute is now defined and the utility curve as well. Then, for each bridge, its attributes are scored according to the utility curves developed in section 3.5.2.

3.5.4. Finding the overall score of bridge

The scores of each attribute for one bridge is multiplied by the corresponding weight of the attribute. Then, all values are summed up resulting in a score for each bridge.

3.5.5. Optimization-based Simulation Model

Using simulation software along with the comparison matrix and bridges scores to distribute the available budget considering the maintenance work programs discussed in section 3.3.4. The feedback from bridge engineers/managers of the work programs were discussed and evaluated in terms of its cost and preferences. The model is progressively elaborated with the progress in data collection. The model is supposed to have the data collected as input and the budget is distributed either to maximize the number of bridges to be maintained or to focus on the top ranked bridges with best maintenance work program.

The optimization-based simulation model defined as follow and Figure 18 show the flow chart,

Definition: optimization-based simulation model to allocate available maintenance budget to a set of bridges in a certain transportation network.

Considerations: the model considers the factors of ranking the bridges in the network level. Also, it considers the available budget for bridge maintenance, the required level of maintenance and maintenance work program and maintenance actions.

Model Parameters: available budget, number of bridges features of bridges, structural elements, factors for ranking are as an input variable. Allocated budget for each bridge, recommended maintenance work program, maintenance action for each bridge and each element as an output of the model. The model considers the following constrains while optimizing the bridge performance plan; available budget, level of maintenance required, level of optimization required.

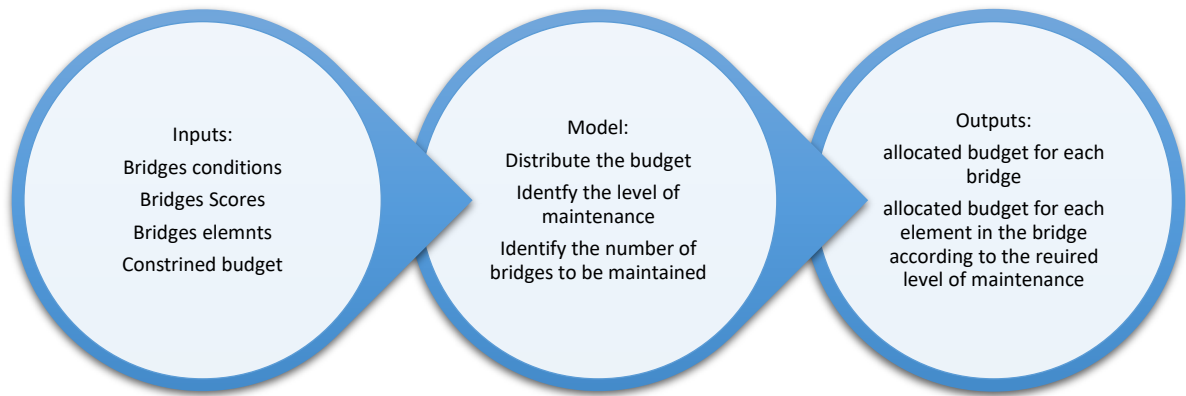


Figure 18 Model Flow Chart

3.6 Summary

This chapter covered the methodology and the tools and techniques that were utilized in order to achieve the study goals. AHP and MAUT methodology were presented along with the calculation steps. The targeted population and sample size were discussed. The data collection and the mean to obtain the data thru interview also discussed. The model development and main parameters were also covered.

CHAPTER 4

DISCUSSION OF COLLECTED DATA

The methodology described in chapter 3 has been applied for ranking of bridge's prioritization factors and for the development of the utility functions for each factor. In addition, the structural components of the bridges representing conventional bridges in Dammam Area have been identified. Also, importance weights of the identified structural components are identified as their maintenance is essential for bridge structural stability and safety. The local experts have been interviewed to share their experience and knowledge about the bridge management system that is followed locally. The interviews are also considered bridge maintenance priorities in Dammam Area specifically the bridges owned by Dammam Municipality which belong to MOMRA. The following sections describe and discuss the obtained results of the data collection.

4.1 Demographic Distribution of Local Experts

An interview has been conducted with 9 local experts in bridge maintenance in order to gather the required data to build the proposed model. The profile of the 9 local experts is illustrated in Figure 19. The local experts 5 owner representative worked as consultant, 3 project managers and 1 bridge engineer. The owner representatives are consultants who are working in bridges construction and maintenance in Dammam Municipality projects. Usually the owner has less technical experience compared to the consultants. Therefore, the owner hires consultant firms in order to supervise the maintenance and construction projects and to assist them in the decision making process. Therefore, consultants have the experience of the owner since they are considering of the owner's main objectives in making decisions related to bridges maintenance priority. In addition, with the

help of consultant technical experience they direct the decision makers towards the best possible bridge maintenance plan.

The owner, consultants and the project managers are the three key personals managing the maintenance projects. The project managers have both technical and managerial experience as they had previously working experience in similar projects. It should be noted that the project managers may have worked in other areas and/or with different owners and therefore their recommendations to the owner during the maintenance project would allow the owner to build better experience. In addition, the project manager can assist the owner's preferences in a certain situation or project in which he have worked.

The bridge engineer has a vast technical experience in bridge maintenance. Furthermore, the engineer has worked on preparation of condition assessment reports, contract bills, cost estimation for maintenance based on bridges conditions and due to his contact with such technical issues he is able to convey the mind of the owner in bridge priority for maintenance specially if he had worked for multiple projects.

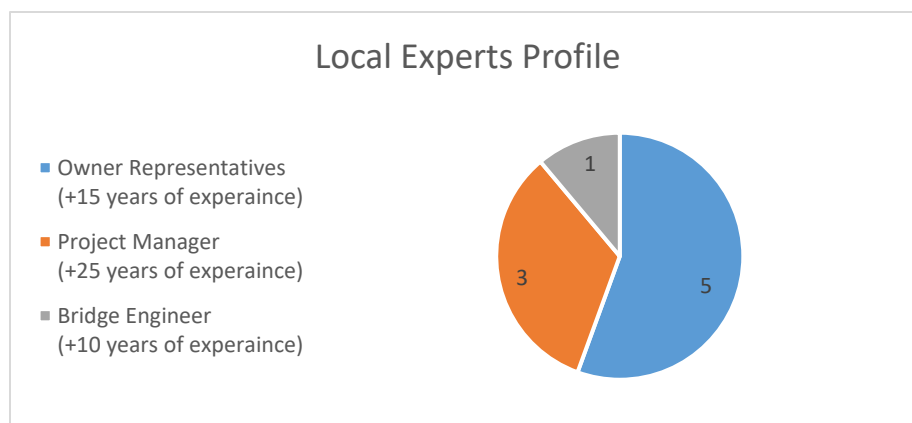


Figure 19 Interviewed Local Expert Profile

4.2 Model Development

The model developed consists of the following steps:

4.2.1. Prioritization Factors at Network Level Identification

The factors extracted from literature review were presented to local experts in order to identify the factors applicable to prioritize bridges for maintenance in KSA. After conducting a polit study with local experts, they have shortlisted the above factors to only six factors and they are described in the following sub sections. Table 13 summarize the factors with respect to previous works

4.2.1.1. Condition Factor

The bridge structure consists of several structural elements working together to transfer the dead and traffic load into the soil. These structural elements are like bridge deck, bearing pads, piers and foundations. According to several pervious researches and manuals prepared by agencies in different locations they proposed several scales to assess the condition of each element. Thus, the overall condition of the bridge can be calculated from its forming elements. The condition assessment describes the status of the element in terms of validity and severity. In other words, it is an evaluation of the difference between the as-constructed and as-is states (Rashidi et al., 2016a). For example, Roads and Maritime Services (RMS) of New South Wales have proposed a scale of 4 condition states ranging from 1 to 4, best to worst respectively (Rashidi et al., 2016a). Another example, National Bridge Inspection Standards (NBIS) (2004) they have a scale of 9 condition rating ranging from 0 to 9, excellent to failed condition, respectively. Other researchers proposed a 5-scale condition states like (Valenzuela et al., 2010; Wakchaure & Jha, 2012) but different consideration for the ranging scale, the earlier one considered 1 as dangerous and the later

considered 1 as excellent. The MOMRA considered in their manual a 7-scale condition states ranging from 7 to 0, good to dangerous condition, respectively, which is according to International program of evaluating bridges (NPIB). As the condition of the elements of the bridge, thus the bridge itself, get worser it means that it requires high strategy of maintenance, and may be replaced completely. The preference of the maintenance strategy is based on the condition assessment report. According to MOMRA they have 4 maintenance strategies that are preventive, curative, rehabilitation and replacement. They have defined thresholds based on the 7-scale condition based on which the maintenance strategy is selected, refer to Table 5 in the manual - part 3 or to section 2.6.5. The overall condition of a single element can be calculated by diving the quantity of the element to units of each condition state then the weighted condition can be determined. Similarly, the overall condition of a bridge can be calculated by finding the overall condition sates of its forming elements then the weighted condition can be determined.

4.2.1.2. Age Factor

The age of the bridge was recognized by many researches in the literature. Age plays a major role in bridge deterioration because of fatigue, whether condition, design life, dynamic load and so many other factors. As the bridge gets old it requires a lot of maintenance till approaching the end of its useful life. Before reaching the end of its life it may be used under so many restrictions on the traffic and usage. The bridge in this case is excluded from maintenance as its maintenance cost approximately equals that required for the reconstruction of new bridge. Many experts recognized the average usual life of bridges in the study area as high as 50 years. Whereas maintenance is most efficient when the bridge age around 30 years. (Rashidi & Gibson, 2012) have agreed that for concrete bridges the life expectancy is about 50 years but for major bridges it can reach as high

as 100 years. They also proposed a scale of 4 categories for age ranging from 1-4 where 1 is recently built (0 to 25) years old and 4 is very old (75 to 100) years old.

4.2.1.3. Location Factor

The location of the bridge matters in terms of the traffic using that bridge. Also, locations can be set by the owner as a preference. Bridges located near important traffic generations, diplomatic, political and military places are prioritized for maintenance as partial damage may interrupt the traffic flow and cause a lot of congestion and additional cost and loss to the community and the government. Bridges near to industrial areas are carrying heavy traffic load due to the passage of heavy trucks from and to the factories located in that area. Heavy and dynamic loads increase the potential for structural damage and thus their need for maintenance increase as well. Also, the permissions for additional loads accelerates the fatigue of the bridge. Bridges located near residential and commercial area are less prioritized compared to the previous categories. Usually, heavy traffic load is banded to enter the residential and commercial areas thus the bridges are more relaxed.

4.2.1.4. Previous maintenance factor

Bridges that lack maintenance are prioritized. Maintenance activities should be recorded in the BMS. The last maintenance activity for a certain bridge can be retrieved and hence if a bridge is being maintained on time then its maintenance can be postponed and other bridges lacking maintenance can be prioritized. Some elements of the bridge must be maintained frequently like the bearing pads their useful life is around 10-15 years based on their design. Such milestone maintenance is important due to the structural importance of the element. Ignorance of such milestone can be controlled by the next factor.

4.2.1.5. Scheduled maintenance factor

After the construction of a bridge is completed a series of maintenance are required and scheduled along its useful life. Such maintenance usually replaces or repairs certain elements whose useful life is expired and failure of any of them may cause further damage to other elements and hence failure of structure. Thus, bridges that are approaching their scheduled maintenance are prioritized. Especially the structurally important elements and their milestone frequent maintenance.

4.2.1.6. Traffic condition factor

The amount and type of the traffic using the bridge represents the vitality of that bridge. Bridges that are carrying a huge traffic are prioritized for maintenance since blockage of any of them causes severe losses to the community, congestion and delay to passengers. The traffic can be expressed as the average annual daily traffic (AADT). AADT is a key parameter for road and bridges construction and maintenance studies (Leduc, 2008). The AADT can be defined as a measure road traffic flow which represents the average number of vehicles that pass at a given location over a year (Roess, Prassas, & McShane, 2008). Traffic counting requires huge efforts and long periods of time to get more accurate records of traffic volume throughout the whole year to account for seasonal fluctuation of traffic profile. The main concern of this study is to prioritize bridges for maintenance. The fact is that the more traffic volume is on a bridge the more the bridge is prioritized for maintenance. Looking at the absolute difference between bridges traffic is the main objective of any study. But also, looking at the differential difference works as well in case the records of traffic volume are not available.

Table 13 Prioritization Factors in Previous Work

Authors	Location	Factors Considered in the study						Factors not considered in this study																																		
		Condition	Age	Location	Previous maintenance	Scheduled maintenance	Traffic condition	Route	Material vulnerability	Environmental	Inspection quality	Load-bearing capacity	Vertical clearance	Width	Bridge barrier	Drainage	Socioeconomic	Political	Historical	Strategic importance	Hydraulic vulnerability	Seismic risk	Remaining service life	Agency cost	Vehicle operating cost	Travel time savings	Visibility distance	Savings in accident costs	Danger due to bridge collapse	Maintenance division facilities	Budget for maintenance division	Bridge structure	Bridge aesthetics	Construction quality	Passing convenience	Weather information	Disruption of public services	Deterioration prediction	Other factors*			
(Ryall, 2010)	UK	✓		✓				✓																																		
(Rashidi, Gibson, & Ho, 2014)	Australia	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓																							
(Valenzuela et al., 2010)	Chile	✓																		✓	✓	✓																				
(Rashid & Herabat, 2008)	Thailand	✓					✓				✓		✓									✓	✓	✓	✓	✓	✓															
(Hai, 2008)	Vietnam			✓			✓				✓																															
(Woodward et al. 2001)	Belgium				✓						✓																		✓													
(Woodward et al. 2001)	France	✓						✓									✓													✓		✓										
(Woodward et al. 2001)	Slovenia	✓						✓																																		
(Chassiakos, Vagiotas, & Theodorakopoulos, 2005)	Greece	✓	✓				✓	✓																									✓									
(Klatte, van Noortwijk, & Vrisou van Eck, 2002)	Netherland						✓				✓																							✓		✓	✓					
(Woodward 2001)	BRIME	✓	✓				✓												✓						✓									✓	✓					✓		
(Elbehairy, 2007)	Canada						✓					✓																					✓						✓			
(Pesti Geza, Khattak, Kannan, & McCoy, 2003)	USA																																✓					✓				
(Zhang Zhanmin, Aki, & Hudson, 2002)	USA	✓	✓																																							
(Alikhani 2009)	Iran				✓		✓		✓		✓	✓				✓		✓				✓		✓						✓		✓	✓	✓							✓	
Local Expert	KSA	✓	✓	✓	✓	✓	✓																																			
Other factors: Filling of expansion joints, Oil and chemical material pouring from vehicles on the bridge, Use sand or salt to prevent vehicles from sliding, Bump creation because of pavement destruction, Vibrations affect the bridge, Fatigue, Volume of traffic passing under the bridge & Bridge design and construction code																																										

4.2.2. Weights of Prioritization Factors

The concept of AHP has been applied for obtaining the weights of prioritization factors for bridge maintenance at the network level. Excel sheet is used to analyze AHP data in order to calculate the relative weights as well as consistency ratios of all considered matrices, as illustrated in Appendix B. Table 14 shows the factors along with the weights of each based on the calculations of AHP and all responses showed a consistent comparison.

Table 14 Weights of Prioritization Factors

Factor	Condition Factor	Traffic Factor	Location Factor	Age Factor	Scheduled Maintenance	History of Maintenance
Weight	25.9%	21.3%	17.0%	12.7%	11.9%	11.2%

Table 15 shows AHP sample calculation for R1. Table 16 shows the individual results of the respondents. Results showed that most experts agreed and evaluated the condition factor as the highest priority factor. This reflects the current practice recommended by the manual of MOMRA for maintenance. As described in section 2.6, there are three stages for bridges prioritization and the first stage is shortlisting bridges based on their condition assessment. This study shows that experts agreed with other factors with different weights contributing to the decision of prioritizing bridges for maintenance as shown in the above table. Traffic factor also contributes to that decision with the second highest weight. The amount of traffic using that bridge decides about its priority for maintenance. The more traffic using a bridge gives it a priority to be maintained first as in case if the bridge is blocked due to its bad condition assessment it greatly impacts a huge number of passengers negatively in terms of time delay and operating cost. The third factor contributes to

same decision is the location factor. The location of the bridge matters in terms of the type of the traffic using that bridge as recognized by the experts. The traffic volume, and thus the traffic load, matters to the bridge carrying that traffic. Bridge are more sensitive to heavier loads which are mainly generated from industrial and commercial areas. This necessitates that bridges with heavier traffic load to be prioritized for maintenance to avoid blockage of these bridges since it affects the logistics of the industries. The age of the bridge gives an indication about the remaining useful life of the bridges. As the bridge becomes very old its priority increases to a certain limit for maintenance after that it is prioritized for reconstruction as it becomes more cost-effectively to reconstruct the bridge rather than maintaining it. The last two factors are related the maintenance activity log of the bridge in terms of the previous and the next maintenance. The bridge which has been maintained recently has less priority than a bridge maintained longer time ago. The bridge may have been ignored in the previous years or it was less prioritized due to the priority of other bridges in the same network. When the bridge periodic maintenance approaching, the bridge has priority to be maintained.

Table 15 AHP Sample Calculation of R1

R1		Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor	
Condition Factor		1.00	5.00	2.00	4.00	3.00	1.00	
Age Factor		0.20	1.00	0.50	0.50	0.33	0.25	
Location Factor		0.50	2.00	1.00	2.00	2.00	1.00	
History of Maintenance		0.25	2.00	0.50	1.00	0.33	0.25	
Scheduled Maintenance		0.33	3.00	0.50	3.00	1.00	0.50	
Traffic Factor		1.00	4.00	1.00	4.00	2.00	1.00	
		3.28	17.00	5.50	14.50	8.67	4.00	
Normalization								
Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor	Row Average		Consistency
0.305	0.294	0.364	0.276	0.346	0.250	0.306		6.243
0.061	0.059	0.091	0.034	0.038	0.063	0.058		6.117
0.152	0.118	0.182	0.138	0.231	0.250	0.178		6.259
0.076	0.118	0.091	0.069	0.038	0.063	0.076		6.120
0.102	0.176	0.091	0.207	0.115	0.125	0.136		6.254
0.305	0.235	0.182	0.276	0.231	0.250	0.246		6.236
1.000	1.000	1.000	1.000	1.000	1.000	1.000		37.228
# of Comparisons		Average Consistency		CI	RI	Consistency		Consistent? Less than 0.1
6		6.204664		0.040933	1.24	0.03301		Yes

Table 16 Respondents Results

Factor/ Respondents	R1	R2	R3	R4	R5	R6	R7	R8	R9
Condition Factor	30.6%	15.1%	18.1%	25.2%	17.6%	23.5%	28.1%	36.1%	39.0%
Traffic Factor	24.6%	17.7%	30.1%	17.8%	17.4%	19.8%	28.8%	14.0%	21.1%
Location Factor	17.8%	27.2%	20.9%	22.4%	26.2%	8.0%	15.1%	6.1%	9.3%
Age Factor	5.8%	8.3%	6.7%	18.2%	10.7%	17.4%	10.2%	22.2%	14.5%
Scheduled Maintenance	13.6%	19.5%	14.2%	9.4%	8.1%	14.0%	9.7%	9.3%	9.4%
History of Maintenance	7.6%	12.2%	10.0%	7.1%	19.9%	17.3%	8.0%	12.3%	6.8%

Table 17 Reliability Test for Prioritization Factors

	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor	Total
R1	0.3057	0.0577	0.1784	0.0758	0.1360	0.2464	1.0000
R2	0.1509	0.0831	0.2720	0.1219	0.1951	0.1771	1.0000
R3	0.1809	0.0672	0.2088	0.0997	0.1425	0.3010	1.0000
R4	0.2519	0.1820	0.2243	0.0708	0.0935	0.1776	1.0000
R5	0.1758	0.1074	0.2622	0.1993	0.0808	0.1744	1.0000
R6	0.2350	0.1738	0.0797	0.1729	0.1401	0.1985	1.0000
R7	0.2813	0.1020	0.1510	0.0803	0.0973	0.2881	1.0000
R8	0.3614	0.2217	0.0607	0.1229	0.0932	0.1401	1.0000
R9	0.3896	0.1452	0.0929	0.0680	0.0938	0.2105	1.0000
Median	0.2519	0.1074	0.1784	0.0997	0.0973	0.1985	0.9331
Mean	0.2592	0.1267	0.1700	0.1124	0.1192	0.2126	1.0000
Mode	0.2519	0.1074	0.1784	0.0997	0.0973	0.1985	0.9331
SD	0.0833	0.0568	0.0789	0.0470	0.0370	0.0548	0.3579
VAR	0.0062	0.0029	0.0055	0.0020	0.0012	0.0027	0.1281
ΣVAR	0.0204						
Ca	0.9456						

4.2.3. Utility Function Curves for Prioritization Factors

With the help of experts, the above factors have been converted to curves as shown and discussed.

4.2.3.1. Condition Factor

According to manual of MOMRA the condition is assessed to a 7-stats condition scale. Experts transformed the scale to a utility curve shown in Figure 20. Some of the experts recommended the linear relation and the others recommended a parabolic relation. The average of all responses yields a parabolic trend line with R^2 value is maximum among other degrees of trend lines which means the most fit trend line. The average response suggests that when the condition is evaluated 1, potential danger, it is scored 1, maximum priority, and when it is 7, new case, it is scored 0, least priority. If the bridge scored 0, very dangerous, then its score is 1 but may be excluded from maintenance prioritization and may be prioritized for replacement.

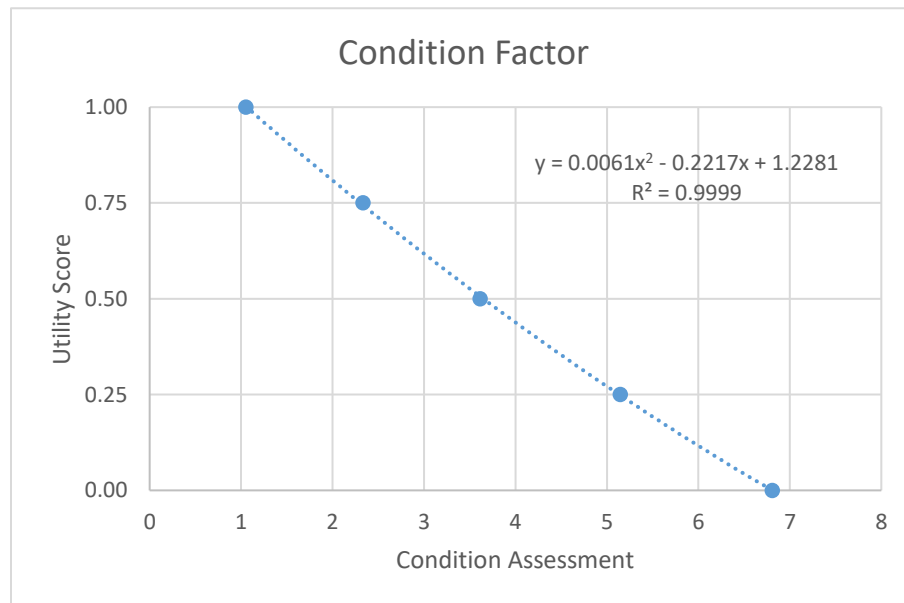


Figure 20 Condition Factor Utility Curve

4.2.3.2. Traffic Factor

The amount of traffic passing over a bridge is represented by the AADT. Experts preferred to use differential prioritization for the AADT. This means that the AADT for all bridges being prioritized for maintenance are classified and the bridge with the highest AADT receives the full score and the bridge with least AADT receives 0 score. The bridges in between receive a score proportional to their AADT. According to experts there are ongoing projects for traffic counting. Based on the findings of this project the AADT can be determined for each bridge. for the mean time the municipality may depend on the ADT or peak hour volume. Figure 21 shows utility curve or the traffic factor.

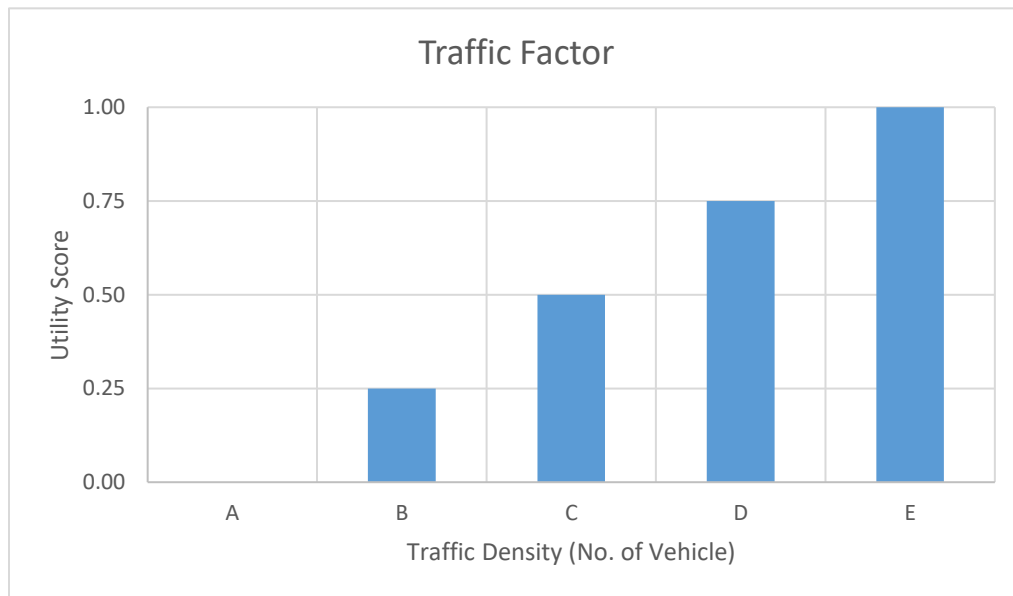


Figure 21 Traffic Factor Utility Curve

A	B	C	D	E
Lowest Traffic				Highest Traffic

4.2.3.3. Location Factor

The location is categorized into four classes based on the traffic type, and thus load, passing over bridges in that location. The type of traffic in residential areas is lighter than any other location as traffic in that locations comprised of light vehicles whereas trucks are prevented from entering these locations. Therefore, the bridges located in residential area have the least priority. The type of traffic passing over the bridges located in commercial area are like light trucks which are heavier than the first class. Thus, it receives a higher priority. The type of traffic using bridge in industrial areas are heavier than the previous classes. Hence, it receives a higher score. The type of traffic using bridge located in military/political area are much heavier and that is not only the reason but also due to the importance of such locations to the government. Experts all agreed to this scale as they see it representative to the bridge's locations in Dammam area. Figure 22 shows utility curve or the location factor.

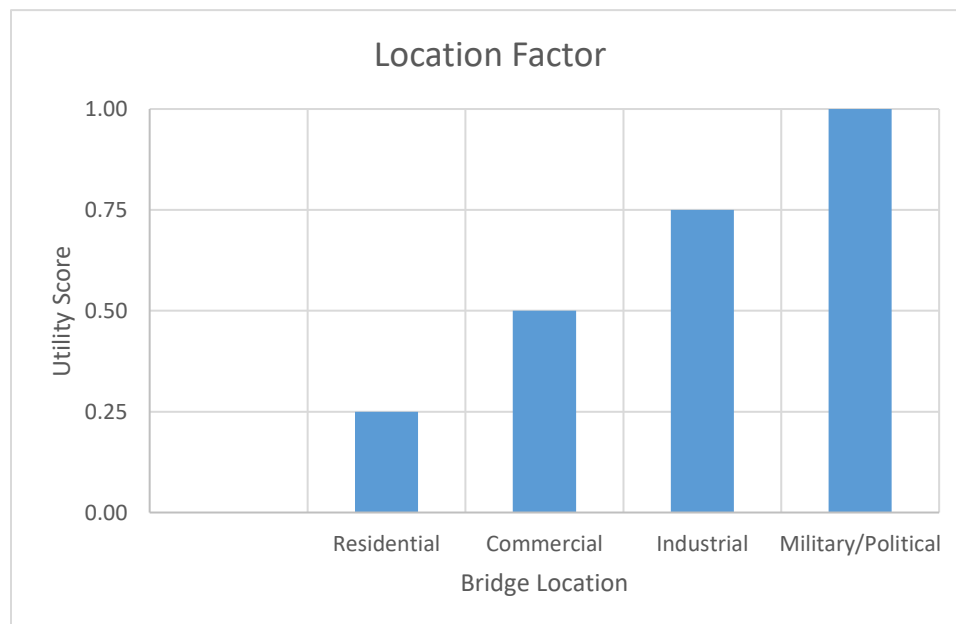


Figure 22 Location Factor Utility Curve

4.2.3.4. Age Factor

Most of experts have recognized the age of the bridges 50 years old. Some of them said 100 years. The experts suggest that a bridge is most preferred and prioritized for maintenance at the age of 35 years old on average. Older bridges are excluded from maintenance and prioritized for replacement. Experts recommended both linear and parabolic relation between the age and the score. The parabolic trend line is the most fit since the value of R^2 for second degree is the highest among the liner and 3rd degree. Figure 23 shows utility curve or the age factor.

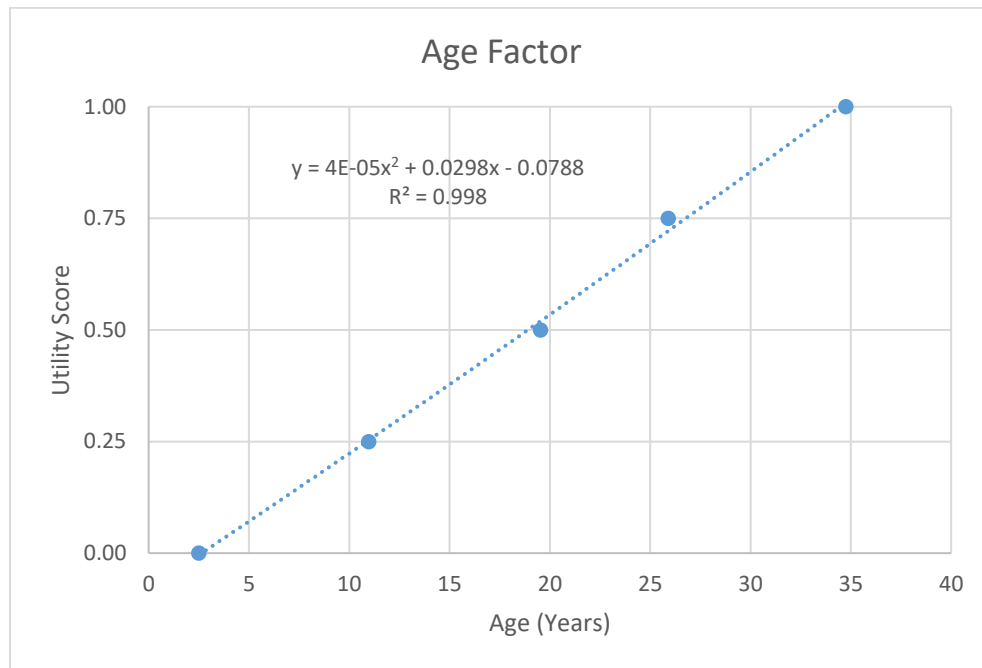


Figure 23 Age Factor Utility Curve

4.2.3.5. Previous and Scheduled Maintenance

The recent activity of maintenance happened for a bridge gives it a priority to be maintained next time based on the period since the last maintenance activity. Experts divide the period based on intervals. The average interval period is around 7 years. This means that if a bridge marinated 10 years ago its score around 0.25 but if it was maintained in the last 20 years its score 0.55. Experts proposed both relation linear and parabolic between previous and score. The second degree parabolic is the most fit as R^2 value was the highest. Figure 24 shows the utility curve of the previous maintenance.

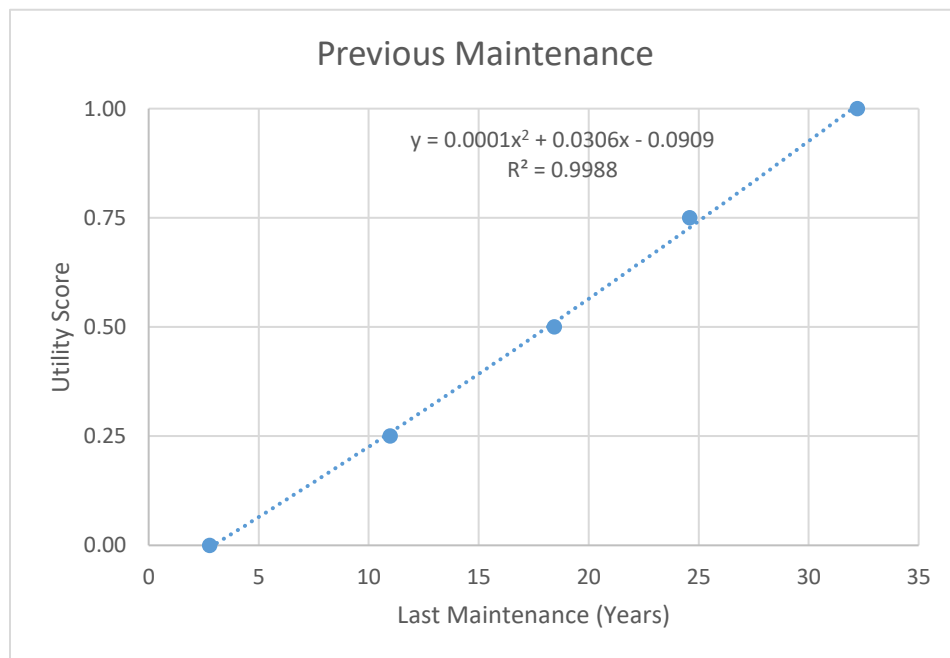


Figure 24 Previous Maintenance Utility Curve

The concept is applied for the scheduled maintenance. When the bridge periodic maintenance becomes near then that bridge is prioritized. The same approach is applied here as well. The experts divided the period into 4-years intervals. Figure 25 shows the utility curve of the scheduled maintenance.

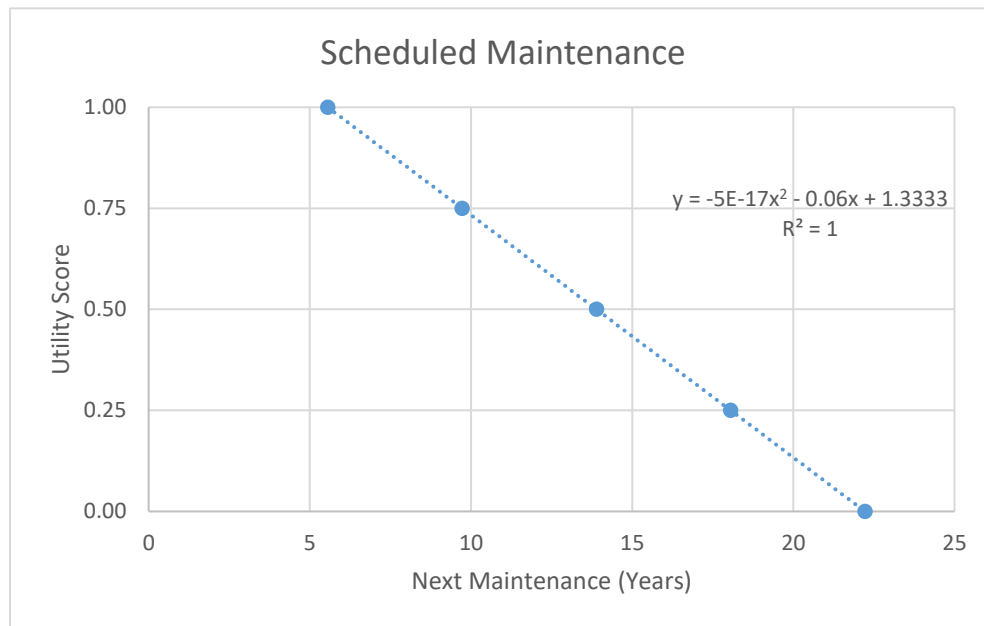


Figure 25 Scheduled Maintenance Utility Curve

4.2.4. Structurally important bridge components

As recognized by the experts, bridge is comprised of the following components in Table 18. AHP has been made between the bridges components to identify the weight of each components. Table 18 show the components and their weights. All responses are illustrated in Appendix C

Table 18 Bridge Components and Weights

Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
17.3%	20.7%	16.9%	13.6%	16.4%	15.1%

Table 19 show the respondents individual response and also shows

Table 19 Respondents Results

	R1	R2	R3	R4	R5	R6	R7	R8	R9
Bridge Deck and Parapet	29.2%	27.0%	22.2%	7.3%	14.2%	10.2%	9.5%	10.1%	25.8%
Bearing Pads	18.3%	10.2%	9.6%	26.6%	27.5%	31.1%	30.1%	22.6%	10.6%
Expansion Joint	7.6%	30.7%	30.5%	10.3%	7.4%	23.0%	28.2%	5.6%	9.1%
Abutment Walls	17.0%	11.0%	13.7%	16.5%	11.2%	8.6%	7.8%	20.6%	16.3%
Pier Columns	17.0%	11.0%	8.1%	28.3%	17.0%	13.0%	12.3%	20.6%	20.3%
Foundations	11.0%	10.2%	16.0%	11.0%	22.7%	14.1%	12.2%	20.6%	17.9%

Table 20 Reliability Test for Bridge Components

	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations	Total
R1	0.2918	0.1827	0.0756	0.1699	0.1699	0.1102	1.0000
R2	0.2695	0.1022	0.3066	0.1098	0.1098	0.1022	1.0000
R3	0.2219	0.0956	0.3049	0.1366	0.0811	0.1598	1.0000
R4	0.0734	0.2655	0.1029	0.1647	0.2831	0.1105	1.0000
R5	0.1418	0.2748	0.0736	0.1122	0.1703	0.2273	1.0000
R6	0.1015	0.3106	0.2300	0.0863	0.1302	0.1414	1.0000
R7	0.0948	0.3006	0.2821	0.0782	0.1228	0.1215	1.0000
R8	0.1006	0.2262	0.0561	0.2057	0.2057	0.2057	1.0000
R9	0.2580	0.1061	0.0913	0.1630	0.2030	0.1786	1.0000
Median	0.1418	0.2262	0.1029	0.1366	0.1699	0.1414	0.9189
Mean	0.1726	0.2071	0.1692	0.1362	0.1640	0.1508	1.0000
Mode	0.1418	0.2262	0.1029	0.1366	0.1699	0.1414	0.9189
SD	0.0869	0.0881	0.1089	0.0428	0.0614	0.0451	0.4332
VAR	0.0067	0.0069	0.0105	0.0016	0.0034	0.0018	0.1876
ΣVAR	0.0309						
Cα	0.9395						

4.2.5. Cronbach's alpha

Cronbach's alpha is reliability test is made to assess the internal consistency. In other words, it tells how a set of responses are closely related as a group. In our case this measure tells whether the responses are in line with each other and their analysis yields reliable and consistent results. Thus, the expert's opinions are related and consistent. Cronbach's alpha measure is used with the equation 4.1:

$$C_{\alpha} = \frac{n}{(n-1)} \left(1 - \frac{\sum V_i}{V} \right) \quad (4.1)$$

Where C_{α} is a value range from 0 to 1. The acceptable range is from 0.7 to 1. Results are summarized in Tables 17 & 20. The C_{α} in both cases it is above 0.90 which means that the responses are reliable.

4.3 Optimization-based Simulation Model for Budget Constrain

It is required to build a model to automate the process of budget allocation in order to ease the use of the input's parameters, simulation and optimization specially when we have a huge number of bridges in the study area. Also, in the future it can be merged to the local bridge management system for the MOMRA. The model utilizes the inputs with the constrains in order to achieve the objectives of the model and eventually presents the outputs in a simple form in order for the owners to take proper decision with summarized information.

4.3.1. Model Description

As illustrated in Figure 26, the model has 5 major steps that are Bridges ranking in network level, Components prioritization, Optimization, simulation and the model output. The developed model incorporates the experience of local experts in order to come up with an optimized work program in terms of maximizing the number of bridges to be maintained and minimizing the total maintenance cost. The work program consists of a prioritized bridge and their components for maintenance. The model can achieve the target by first prioritizing the bridges in the network level and that can be done using the prioritization factors along with the corresponding utility curves with the bridges data from the BMS then the rank for each bridge can be found. These factors were discussed in the previous section. Second, the components of the bridges are identified and their weights in terms of their priority to be maintained as their maintenance is important to maintain the safety of the traffic and the stability of the structure. From that, and using the components condition states the component priority can be found. Third, based on the condition state of each component the recommended maintenance strategy is determined and according to the weight of each strategy the overall priority of each component is found. This step is the first step in the

simulation process. After that, the overall priority along with the maintenance cost of each component are the main inputs to the optimization process by picking different values to these variables from the probability distribution. Fourth, the optimization process then looks for the solution which satisfies the objective functions which are the maximum priority thus maximum number of bridges and minimum total maintenance cost. The near optimum solution consists of a set of components in which the sum of their priority is at maximum and the sum of their maintenance cost is the least and below budget. Fifth, the outcomes of the model were presented to the owner/engineer for their recommendation.

The model has the advantage of converting the subjective nature of the problem into an objective manner by identifying factors of prioritization and establishing their utility curves by linking this model to the BMS then the priority can be directly calculated. the model has two parts: the first one is the simulation part which is the output of the second stage in this model. The simulation provides a way to allocate the budget based on the priorities of the components only. Whereas the second part, optimization part, third stage, considers the maintenance strategy for each component in addition to the component priority. Based on that, the model looks for an optimal solution to allocate the budget based on the overall priority and the objective functions.

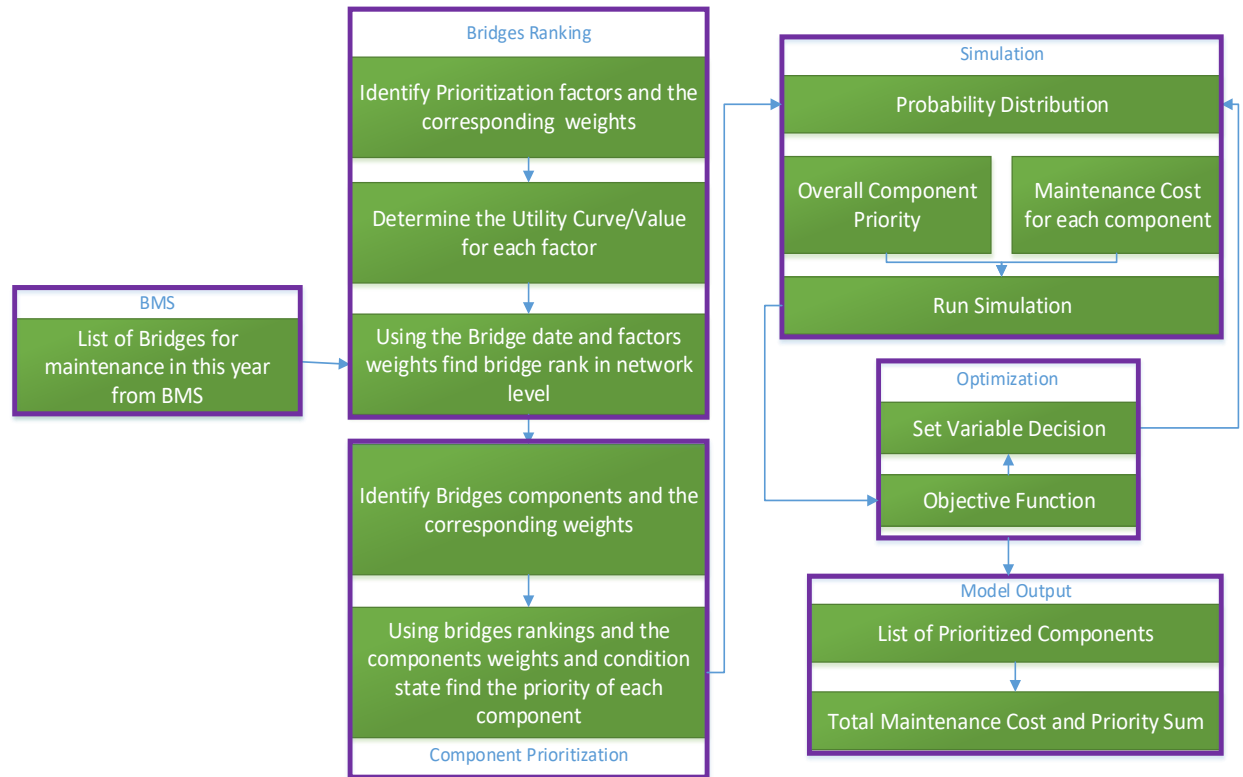


Figure 26 Model Architecture

4.3.2. Computation process

As shown in Figure 27, the model does the following steps to find the optimal solution:

1. The model starts with the list of bridges to be marinated this year from the existing local BMS.
2. The model asks for the data of these bridges from BMS. These data are the factors values based on which the bridge is prioritized like bridge condition assessment, age, location, traffic volume and maintenance log.
3. Using the above data, the model transfers these data into utility values based on the saved or predefined utility curves in the model.

4. The utility value for each factor in each bridge is multiplied by the corresponding predefined weight of each factor.
5. The sum of the products in the above step in each bridge yields the score of each bridge which represents the rank of the bridge, the higher the score the higher rank is.
6. The components condition state along with the bridge's rank to which the component belongs and the corresponding predefined component's weight are multiplied by each other resulting in the priority of that component. The same is done to all components.
7. The model now starts the optimization by considering a weight for the maintenance strategy which is based on the condition state of the component. The priority of each component is multiplied by the weight of corresponding maintenance strategy resulting in the overall priority of each component.
8. The maintenance cost, based on the bridge inventory and market condition, is given to the model as an input.
9. The Overall priority along with the maintenance cost for each component are the inputs for the simulation and then the optimization process after determining the variable's probability distribution.
10. The model randomly selects a set of components, the set size may be any number between 1 and $N \times C$ which is the total number of components involved, and sums up their priorities and maintenance costs. Then model compares the results with the objective function. If the set satisfies the constraints the set is recorded and prioritized.
11. The random selection methodology uses the concept of binary decisions. The component is either included in the work program or not. If it is to be included then the decision given is a value of 1 to be multiplied by the overall priority. If the decision is not to include then

the value given is 0. This is done randomly and iteratively while the model is creating sets of components to be included in this work program, which means having the value of 1 multiplied by their priority, then some of these sets have more potential to be the optimum solution since these solutions satisfy the objective function. The near optimum solution out of these solutions is the one with the most priority and least cost which also satisfies the constrained budget less than the budget.

12. The termination condition is limited either to the number of iterations due to the large job size or the whole combinations were all assumed and tested due to the small job size.
13. The model reports the priority and the maintenance cost of the feasible solutions and from which the component set is identified.

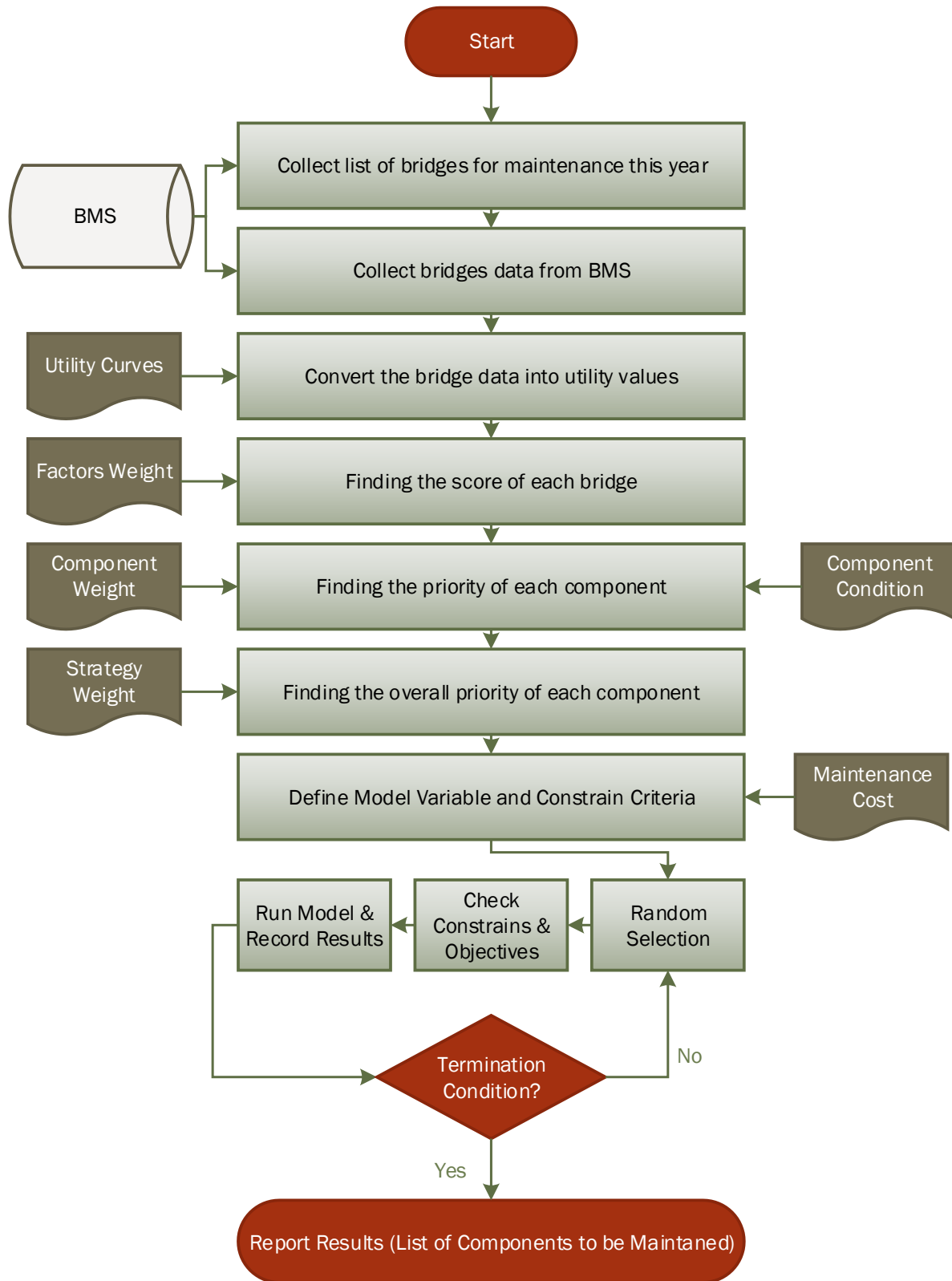


Figure 27 Computation Process Flow Chart

4.3.3. Objective function

The objective function of the model can be mathematically expressed as Equation 6. The main variable is the component priority. Also, the number of components to be maintained is a variable but this variable is implicit in the priority variable which means that the higher the sum of priority the more components are included. From this fact and the main objectives which are increasing the number of components to be maintained while reducing the total maintenance cost the optimization objective function can be formed as equation (4.2):

$$Max\ Priority = \sum_{B=1}^{B=N} \sum_{C=1}^{C=6} (BR_B \times CW_C \times UCA_{BC} \times MSW_{BC}) \quad (4.2)$$

Where:

B is the Bridge Number, C is the Component Number, BR_N is the Bridge N Rank, CW_C is the Component C Weight, UCA_{BC} is Utility Value of Condition Assessment corresponds to Component C in Bridge B, MSW_C is the Maintenance Strategy Weight corresponds to Component C.

This means that the model is looking for the greatest sum of the priorities which means that the largest number of components are included in the maintenance this year but taking into consideration the budget constraints which corresponds to each iterative sum of the priority as the model starts with the first component sum of priority and then takes the corresponding cost and sums it. The second iteration takes the first and second component and sums their priorities and the corresponding costs and so on. The model records the whole iterations and finds the maximum sum of priority and compares the corresponding cost with the budget if the budget is less then, the

model looks for the second maximum sum and compares it with the budget and so on. Till each to a certain priority sum which corresponds to a total cost less than the budget. The priorities forming that sum are identified by the model as the components for maintenance this year.

4.3.4. Constraints

The constraints imposed on the model by the user is the budget cost for maintenance this year.

This means that equation 4.3 represent the model constrain:

$$\sum_{B=1}^{B=N} \sum_{C=1}^{C=6} (MC_{BC}) \leq \text{Budgeted Cost} \quad (4.3)$$

Where (B=1,2, ..., N) number of bridges and (C=1,2,3,4,5,6) is the number of components in each bridge. Also, MC_{BC} is the maintenance cost for Component C in Bridge B.

On the other hand, the priority has the max limit of the summation of all component's priority.

4.4 Validation

4.4.1. Example project

The model considers a hypothetical network of 4 bridges and both the cost of maintenance and constrained budget are assumed. Using a hypothetical network case is due to the fact that bridges in Dammam area which belong to Dammam Municipality are new according to experts. The oldest bridge was constructed 2006G almost 15 years ago only. This section describes the model step by step according to the methodology presented in Chapter 3 along with the collected data from experts.

4.4.1.1. Model Input Data

The inputs parameters to the model consists mainly from the bridge's information including condition assessment, location of the bridge, age of the bridges, traffic volume passing over the bridges and previous and next maintenance dates. Table 21 summarizes the information of the bridges under consideration in the hypothetical case.

Table 21 Hypothetical Bridges Information

	Bridge 1 (B1)	Bridge 2 (B2)	Bridge 3 (B3)	Bridge 4 (B4)
Condition Assessment	4	6	3	5
Age (Years)	15	9	23	26
Location	Industrial	Industrial	Commercial	Political
Previous of Maintenance	10	0	15	5
Scheduled Maintenance	5	6	0	10
Traffic Volume (ADT)	78563	89487	54127	104369

It should be noticed that condition assessment for bridge components along with its quantities defined as input data. Table 22 summarize the Bridges components condition assessment and their quantities.

In addition to the above information the weights of prioritization factors and bridge components along with the utility curves are obtained from expert's interview as previously described in section 3.3.

The Maintenance Cost of the components are key inputs to model as the whole process is about to select among of them. Table 23 Summarize the maintenance cost of each components.

Table 22 Bridges Components Details

	Condition Assessment				
		Bridge 1 (B1)	Bridge 2 (B2)	Bridge 3 (B3)	Bridge 4 (B4)
Bridge Deck and Parapet	M ²	4	6	3	5
Bearing Pads	EA	3	5	4	5
Expansion Joint	LM	5	4	3	4
Abutment Walls	M ³	4	6.5	2	3
Pier Columns	M ³	4	6.5	2	6
Foundations	M ³	4	7	4	6
	Quantity				
		Bridge 1 (B1)	Bridge 2 (B2)	Bridge 3 (B3)	Bridge 4 (B4)
Bridge Deck and Parapet	M ²	1314	2044	876	1752
Bearing Pads	EA	44	60	24	60
Expansion Joint	LM	53.8	68.4	39.2	68.4
Abutment Walls	M ³	860	950	685	890
Pier Columns	M ³	350	490	280	420
Foundations	M ³	900	1125	675	810
Total		3521.8	4737.4	2579.2	4000.4

Table 23 Maintenance Cost for Bridge Components

		Bridge 1 (B1)	Bridge 2 (B2)	Bridge 3 (B3)	Bridge 4 (B4)
Bridge Deck and Parapet	SAR	394,200.00	613,200.00	262,800.00	525,600.00
Bearing Pads	SAR	660,000.00	900,000.00	360,000.00	900,000.00
Expansion Joint	SAR	134,500.00	171,000.00	98,000.00	171,000.00
Abutment Walls	SAR	645,000.00	712,500.00	513,750.00	667,500.00
Pier Columns	SAR	262,500.00	367,500.00	210,000.00	315,000.00
Foundations	SAR	675,000.00	843,750.00	506,250.00	607,500.00
Total	SAR	2,771,200.00	3,607,950.00	1,950,800.00	3,186,600.00
		11,516,550.00			

The input data is processed in 3 steps. The first step is to conduct the prioritization among the 4 bridges in the network level in order to come up with the overall score for each bridge which represents the rank of the bridge which is used in the second step as a weight for each bridge with respect to its components. In the first step the bridge's information along with the utility curves and weights of each factor is used to convert the information into utility values from the curves or the trendline equation and find the overall score for each bridge. Table 24 summarizes the first Step. The overall score is computed by multiplying each utility value by the corresponding weight and sum the same for all factors in each bridge.

Table 24 Overall Score of each Bridge

Prioritization Factor	Weight	Bridge 1 (B1)	Bridge 2 (B2)	Bridge 3 (B3)	Bridge 4 (B4)
Condition Assessment	25.9%	0.438	0.067	0.637	0.297
Age (Years)	12.7%	0.377	0.193	0.628	0.723
Location	17.0%	0.750	0.750	0.500	1.000
Previous of Maintenance	11.2%	0.225	0.000	0.391	0.065
Scheduled Maintenance	11.9%	1.000	0.973	1.000	0.733
Traffic Volume (ADT)	21.3%	0.500	0.750	0.250	1.000
Overall Score		0.540	0.445	0.546	0.646

The second step utilizes the scores of each bridge along with the component's weights and their condition assessment in order to find out the priority of each component. Table 25 summarize the second step. The priority is computed by multiplying the utility value of condition assessment by the weight/rank of the bridge by the weight of the component. The figures in the tale is multipled by 1000 only for better illustration. The higher value means higher priority.

Table 25 Components Priority

Bridge		Bridge 1 (B1)	Bridge 2 (B2)	Bridge 3 (B3)	Bridge 4 (B4)
Components	Weight	0.540	0.445	0.546	0.646
Bridge Deck and Parapet	17.3%	0.439	0.118	0.618	0.272
Bearing Pads	20.7%	0.618	0.272	0.439	0.272
Expansion Joint	16.9%	0.272	0.439	0.618	0.439
Abutment Walls	13.6%	0.439	0.045	0.809	0.618
Pier Columns	16.4%	0.439	0.045	0.809	0.118
Foundations	15.1%	0.439	0.000	0.439	0.118
		Components Priority			
		Bridge 1 (B1)	Bridge 2 (B2)	Bridge 3 (B3)	Bridge 4 (B4)
Bridge Deck and Parapet		40.9	9.0	58.2	30.3
Bearing Pads		69.1	25.1	49.6	36.4
Expansion Joint		24.8	33.0	57.1	48.0
Abutment Walls		32.3	2.7	60.2	54.4
Pier Columns		38.8	3.3	72.4	12.4
Foundations		35.7	0.0	36.1	11.4

The third step is to arrange the results in descending order priority wise. Table 26 summarize the results. The priority and maintenance costs are the main variables in the model and these variables has uncertainty to be considered in software application.

Table 26 Results of Components Priority

SN	Code	Name	Priority	Maintenance Cost
1	B3C5	Bridge 3: Pier Columns	72.4135	210,000.00
2	B1C2	Bridge 1: Bearing Pads	69.0753	660,000.00
3	B3C4	Bridge 3: Abutment Walls	60.1719	513,750.00
4	B3C1	Bridge 3: Bridge Deck and Parapet	58.2127	262,800.00
5	B3C3	Bridge 3: Expansion Joint	57.0749	98,000.00
6	B4C4	Bridge 4: Abutment Walls	54.371	667,500.00
7	B3C2	Bridge 3: Bearing Pads	49.6252	360,000.00
8	B4C3	Bridge 4: Expansion Joint	47.9678	171,000.00
9	B1C1	Bridge 1: Bridge Deck and Parapet	40.8821	394,200.00
10	B1C5	Bridge 1: Pier Columns	38.8375	262,500.00
11	B4C2	Bridge 4: Bearing Pads	36.4018	900,000.00
12	B3C6	Bridge 3: Foundations	36.1284	506,250.00
13	B1C6	Bridge 1: Foundations	35.7204	675,000.00
14	B2C3	Bridge 2: Expansion Joint	33.0214	171,000.00
15	B1C4	Bridge 1: Abutment Walls	32.2719	645,000.00
16	B4C1	Bridge 4: Bridge Deck and Parapet	30.3309	525,600.00
17	B2C2	Bridge 2: Bearing Pads	25.0592	900,000.00
18	B1C3	Bridge 1: Expansion Joint	24.8498	134,500.00
19	B4C5	Bridge 4: Pier Columns	12.4426	315,000.00
20	B4C6	Bridge 4: Foundations	11.444	607,500.00
21	B2C1	Bridge 2: Bridge Deck and Parapet	9.01655	613,200.00
22	B2C5	Bridge 2: Pier Columns	3.26404	367,500.00
23	B2C4	Bridge 2: Abutment Walls	2.71225	712,500.00
24	B2C6	Bridge 2: Foundations	0	843,750.00

The aim of this study is to optimize the bridge maintenance budget allocation and to maximize the number of bridges to be maintained and the total maintenance cost considered to be within the constrained budget while maintaining a proper level of maintenance. Thus, and based on the recommendation of the MOMRA manual for the recommended maintenance strategy based on the condition assessment of a component, the components are further prioritized based on the condition assessment and the recommended maintenance strategy. The aim here is to prioritize components for maintenance to increase their useful life while other components may require replacement or preventive maintenance. Hence, recall the table 8 Recommended Maintenance Strategy, a score of 1 is given to Rehabilitation and 0.75 Remedial/Curative and 0.5 for Preventive and 0.25 for Replacement.

The cost of replacement is usually high and it is behind the scope of maintenance. In addition, the need for preventive maintenance is less prioritized. Moreover, the necessity for rehabilitation is more than the remedial since the component which requires remedial maintenance still is in a good condition compared to the component which requires rehabilitation as the first component can be deferred to the next year but the second component is at its proper time for maintenance. The cost of these strategies can be utilized for components which require rehabilitation maintenance. Hence, the number of components increases achieving the target of the study. Table 27 shows the condition assessment and the corresponding score for maintenance strategy.

Table 27 Maintenance Strategy Score

Recommended Maintenances	Preventive	Remedial/Curative	Rehabilitation	Replacement
Score	0.5	0.75	1	0.25
Condition State	More than 5	5 to 4	4 to 3	Less than 3
Utility Value	0.272 or less	0.272-0.439	0.439-0.618	0.618 or more

Accordingly, in our case the priority changed resulting in a reduction in total cost by 379,250.00 SAR. This also a good result in terms of the either increasing the number of components to be maintained or reducing the total cost. Table 28 summarize the optimization results.

Table 28 Results of Optimized Components Priority

Condition	Code	Name	Component Priority	Maintenance Strategy Priority	Overall Priority	Maintenance Cost
0.6179	B1C2	Bridge 1: Bearing Pads	69.07525287	1	69.07525287	660,000.00
0.6179	B3C1	Bridge 3: Bridge Deck and Parapet	58.21273196	1	58.21273196	262,800.00
0.6179	B3C3	Bridge 3: Expansion Joint	57.07485295	1	57.07485295	98,000.00
0.6179	B4C4	Bridge 4: Abutment Walls	54.37097127	1	54.37097127	667,500.00
0.4389	B3C2	Bridge 3: Bearing Pads	49.62519904	0.75	37.21889928	360,000.00
0.4389	B4C3	Bridge 4: Expansion Joint	47.96778515	0.75	35.97583887	171,000.00
0.4389	B1C1	Bridge 1: Bridge Deck and Parapet	40.88207914	0.75	30.66155935	394,200.00
0.4389	B1C5	Bridge 1: Pier Columns	38.83745163	0.75	29.12808872	262,500.00
0.2721	B4C2	Bridge 4: Bearing Pads	36.40178679	0.75	27.3013401	900,000.00
0.4389	B3C6	Bridge 3: Foundations	36.12840886	0.75	27.09630664	506,250.00
0.4389	B1C6	Bridge 1: Foundations	35.72041061	0.75	26.79030796	675,000.00
0.4389	B2C3	Bridge 2: Expansion Joint	33.02135022	0.75	24.76601266	171,000.00
0.4389	B1C4	Bridge 1: Abutment Walls	32.2719052	0.75	24.2039289	645,000.00
0.2721	B4C1	Bridge 4: Bridge Deck and Parapet	30.33093561	0.75	22.74820171	525,600.00
0.2721	B2C2	Bridge 2: Bearing Pads	25.05923812	0.75	18.79442859	900,000.00
0.2721	B1C3	Bridge 1: Expansion Joint	24.84979185	0.75	18.63734389	134,500.00
0.8091	B3C5	Bridge 3: Pier Columns	72.41353322	0.25	18.10338331	210,000.00
0.8091	B3C4	Bridge 3: Abutment Walls	60.17188517	0.25	15.04297129	513,750.00
0.1175	B4C5	Bridge 4: Pier Columns	12.44264994	0.5	6.221324968	315,000.00
0.1175	B4C6	Bridge 4: Foundations	11.44401978	0.5	5.722009892	607,500.00
0.1175	B2C1	Bridge 2: Bridge Deck and Parapet	9.016547881	0.5	4.50827394	613,200.00
0.044775	B2C5	Bridge 2: Pier Columns	3.264042252	0.5	1.632021126	367,500.00
0.044775	B2C4	Bridge 2: Abutment Walls	2.712249587	0.5	1.356124794	712,500.00
0	B2C6	Bridge 2: Foundations	0	0.5	0	843,750.00

Table 29 lists out the components with their priority and their sum and cost, as well.

Table 29 Components Priority List

Code	Name	Overall Priority	Cum. Priority	Maintenance Cost	Cum. Maintenance Cost
B1C2	Bridge 1: Bearing Pads	69.1	69.1	660,000.00	660,000.00
B3C1	Bridge 3: Bridge Deck and Parapet	58.2	127.3	262,800.00	922,800.00
B3C3	Bridge 3: Expansion Joint	57.1	184.4	98,000.00	1,020,800.00
B4C4	Bridge 4: Abutment Walls	54.4	238.7	667,500.00	1,688,300.00
B3C2	Bridge 3: Bearing Pads	37.2	276.0	360,000.00	2,048,300.00
B4C3	Bridge 4: Expansion Joint	36.0	311.9	171,000.00	2,219,300.00
B1C1	Bridge 1: Bridge Deck and Parapet	30.7	342.6	394,200.00	2,613,500.00
B1C5	Bridge 1: Pier Columns	29.1	371.7	262,500.00	2,876,000.00
B4C2	Bridge 4: Bearing Pads	27.3	399.0	900,000.00	3,776,000.00
B3C6	Bridge 3: Foundations	27.1	426.1	506,250.00	4,282,250.00
B1C6	Bridge 1: Foundations	26.8	452.9	675,000.00	4,957,250.00
B2C3	Bridge 2: Expansion Joint	24.8	477.7	171,000.00	5,128,250.00
B1C4	Bridge 1: Abutment Walls	24.2	501.9	645,000.00	5,773,250.00
B4C1	Bridge 4: Bridge Deck and Parapet	22.7	524.6	525,600.00	6,298,850.00
B2C2	Bridge 2: Bearing Pads	18.8	543.4	900,000.00	7,198,850.00
B1C3	Bridge 1: Expansion Joint	18.6	562.1	134,500.00	7,333,350.00
B3C5	Bridge 3: Pier Columns	18.1	580.2	210,000.00	7,543,350.00
B3C4	Bridge 3: Abutment Walls	15.0	595.2	513,750.00	8,057,100.00
B4C5	Bridge 4: Pier Columns	6.2	601.4	315,000.00	8,372,100.00
B4C6	Bridge 4: Foundations	5.7	607.1	607,500.00	8,979,600.00
B2C1	Bridge 2: Bridge Deck and Parapet	4.5	611.7	613,200.00	9,592,800.00
B2C5	Bridge 2: Pier Columns	1.6	613.3	367,500.00	9,960,300.00
B2C4	Bridge 2: Abutment Walls	1.4	614.6	712,500.00	10,672,800.00
B2C6	Bridge 2: Foundations	0	614.6	843,750.00	11,516,550.00

4.4.1.2. Uncertainty Molding Mont Carlo Simulation

The developed model is capable of accounting for uncertainty while searching for the optimum bridges' maintenance plan. The Oracle Crystal Ball software is used to carry out the calculation using Mont Carlo Simulation. The simulation is a technique applied to assist the decision makers to understand the effect of risk and uncertainty in selecting the most attractive bridge maintenance plan. As depicted in Figure 28 two main uncertain variables are considered in the optimization model. They are (1) estimated maintenance cost of bridge elements and (2) utilities values of each posterization factor, as defined by the user in MAUT. Those variables are defined in crystal ball as forecasting cell and they are highlighted in green.

The green cells show the assumption variables which have uncertainty and are considered normally distributed with the mean value as presented in the Table 30 and the standard deviation of $\pm 10\%$ of the value of each variable. The purpose is the match the case of the hypothetical project as a deterministic case. The yellow cells are the defined as the decision variables and considered binary distributed with 0 and 1 values each have a chance of 50%. Thru this decision variable the random selection methodology can be applied. The light blue cells are the forecast variables and they are the output variables of the model. Thru the output results for each random selection the objective function can be tested.

The uncertainty is examined in three different cases in which each case has different consideration. Then the results are compared to see the effect of uncertainty on the model and on the optimal solution and final decision. The first case is deterministic case in which no uncertainty is considered. The second case considers uncertainty in the two variables, priority and cost. The third case considers uncertainty in one variable, priority as the main variable.

Table 30 Parameter of Developed Model

Simulation Parameter	Data Source	Probability Distribution	Parameter Type
Component Priority	Component prioritization – Model	Normal Distribution	Assumption
Component Maintenance Cost	BMS	Normal Distribution	Assumption
Decision	Assumed Randomly	Discrete	Decision
Total Priority	Calculated	-	Forecast
Total Maintenance Cost	Calculated	-	Forecast

	A	B	C	D	E	F	G
1	Code	Name	Overall Priority	Maintenance Cost	Decision	Selected Priority	Selected Maintenance Cost
2	B1C2	Bridge 1:Bearing Pads	69.1	660,000.00	1	69.08	660,000.00
3	B3C1	Bridge 3:Bridge Deck and Parapet	58.2	262,800.00	0	0.00	-
4	B3C3	Bridge 3:Expansion Joint	57.1	98,000.00	0	0.00	-
5	B4C4	Bridge 4:Abutment Walls	54.4	667,500.00	0	0.00	-
6	B3C2	Bridge 3:Bearing Pads	37.2	360,000.00	0	0.00	-
7	B4C3	Bridge 4:Expansion Joint	36.0	171,000.00	1	35.98	171,000.00
8	B1C1	Bridge 1:Bridge Deck and Parapet	30.7	394,200.00	0	0.00	-
9	B1C5	Bridge 1:Pier Columns	29.1	262,500.00	1	29.13	262,500.00
10	B4C2	Bridge 4:Bearing Pads	27.3	900,000.00	1	27.30	900,000.00
11	B3C6	Bridge 3:Foundations	27.1	506,250.00	1	27.10	506,250.00
12	B1C6	Bridge 1:Foundations	26.8	675,000.00	1	26.79	675,000.00
13	B2C3	Bridge 2:Expansion Joint	24.8	171,000.00	1	24.77	171,000.00
14	B1C4	Bridge 1:Abutment Walls	24.2	645,000.00	1	24.20	645,000.00
15	B4C1	Bridge 4:Bridge Deck and Parapet	22.7	525,600.00	1	22.75	525,600.00
16	B2C2	Bridge 2:Bearing Pads	18.8	900,000.00	0	0.00	-
17	B1C3	Bridge 1:Expansion Joint	18.6	134,500.00	0	0.00	-
18	B3C5	Bridge 3:Pier Columns	18.1	210,000.00	1	18.10	210,000.00
19	B3C4	Bridge 3:Abutment Walls	15.0	513,750.00	0	0.00	-
20	B4C5	Bridge 4:Pier Columns	6.2	315,000.00	1	6.22	315,000.00
21	B4C6	Bridge 4:Foundations	5.7	607,500.00	1	5.72	607,500.00
22	B2C1	Bridge 2:Bridge Deck and Parapet	4.5	613,200.00	1	4.51	613,200.00
23	B2C5	Bridge 2:Pier Columns	1.6	367,500.00	1	1.63	367,500.00
24	B2C4	Bridge 2:Abutment Walls	1.4	712,500.00	1	1.36	712,500.00
25	B2C6	Bridge 2:Foundations	0	843,750.00	0	0.00	-
26						324.63	7,342,050.00

Figure 28 Crystal Ball Variables and Base Case

The objective function is defined in the OptQuest tool in Crystal Ball which conducts the optimization-based simulation and. Figure 29 shows the Objective Function defined in OptQuest.

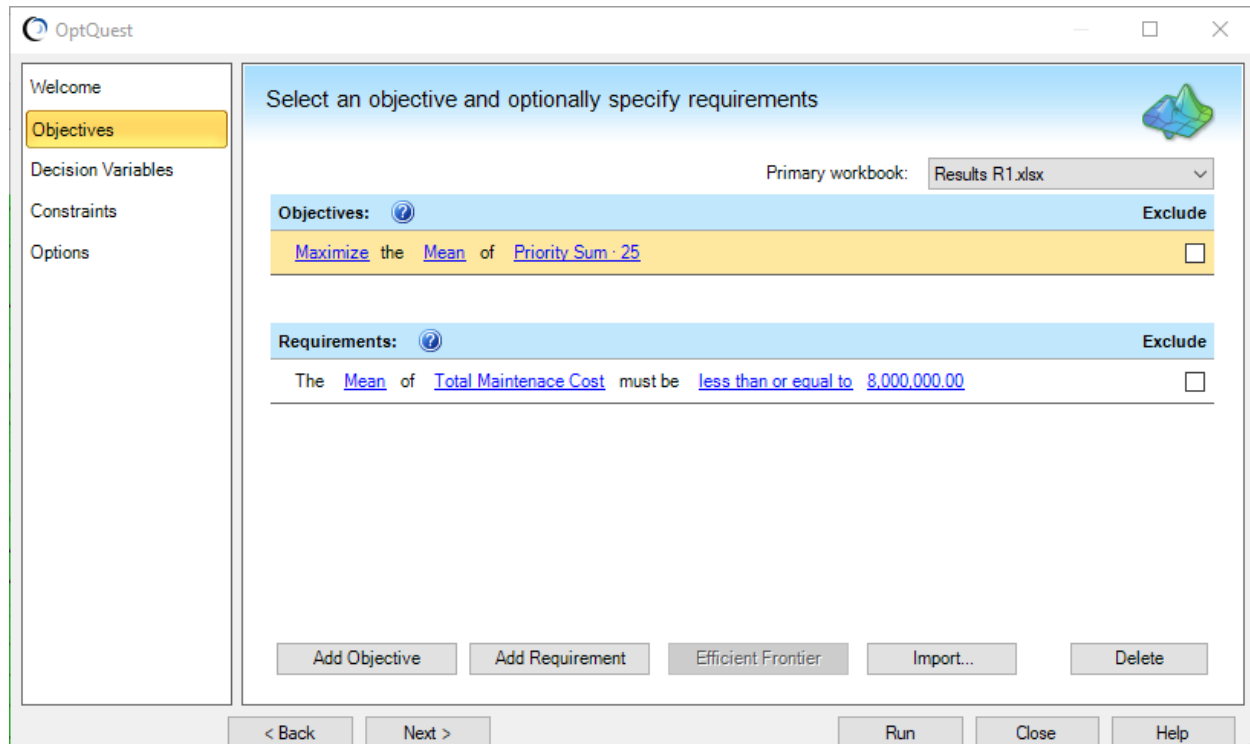


Figure 29 Objective Function in OptQuest

When model starts, it takes the base case and do the calculation and find the forecast variable and test the objective functions. Then another set of decisions are assumed and the assumption variables are changing according to their probability distribution, as well. OptQuest utilizes metaheuristics to direct its search algorithm for better solutions. This approach is similar to the adaptive memory which remembers good solutions worked before and recombines them into another new solutions. The software randomly changes the decision variable, 1 & 0, to get one solution and test the constrain and requirements. If the solution was near to the constrain the software remembers the set and generate another set close to that set. When the model finishes all

iteration and trails, it reports the Figure 30 which shows the best solution according to the objective functions and the requirement and for the number of simulations set which have been done. The performance chart shows that for the 100 simulations that it had done the maximum priority sum it got was the around 585.5 which satisfies the objective functions. It is all most close to the results if we run the model for more trails.

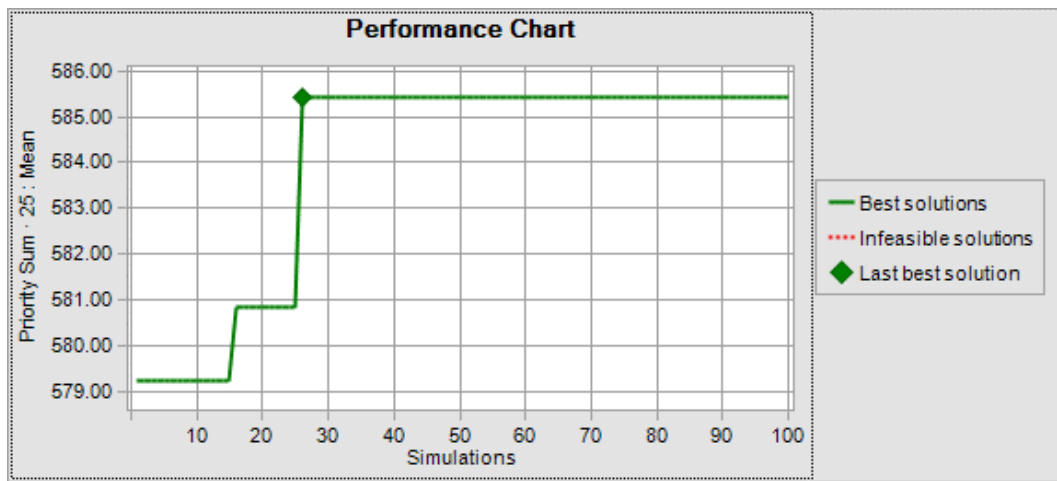


Figure 30 Performance Chart of Model

After running the model for more trials then the results show total sum of priority is 586.38 which matches the objectives. The software also affords to show breakdown of the best result as shown in Figure 31.

	A	B	C	D	E	F	G
1	Code	Name	Overall Priority	Maintenance Cost	Decision	Selected Priority	Selected Maintenance Cost
2	B1C2	Bridge 1:Bearing Pads	69.1	660,000.00	1	69.08	660,000.00
3	B3C1	Bridge 3:Bridge Deck and Parapet	58.2	262,800.00	1	58.21	262,800.00
4	B3C3	Bridge 3:Expansion Joint	57.1	98,000.00	1	57.07	98,000.00
5	B4C4	Bridge 4:Abutment Walls	54.4	667,500.00	1	54.37	667,500.00
6	B3C2	Bridge 3:Bearing Pads	37.2	360,000.00	1	37.22	360,000.00
7	B4C3	Bridge 4:Expansion Joint	36.0	171,000.00	1	35.98	171,000.00
8	B1C1	Bridge 1:Bridge Deck and Parapet	30.7	394,200.00	1	30.66	394,200.00
9	B1C5	Bridge 1:Pier Columns	29.1	262,500.00	1	29.13	262,500.00
10	B4C2	Bridge 4:Bearing Pads	27.3	900,000.00	1	27.30	900,000.00
11	B3C6	Bridge 3:Foundations	27.1	506,250.00	1	27.10	506,250.00
12	B1C6	Bridge 1:Foundations	26.8	675,000.00	1	26.79	675,000.00
13	B2C3	Bridge 2:Expansion Joint	24.8	171,000.00	1	24.77	171,000.00
14	B1C4	Bridge 1:Abutment Walls	24.2	645,000.00	1	24.20	645,000.00
15	B4C1	Bridge 4:Bridge Deck and Parapet	22.7	525,600.00	1	22.75	525,600.00
16	B2C2	Bridge 2:Bearing Pads	18.8	900,000.00	1	18.79	900,000.00
17	B1C3	Bridge 1:Expansion Joint	18.6	134,500.00	1	18.64	134,500.00
18	B3C5	Bridge 3:Pier Columns	18.1	210,000.00	1	18.10	210,000.00
19	B3C4	Bridge 3:Abutment Walls	15.0	513,750.00	0	0.00	-
20	B4C5	Bridge 4:Pier Columns	6.2	315,000.00	1	6.22	315,000.00
21	B4C6	Bridge 4:Foundations	5.7	607,500.00	0	0.00	-
22	B2C1	Bridge 2:Bridge Deck and Parapet	4.5	613,200.00	0	0.00	-
23	B2C5	Bridge 2:Pier Columns	1.6	367,500.00	0	0.00	-
24	B2C4	Bridge 2:Abutment Walls	1.4	712,500.00	0	0.00	-
25	B2C6	Bridge 2:Foundations	0	843,750.00	0	0.00	-
26						586.38	7,858,350.00

Figure 31 Best Solution Output

One case has been considered which is deterministic and yielded the results show in Figure 32 Total Maintenance Cost is 7,858,350.00 SAR and Priority Sum is 586.38. considering other two cases with uncertainty in both priority and cost considering different distributions and assumptions. The other case with priority only.

The second case is for uncertainty in both priority and cost. The priority variable is assumed as Triangular distribution the cost variable is assumed as Gamma distribution. Figure 32 shows the base case.

	A	B	C	D	E	F	G
1	Code	Name	Overall Priority	Maintenance Cost	Decision	Selected Priority	Selected Maintenance Cost
2	B1C2	Bridge 1:Bearing Pads	69.1	660,000.00	0	0.00	-
3	B3C1	Bridge 3:Bridge Deck and Parapet	58.2	262,800.00	0	0.00	-
4	B3C3	Bridge 3:Expansion Joint	57.1	98,000.00	0	0.00	-
5	B4C4	Bridge 4:Abutment Walls	54.4	667,500.00	0	0.00	-
6	B3C2	Bridge 3:Bearing Pads	37.2	360,000.00	0	0.00	-
7	B4C3	Bridge 4:Expansion Joint	36.0	171,000.00	0	0.00	-
8	B1C1	Bridge 1:Bridge Deck and Parapet	30.7	394,200.00	0	0.00	-
9	B1C5	Bridge 1:Pier Columns	29.1	262,500.00	0	0.00	-
10	B4C2	Bridge 4:Bearing Pads	27.3	900,000.00	0	0.00	-
11	B3C6	Bridge 3:Foundations	27.1	506,250.00	0	0.00	-
12	B1C6	Bridge 1:Foundations	26.8	675,000.00	0	0.00	-
13	B2C3	Bridge 2:Expansion Joint	24.8	171,000.00	0	0.00	-
14	B1C4	Bridge 1:Abutment Walls	24.2	645,000.00	0	0.00	-
15	B4C1	Bridge 4:Bridge Deck and Parapet	22.7	525,600.00	0	0.00	-
16	B2C2	Bridge 2:Bearing Pads	18.8	900,000.00	0	0.00	-
17	B1C3	Bridge 1:Expansion Joint	18.6	134,500.00	0	0.00	-
18	B3C5	Bridge 3:Pier Columns	18.1	210,000.00	0	0.00	-
19	B3C4	Bridge 3:Abutment Walls	15.0	513,750.00	0	0.00	-
20	B4C5	Bridge 4:Pier Columns	6.2	315,000.00	0	0.00	-
21	B4C6	Bridge 4:Foundations	5.7	607,500.00	0	0.00	-
22	B2C1	Bridge 2:Bridge Deck and Parapet	4.5	613,200.00	0	0.00	-
23	B2C5	Bridge 2:Pier Columns	1.6	367,500.00	0	0.00	-
24	B2C4	Bridge 2:Abutment Walls	1.4	712,500.00	0	0.00	-
25	B2C6	Bridge 2:Foundations	0	843,750.00	0	0.00	-
26						-	-

Figure 32 Base Case for Uncertainty Analysis

After running the model, the results are depicted in Figure 33. Priority became 474.41 and total maintenance cost is 7,597,540.078 SAR and the components is different than the deterministic case but most components are included in both cases.

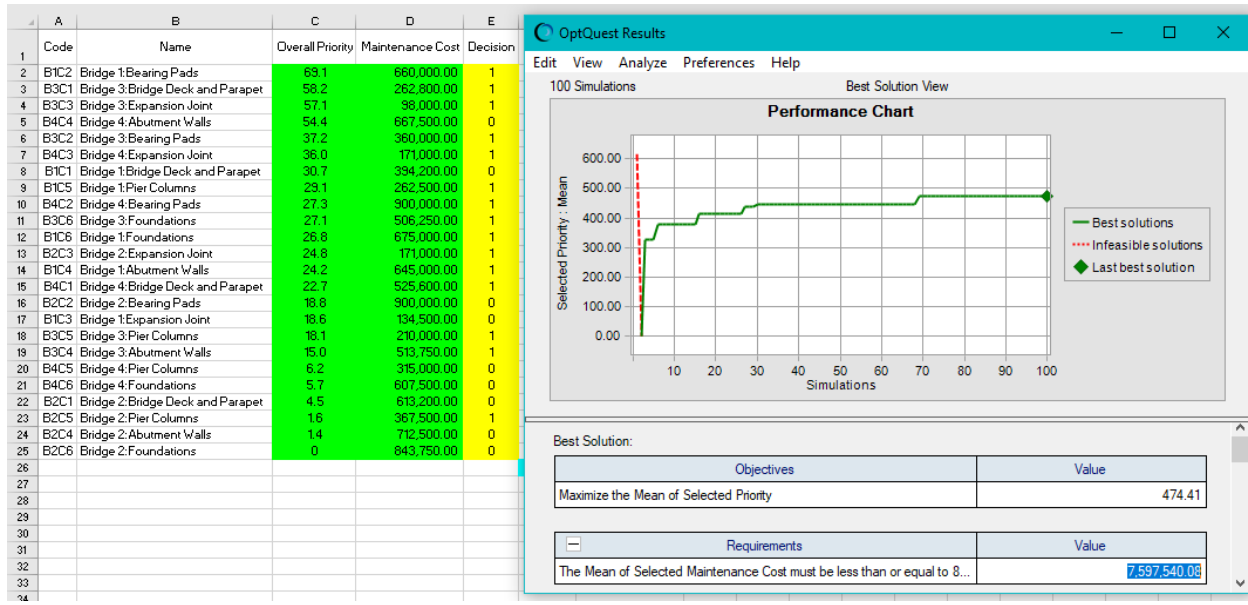


Figure 33 Results of Model for Uncertainty in Priority and Cost

The third case is to consider the uncertainty in priority only. Considering the same distribution as second case. The results are depicted in Figure 34. the priority is 572.40 and the total maintenance cost is 7,770,300.00 SAR. Also, most components are included in all of the cases but with some changes.

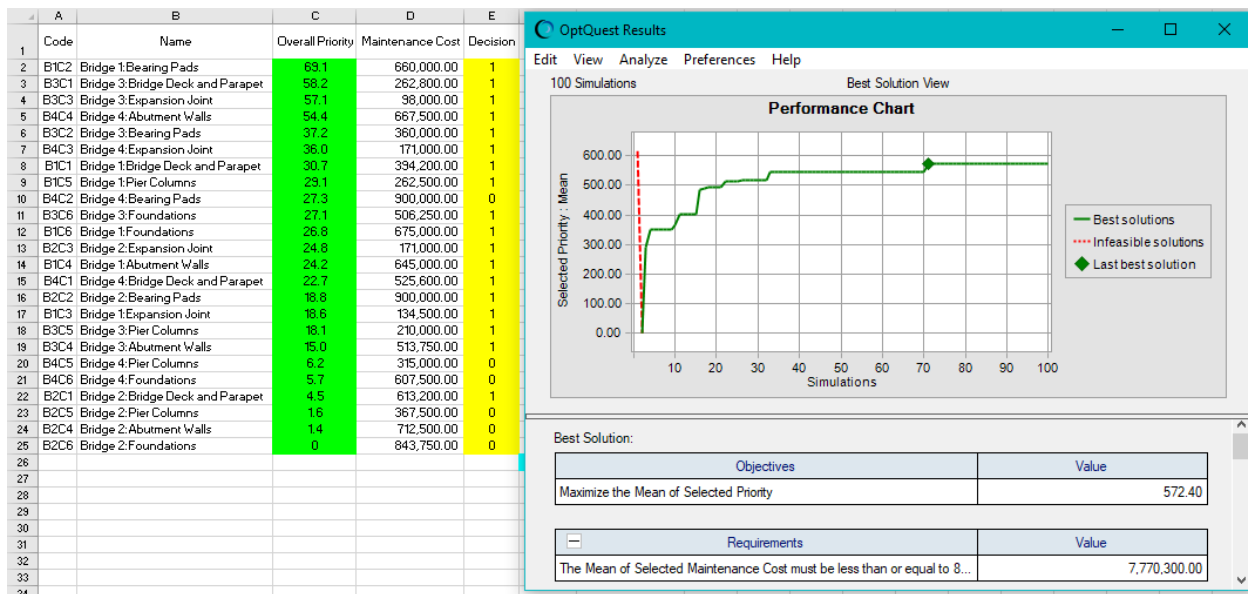


Figure 34 Results of Model for Uncertainty in Priority

Table 31 summarizes the results of the above 3 cases. It can be noticed that solutions are close to each other but uncertainty plays a major role in selecting the more attractive solution which is not necessary to be the optimal one. The more attractive solution may be selected based on the owner preferences. Owner may select the solution based on the remaining amount in the budget which works as contingency for him since the actual cost may exceed the estimated cost and hence the owner have a buffer to accommodate the overrun.

Comparing the cases to each other the deterministic case yielded the greatest number of components and consumes most of the budget. Whereas uncertainty in both variables reduces the number of elements to be maintained. The uncertainty in priority only assuming that no uncertainty in cost yields a solution in between.

Eventually, actual cost may become even different than these solutions and the maintained components, as well. Owner with experience may develop a probabilistic distribution which is fit to each variable.

Table 31 Uncertainty cases Summary

Case	Case Type	Priority Prob. Dist.	Cost Prob. Dist.	Optimal Solution	
				Priority	Cost (SAR)
Case 1	Deterministic	NA	NA	586.38	7,858,350.00
Case 2	2-variables Uncertainty	Triangular	Gamma	474.41	7,597,540.08
Case 3	1-Variable Uncertainty	Triangular	NA	572.4	7,770,300.00

4.4.1.3. Efficient Frontier Analysis

The efficient frontier analysis is used to enhance the analysis of the model output. In this analysis, the value of the objective function is plotted against the standard deviation of the distribution of that value (i.e., priority sum). Efficient frontier analysis determines the curve that plots an objective value against changes to a constraint. This analysis allows for comparisons of mean costs of bridges maintenance against different levels of risk to enable decision maker in making well informed decisions. The objective function is set to minimize the maximize the mean of the project unit total cost. Also, the user can impose a condition that limits the standard deviation of the bridge priority sum. Figures 35 and 36 displays a plot of the model objective value (mean of bridge priority sum) against its standard deviation that is being tested. The best solution for each test point is displayed as a diamond in the chart. As it can be seen from the figure, each priority sum had a specific mean of bridges maintenance plan and its associated standard deviation. For any given

mean, there is one maintenance plan that has the smallest associated standard deviation. Figure 38 depicts the relationship between the generated means and standard deviations. The technique used to search for optimal solutions on the efficient frontier in this example project uses the mean and standard deviation as the criteria for balancing risk and bridge priority sum. This criterion is called mean-standard deviation coefficient. Table 32 represents the best solution values for each specific test point. Table 33 shows the maintenance plans output from Efficient frontier analysis. The maintenance plan that lie directly on the curve are called efficient (Markowitz, 1991). As it can be seen from Fig. 37 it is impossible to obtain a higher mean of bridge priority sum without generating higher standard deviations or lower standard deviations without generating a smaller mean of bridge priority. This method uses the mean and standard deviation of bridge priority as the criteria to assess risk involved. Thus, the decision maker must face the trade-off between smaller bridge maintenance cost with higher risk, and lower maintenance cost with higher risk. Although the model selected the maintenance plan that consists 13 Components, it may be more attractive for the decision maker to choose a maintenance plan that consists of less number of bridge/components to be fixed to minimize the risk (point 6). The owner has to decide if it is worth it to fix a smaller number of bridge and to minimize the risk.

To further enhance the analysis, a multi-objective optimization can be performed (minimizing maintenance plan and minimizing risks). A weighted combination of the multiple objectives approach is used. A weighted combination of the maintenance plan and risk objectives is presented as follows:

$$\text{Min Project Total Cost} = \text{Mean of project total cost} - (R \times \text{STDV of project cost}) \quad (4.1)$$

where $R > 0$; and it is a risk aversion constant to be set by the decision maker. Geometrically, the near optimal solution for a multi-objective function occurs in the saddle point between the optimal endpoints of the individual objectives. In this case, the optimal solution occurs somewhere on the efficient frontier between the minimum maintenance cost while maximization items to be fixed and the risk. The Figures 35 to 37 was obtained with 95% confidence level.

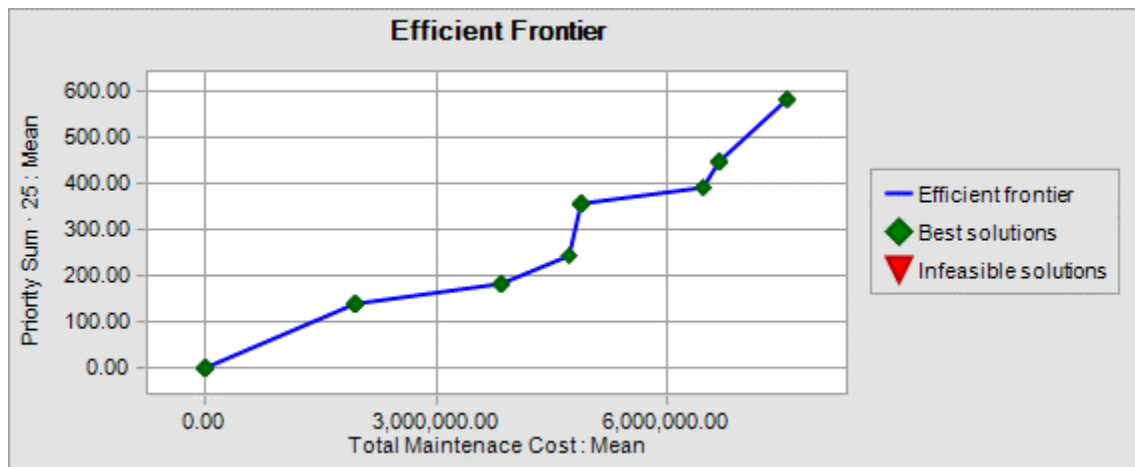


Figure 35 Efficient Frontier Report at 100,000 Step

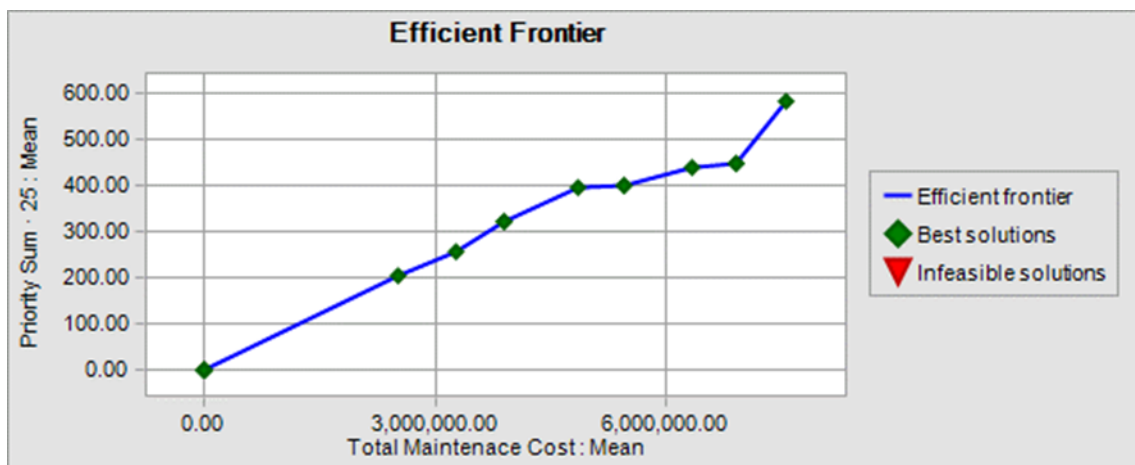


Figure 36 Efficient Frontier Report at 500,000 Step

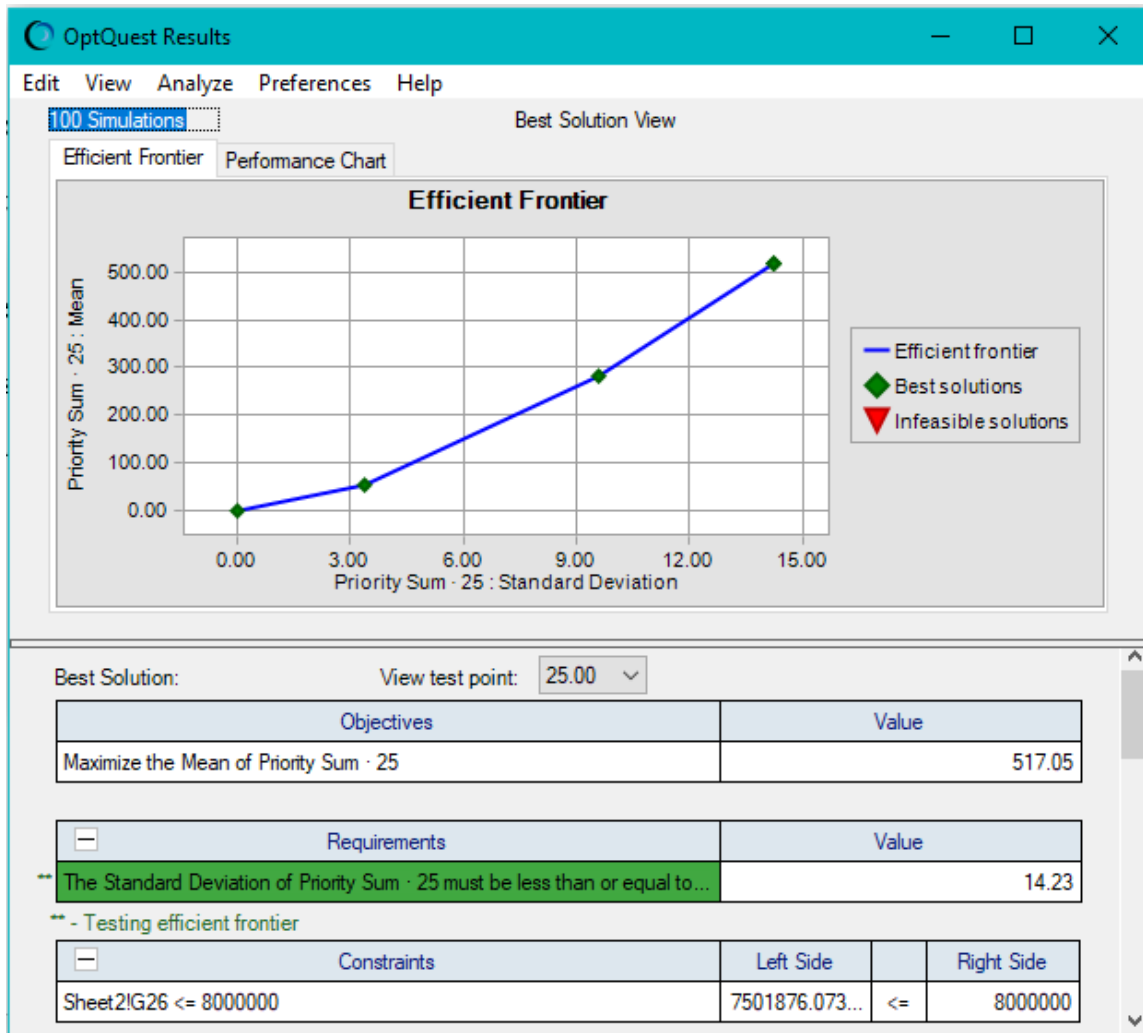


Figure 37 Mean VS ST. DV. Efficient Frontier

Table 32 Efficient frontier analysis

Test Results	Variable	Cost	Objective	Standard Deviation
Test Point 1.00	Maintenance Plan 1	1,721,250	52.08	3.36
Test Point 2.00	Maintenance Plan 2	7,191,600	283.03	9.59
Test Point 3.00	Maintenance Plan 3	7,801,000	517.05	14.23

Table 33 Maintenance Plans Output from Efficient frontier analysis

Code	Name	Overall Priority	Maintenance Cost	Plan 1		Plan 2		Plan 3	
				Decision	Cost	Decision	Cost	Decision	Cost
B1C2	Bridge 1: Bearing Pads	69.08	660,000	0	-	0	-	1	660,000
B3C1	Bridge 3: Bridge Deck and Parapet	58.21	262,800	0	-	1	262,800	1	262,800
B3C3	Bridge 3: Expansion Joint	57.07	98,000	0	-	0	-	0	-
B4C4	Bridge 4: Abutment Walls	54.37	667,500	0	-	0	-	1	667,500
B3C2	Bridge 3: Bearing Pads	37.22	360,000	0	-	1	360,000	1	360,000
B4C3	Bridge 4: Expansion Joint	35.98	171,000	0	-	0	-	1	171,000
B1C1	Bridge 1: Bridge Deck and Parapet	30.66	394,200	0	-	0	-	1	394,200
B1C5	Bridge 1: Pier Columns	29.13	262,500	0	-	0	-	1	262,500
B4C2	Bridge 4: Bearing Pads	27.30	900,000	0	-	1	900,000	1	900,000
B3C6	Bridge 3: Foundations	27.10	506,250	1	506,250	1	506,250	1	506,250
B1C6	Bridge 1: Foundations	26.79	675,000	0	-	1	675,000	1	675,000
B2C3	Bridge 2: Expansion Joint	24.77	171,000	0	-	0	-	1	171,000
B1C4	Bridge 1: Abutment Walls	24.20	645,000	0	-	1	645,000	1	645,000
B4C1	Bridge 4: Bridge Deck and Parapet	22.75	525,600	0	-	1	525,600	0	-
B2C2	Bridge 2: Bearing Pads	18.79	900,000	1	900,000	1	900,000	1	900,000
B1C3	Bridge 1: Expansion Joint	18.64	134,500	0	-	0	-	1	134,500
B3C5	Bridge 3: Pier Columns	18.10	210,000	0	-	1	210,000	1	210,000
B3C4	Bridge 3: Abutment Walls	15.04	513,750	0	-	1	513,750	1	513,750
B4C5	Bridge 4: Pier Columns	6.22	315,000	1	315,000	0	-	0	-
B4C6	Bridge 4: Foundations	5.72	607,500	0	-	0	-	0	-
B2C1	Bridge 2: Bridge Deck and Parapet	4.51	613,200	0	-	1	613,200	0	-
B2C5	Bridge 2: Pier Columns	1.63	367,500	0	-	1	367,500	1	367,500
B2C4	Bridge 2: Abutment Walls	1.36	712,500	0	-	1	712,500	0	-
B2C6	Bridge 2: Foundations	0.00	843,750	0	-	0	-	0	-
	Total				1,721,250		7,191,600		7,801,000

4.4.1.4. Risk Assessment

The risk assessment can be done using the Oracle Crystal ball simulation software. The software is utilized to determine the possible variation in the total maintenance cost which shows the possible maintenance costs with 95% confidence level and normal distribution for maintenance cost and $\pm 10\%$ standard deviation. Figure 39 shows the results from the software. The results show that it is not possible to have the whole components of the bridge in the maintenance this year as the total cost may lower till 10.8M SAR but our budget is only 8M. there is also possibility for the cost to increase to more than 12M SAR.

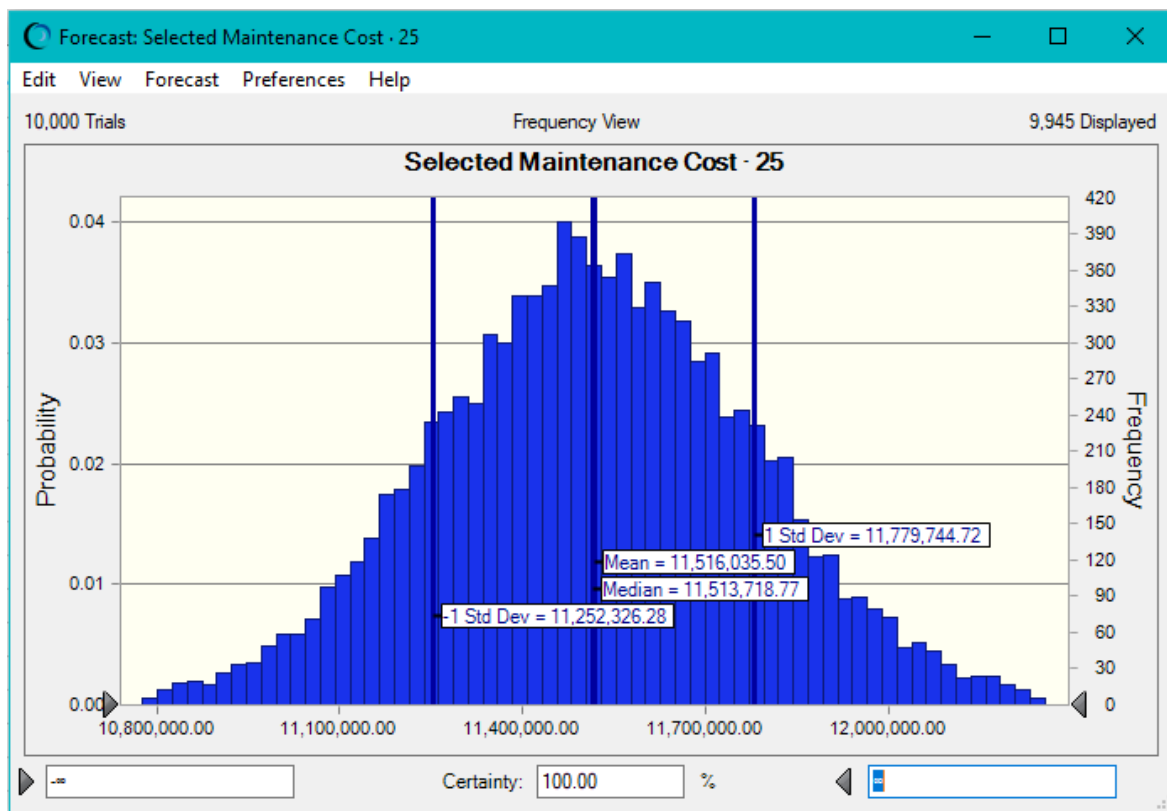


Figure 38 Risk Analysis for Total Maintenance Cost

The same is done for the budgeted cost and the selected components according to the model results. Figure 40 shows the results from the software. The results show that 75.11% the budget remain the same and only 24.89% chance of requesting additional budget. The budget can range from 7,262,970.95 SAR to 8,448,299.84 SAR.

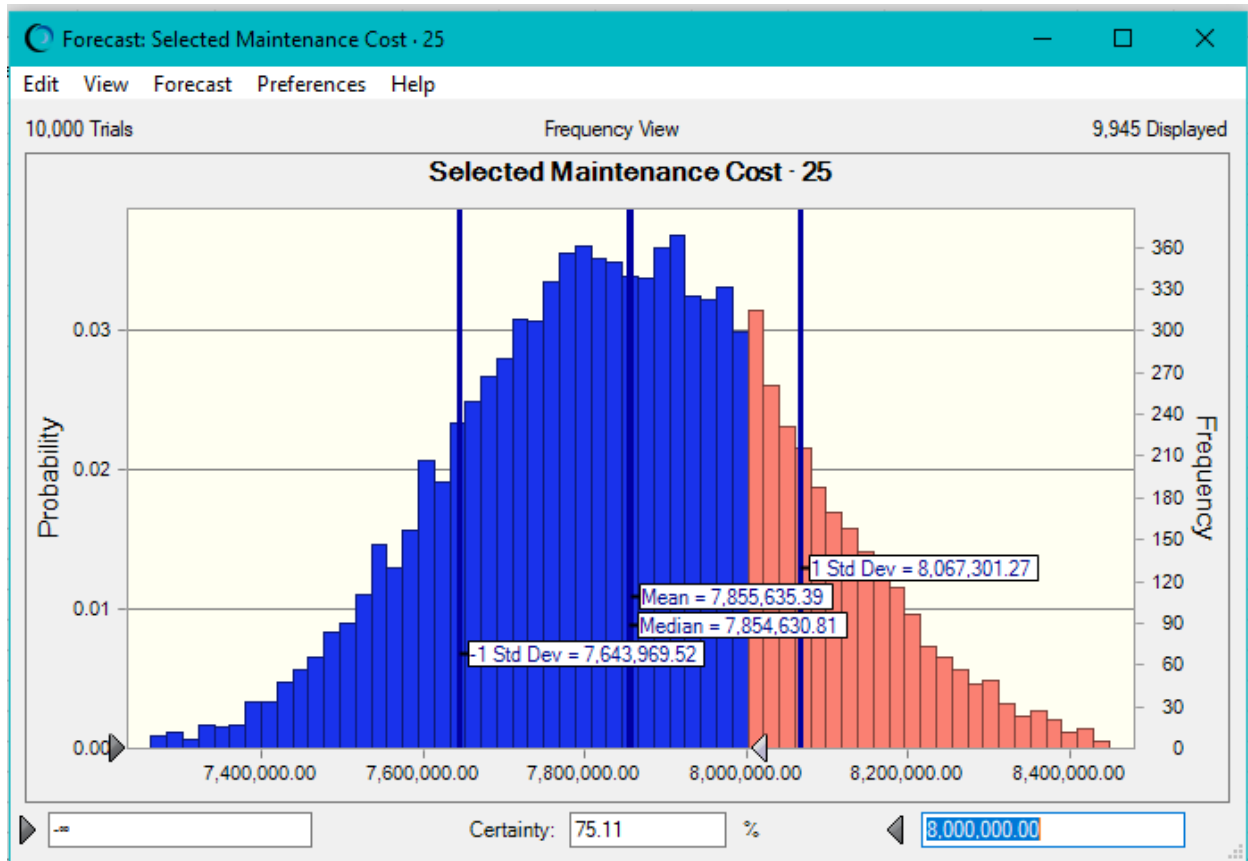


Figure 39 Risk Analysis for Budgeted Cost – Optimal Solution

If considering the second-best solution by eliminating the last component the model sensitivity is shown in Figure 41. The results show that 98.56% the budget remain the same and only 1.44% chance of requesting additional budget. The budget can range from 6,958,099.40 SAR to 8,130,823.09 SAR.

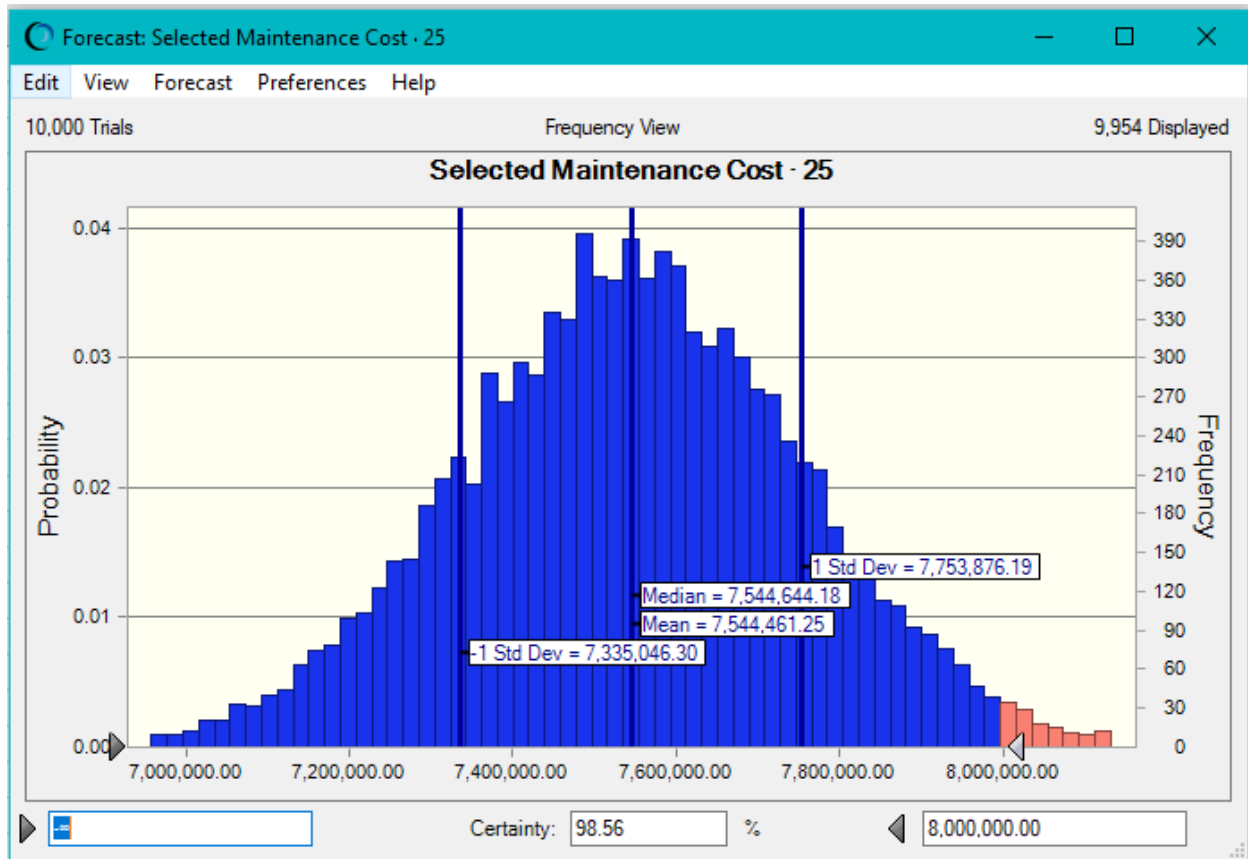


Figure 40 Risk Analysis for Budgeted Cost – 2nd Optimal Solution

This solution seems better than the first option since this solution allows for budget overrun in case of an unexpected situation.

4.4.1.5. Experts Feedback

The model and the example project are presented to two local experts and the following is their feedback

1. The experts agreed with results of the AHP for both the factors and components weights.
2. Also, they agreed with the proposed weights of maintenance strategy.
3. Experts agreed that results of the model to be a list of components to be maintained since all contract bills of bridge maintenance projects are comprised of separate items for each component.
4. Experts agreed that the fact that bridge components from structural integrity point of view are independent if some components in one bridge have been maintained and the other components are to be maintained later when the budget constraint is resolved although this fact needs to be proved from the design point of view.
5. Experts proposed to develop a model for each component and the priority selection is to be based on a comprehensive model with different factors. Thus, for bearing pads the priority is to be only among all bearing pads and so on. But when it is maintenance time the selection of components is based on criteria related to either structural importance, owner preferences or life cycle cost or any other factors based on owner requirements.
6. Experts also agreed with the uncertainty in the model and its source from the subjective assessment. They also stated that more inputs to the model yield more accurate results and this is to be accomplished through objective inspection rather than visual inspection.

4.5 Summary

This chapter presented the data collected and the analysis of these data. The data collected were AHP matrix for prioritization factor and bridge components and utility values for periodization factors for MAUT. The calculation steps presented in chapter 3 were applied in order to analyze these data. As illustrated in this chapter, 9 local experts were interviewed. The results showed the weight of each prioritization factor, the weight of each component and the MAUT curves were established. Then, the model for budget allocation for bridge maintenance was developed. The model was validated through an example project. Application for Oracle crystal ball was presented. Uncertainty was discussed and illustrated by cases. Risk assessment was also presented in this chapter.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This chapter summarizes the study and states the findings of the research. In addition, it concludes the work in the study and gives recommendations to users and readers. Moreover, it presents potential areas for future studies.

5.1 Summary of the Study

Bridges constitute a major component of the road network. It helps reduce the traffic congestion and eliminate conflict while maintaining an acceptable level of service. Bridges as any other infrastructure require maintenance with time due to the effect of dynamic load, weather and fatigue. The aim of bridge maintenance is to keep the bridge at an acceptable level of service throughout its useful life. The maintenance required for a bridge depends mainly upon the condition assessment at the time of maintenance. In case of a constrained budget for bridges maintenance, there are other important factors that assist the bridge owner in identifying their priority for maintenance. Here, in Saudi Arabia, Dammam Municipality which belong to MOMRA, this study is conducted in order to assist municipality optimizing the allocation of a constrained budget for bridges maintenance. This study went through the following steps. First, prioritization factors for bridge maintenance have been gathered and their weight have been identified using AHP technique then utility curves for each factor have been established. Second, typical bridge components have been identified and their weight as well using AHP technique. Third, the research also proposed an optimization model for selecting the optimum maintenance plan under the constraint of budget available. The optimization model integrates Monte Carlo

simulation to consider for the uncertainties associated with the MAUT input and the estimation of bridge maintenance cost. It also adopts the use of Efficient frontier analysis to assess the risk of the selected maintenance plan. Third, a hypothetical case has been considered to test and to validate the model.

5.2 Findings

The findings of this research can be summarized as following:

1. The bridge management system followed by the municipality, the targeted area in this research, which is a manual issued by MOMRA has a vary board methodology in prioritizing bridges for maintenance which depends mainly on the bridges conditions and on benefits of cost saving from deferring the maintenance of the bridges to the next year resulting in accumulating the maintenance of less expensive components and delaying the maintenance of components with acceptable or poor conditions.
2. The study identified the prioritization factors of bridges for maintenance is Saudi Arabia which are condition factor, age factor, location factor and pervious & scheduled maintenance.
3. The highest score identified factors are Condition factor and Traffic factor and Location Factor.

5.3 Contribution

The main contribution of this research can be summarized as following:

1. Developing an optimization-based simulation model that is capable of finding the optimum bridges maintenance plan taking into consideration the available constraints budget and the importance of the bridges under consideration while maintaining acceptable level of

maintenance. Appendix B provides an instruction manual to the users which guides them in how to use the model to come up with a proper maintenance plan.

2. considering uncertainties associated with component priority which is based on condition assessment which was done by means of subjective and objective inspections.
3. considering uncertainties associated with maintenance cost while optimizing the maintenance plan.
4. Allowing the decision maker carryout IF Then Analysis to assess the risk associated with a selected maintenance plan by which the decision maker may select the most attractive solution rather than the optimum one with high risk.

5.4 Conclusion

Bridge maintenance is a crucial task to be done by the owner in order to keep the bridges at an acceptable level of service. Owners usually have a constrained budget to maintain their bridges and require a clear and efficient methodology to assist them in allocating the budget to candidate bridges. The developed model is optimization-based simulation which has the objective to maximize the number of bridges for maintenance. Also, it considers uncertainty in the main variables of the model which are the priority and maintenance cost. Uncertainty must be managed in order to obtain accurate results. The main source of uncertainty is from the subjectivity of the owners and the way to overcome this issue is to look for objective manners to determine the cost and priority. The model was developed with the help of the local experts. The model is validated through hypothetical project and the feedback from local experts who have agreed with the methodology and results. Also, the model was implemented by Oracle Crystal ball software.

5.5 Recommendation

It is recommended for the bridge owner, mainly MOMRA, to merge and integrate the model with the BMS of Municipality thus bridges prioritization is updated always.

5.6 Future Study

The optimization-based simulation model for budget allocation has certain potential areas for improvements. This model represents a decision support tool for the owner of the bridges in order to increase the efficiency of the local bridge management system and to help them in conducting objective rather than subjective assessment to the bridges in their BMS to have a more reliable system and to ensure proper management practices. Listed below are the potential areas of improvements in this study.

1. Due to lacking experts in this field and due to the fact that bridges in Dammam area which belong to Municipality are new it is recommended to keep updating the utility curves specially the traffic volume AADT.
2. The model selects the components based on their priority but actually there must be a structural integrity test for the selected components as practically there are some cases where whole components need to be maintained in order to have an integrated structure and this may be cheaper in the future rather than having redundant maintenance.
3. Put more emphasis on structural component in terms of adding weights of components of different types of bridges in order to allow the budget allocation of different types of bridge.

Also, adding a corresponding factor to prioritize each bridge type and establish its utility curve.

4. Develop a separate model for each structural component and develop a comprehensive model integrating all sub models for components according to expert recommendations.
5. Test the efficiency of budget allocation using this model versus life cycle cost methodology in terms of investing in bridges which may allow the owner to invest in bridge maintenance in case the bridges conditions are acceptable and the maintenance is not needed urgently.
6. Conduct the same research on MOT bridges.
7. Bridge engineers are encouraged to develop a model for bridge testing which converts the results of destructive and non-destructive tests into a condition state for the bridge and its components then integrate both models to increase the objectivity of the model.
8. Prioritization factors may be updated with respect to time, economic conditions, and upon changing the strategy of the government or by inventing new modes of transportation. Hence, owner prioritization factors are to be updated frequently.

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APPENDIX A: DATA COLLECTION LETTER

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

Ministry of Higher Education
King Fahd University of Petroleum & Minerals
COLLEGE OF ENVIRONMENTAL DESIGN
Dept. of Construction Engineering & Management



وزارة التعليم العالي
جامعة الملك فهد للبترول والمعادن
كلية تصميم البيئة
قسم هندسة وإدارة التشييد

23 February 2020

To whom it may concern

We would like to inform that Mr. Amin Salam Abu Saa (Academic number: G201703810) is a student in the program of Master of Science in Construction Engineering and Management at King Fahd University of Petroleum and Minerals, Dharan, Saudi Arabia. He works now in a research related to allocating a constrained budget to maintain a set of bridges owned by Municipality of Eastern Province in Dammam Area. Therefore, he needs to gather as well as obtain various type of data and information (such as current practices of bridge management system in Municipality of Eastern Province, factors of prioritizing bridges for maintenance in Dammam Area, importance and priority of structural elements of bridges for maintenance, condition assessment reports of a set of bridges in Dammam Area as well as estimated costs of maintenance for these bridges) for bridge management system. In this regard, kindly we wish from you to support Mr. Amin with the information needed to accomplish his study.

Best Regards

Dr. Khalaf Al-Ofi
Chairman of Construction Engineering and Management Department
Fahd University of Petroleum and Minerals
Dharan, Saudi Arabia

إلى من يهمه الأمر

نود إفادتكم بأن السيد أمين سلام أبو صاع ورقمه الأكاديمي (201703810) طالب ببرنامج الماجستير في علوم هندسة وإدارة التشييد بجامعة الملك فهد للبترول والمعادن بالظهران بالمملكة العربية السعودية، حيث يعمل حالياً بدراسة تتعلق بتخصيص ميزانية محدودة لصيانة مجموعة من الجسور التابعة لأمانة المنطقة الشرقية في منطقة الدمام، لذلك فإنه بحاجة لجمع والحصول على البيانات والمعلومات المختلفة مثل نظام إدارة الجسور المتبع في أمانة المنطقة الشرقية، العوامل التي تؤثر على أولوية الجسور للصيانة في منطقة الدمام، أهمية وألوية العناصر الإنشائية للجسور، تقارير الحالة الإنشائية لمجموعة من الجسور بمنطقة الدمام وكذلك التكلفة التقديرية لصيانة تلك الجسور، ومن هذا المنطلق نأمل من سعادتك دعم السيد أمين بالمعلومات الكافية كي يتمكن من إتمام دراسته.

وتقبلوا خالص التحية والتقدير ،،،

د/ خلف العوفي
رئيس قسم هندسة وإدارة التشييد
جامعة الملك فهد للبترول والمعادن
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Figure 41 Data Collection Letter

APPENDIX B: User Instruction Manual

The following guidelines are to be followed when using the model in order to come up with a proper maintenance plan:

1. Conduct inventory for all bridges in the concerned area. The inventory must figure out the following:
 - 1.1. Bridge overall condition state, in scale of 7 condition state as per MOMRA manual, and the individual condition state of each component, deck slab, bearing pad, expansion joint, piers, abutment and foundations.
 - 1.2. Bridge age in years since it was handed over to the municipality after the warranty period.
 - 1.3. Bridge location, in terms of residential, commercial, industrial and political/military.
 - 1.4. Time since last maintenance activity in years.
 - 1.5. Time till next scheduled maintenance activity in years.
 - 1.6. Average daily traffic in number of vehicles.
 - 1.7. Maintenance cost based on the inventory for each component of each bridge in SAR.
2. Using the inventory data listed above (prioritization factors) and the established utility curves in this study for these factors (section 4.2.3), determine the utility value for each factor in each bridge.
3. Calculate the overall score of each bridge by summing the products of multiplying the utility value by the weight of each factor. The weights are also determined in this study (section 4.2.2).

4. Using the resulted bridge scores in the previous step 3, the weights of the structural components (section 4.2.4) and the utility value corresponds to the condition state of each component determine the component priority by multiplying the previous values together.
5. The user must set his preference for the weights of the maintenance strategies/action according to Table 27.
6. Using the condition state for the component determines the maintenance strategy selected for that component and its weight.
7. Using the priority for the component calculated in step 4 and the weight of selected maintenance strategy determine the overall priority for that component.
8. List out the components of all bridges in the concerned area and list the corresponding overall priority calculated in step 7 and maintenance cost found in step 1.7 for each component.
9. User is now in front of two options as below:
 - 9.1. Either to go with a deterministic solution, in this case sort out the list in step 8 based on the overall priority in descending order along with the component name and its maintenance cost. Starting from top of the list, select the components that sum maintenance cost less than or equal to the budgeted cost.
 - 9.2. Or, use the same list in step 8 as an input to Monte Carlo simulation software like Oracle Crystal Ball and follow the same procedure described in section 4.4.1.2 – 4.4.1.4 to find the most attractive solution.
10. The user is supposed to conduct If-Then analysis on the generated maintenance plans and test the risk inherent in each plan and determine the most plan which suits his confidence level of the input data.

APPENDIX C: PRIORITIZATION FACTORS AHP

RESPONSES

Table 34 R1 Responses for AHP of Factors

R1	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	5.00	2.00	4.00	3.00	1.00
Age Factor	0.20	1.00	0.50	0.50	0.33	0.25
Location Factor	0.50	2.00	1.00	2.00	2.00	1.00
History of Maintenance	0.25	2.00	0.50	1.00	0.33	0.25
Scheduled Maintenance	0.33	3.00	0.50	3.00	1.00	0.50
Traffic Factor	1.00	4.00	1.00	4.00	2.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.204664	0.040933	1.24	0.03301	Yes	

Table 35 R2 Responses for AHP of Factors

R2	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	3.00	0.50	1.00	1.00	0.50
Age Factor	0.33	1.00	0.50	0.50	0.50	0.50
Location Factor	2.00	2.00	1.00	2.00	2.00	2.00
History of Maintenance	1.00	2.00	0.50	1.00	0.50	0.50
Scheduled Maintenance	1.00	2.00	0.50	2.00	1.00	2.00
Traffic Factor	2.00	2.00	0.50	2.00	0.50	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.296394	0.059279	1.24	0.047805	Yes	

Table 36 R3 Responses for AHP of Factors

R3	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	2.00	0.50	3.00	2.00	0.50
Age Factor	0.50	1.00	0.33	0.50	0.33	0.33
Location Factor	2.00	3.00	1.00	2.00	2.00	0.33
History of Maintenance	0.33	2.00	0.50	1.00	0.50	0.50
Scheduled Maintenance	0.50	3.00	0.50	2.00	1.00	0.50
Traffic Factor	2.00	3.00	3.00	2.00	2.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.37116	0.074232	1.24	0.059865	Yes	

Table 37 R4 Responses for AHP of Factors

R4	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	2.00	1.00	2.00	3.00	2.00
Age Factor	0.50	1.00	0.50	3.00	2.00	2.00
Location Factor	1.00	2.00	1.00	3.00	2.00	1.00
History of Maintenance	0.50	0.33	0.33	1.00	0.50	0.33
Scheduled Maintenance	0.33	0.50	0.50	2.00	1.00	0.33
Traffic Factor	0.50	0.50	1.00	3.00	3.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.31008	0.062016	1.24	0.050013	Yes	

Table 38 R5 Responses for AHP of Factors

R5	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	2.00	0.67	0.50	3.00	1.00
Age Factor	0.50	1.00	0.50	0.50	1.50	0.67
Location Factor	1.50	2.00	1.00	2.00	2.00	2.00
History of Maintenance	2.00	2.00	0.50	1.00	3.00	0.67
Scheduled Maintenance	0.33	0.67	0.50	0.33	1.00	0.50
Traffic Factor	1.00	1.50	0.50	1.50	2.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.23043	0.046086	1.24	0.037166	Yes	

Table 39 R6 Responses for AHP of Factors

R6	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	2.00	2.00	2.00	2.00	1.00
Age Factor	0.50	1.00	2.00	0.50	1.50	2.00
Location Factor	0.50	0.50	1.00	0.50	0.33	0.50
History of Maintenance	0.50	2.00	2.00	1.00	2.00	0.33
Scheduled Maintenance	0.50	0.67	3.00	0.50	1.00	1.00
Traffic Factor	1.00	0.50	2.00	3.00	1.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.582556	0.116511	1.24	0.093961	Yes	

Table 40 R7 Responses for AHP of Factors

R7	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	3.00	3.00	3.00	2.00	1.00
Age Factor	0.33	1.00	0.50	1.00	2.00	0.33
Location Factor	0.33	2.00	1.00	2.00	2.00	0.50
History of Maintenance	0.33	1.00	0.50	1.00	0.50	0.33
Scheduled Maintenance	0.50	0.50	0.50	2.00	1.00	0.25
Traffic Factor	1.00	3.00	2.00	3.00	4.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.23921	0.047842	1.24	0.038582	Yes	

Table 41 R8 Responses for AHP of Factors

R8	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	3.00	5.00	3.00	2.00	4.00
Age Factor	0.33	1.00	2.00	3.00	3.00	3.00
Location Factor	0.20	0.50	1.00	0.50	0.50	0.33
History of Maintenance	0.33	0.33	2.00	1.00	3.00	0.50
Scheduled Maintenance	0.50	0.33	2.00	0.33	1.00	0.50
Traffic Factor	0.25	0.33	3.00	2.00	2.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.573627	0.114725	1.24	0.09252	Yes	

Table 42 R9 Responses for AHP of Factors

R9	Condition Factor	Age Factor	Location Factor	History of Maintenance	Scheduled Maintenance	Traffic Factor
Condition Factor	1.00	4.00	3.00	4.00	3.00	4.00
Age Factor	0.25	1.00	3.00	3.00	1.00	0.50
Location Factor	0.33	0.33	1.00	2.00	1.00	0.33
History of Maintenance	0.25	0.33	0.50	1.00	1.00	0.33
Scheduled Maintenance	0.33	1.00	1.00	1.00	1.00	0.33
Traffic Factor	0.25	2.00	3.00	3.00	3.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.401352	0.08027	1.24	0.064734	Yes	

APPENDIX D: BRIDGE COMPONENTS AHP

RESPONSES

Table 43 R1 Responses for AHP of Components

R1	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	2.00	3.00	2.00	2.00	2.00
Bearing Pads	0.50	1.00	3.00	1.00	1.00	2.00
Expansion Joint	0.33	0.33	1.00	0.50	0.50	0.50
Abutment Walls	0.50	1.00	2.00	1.00	1.00	2.00
Pier Columns	0.50	1.00	2.00	1.00	1.00	2.00
Foundations	0.50	0.50	2.00	0.50	0.50	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.099603	0.019921	1.24	0.016065	Yes	

Table 44 R2 Responses for AHP of Components

R2	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	3.00	1.00	2.00	2.00	3.00
Bearing Pads	0.33	1.00	0.33	1.00	1.00	1.00
Expansion Joint	1.00	3.00	1.00	3.00	3.00	3.00
Abutment Walls	0.50	1.00	0.33	1.00	1.00	1.00
Pier Columns	0.50	1.00	0.33	1.00	1.00	1.00
Foundations	0.33	1.00	0.33	1.00	1.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.027501	0.0055	1.24	0.004436	Yes	

Table 45 R3 Responses for AHP of Components

R3	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	2.00	0.50	2.00	3.00	2.00
Bearing Pads	0.50	1.00	0.50	0.50	1.00	0.50
Expansion Joint	2.00	2.00	1.00	2.00	3.00	3.00
Abutment Walls	0.50	2.00	0.50	1.00	2.00	0.50
Pier Columns	0.33	1.00	0.33	0.50	1.00	0.50
Foundations	0.50	2.00	0.33	2.00	2.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.223741	0.044748	1.24	0.036087	Yes	

Table 46 R4 Responses for AHP of Components

R4	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	0.33	0.50	0.50	0.33	0.50
Bearing Pads	3.00	1.00	3.00	2.00	1.00	2.00
Expansion Joint	2.00	0.33	1.00	0.50	0.33	1.00
Abutment Walls	2.00	0.50	2.00	1.00	0.50	2.00
Pier Columns	3.00	1.00	3.00	2.00	1.00	3.00
Foundations	2.00	0.50	1.00	0.50	0.33	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.104225	0.020845	1.24	0.016811	Yes	

Table 47 R5 Responses for AHP of Components

R5	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	0.50	2.00	2.00	0.67	0.50
Bearing Pads	2.00	1.00	2.00	2.00	2.00	2.00
Expansion Joint	0.50	0.50	1.00	0.50	0.33	0.25
Abutment Walls	0.50	0.50	2.00	1.00	0.67	0.50
Pier Columns	1.50	0.50	3.00	1.50	1.00	0.67
Foundations	2.00	0.50	4.00	2.00	1.50	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.214569	0.042914	1.24	0.034608	Yes	

Table 48 R6 Responses for AHP of Components

R6	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	0.25	0.25	1.00	0.50	2.00
Bearing Pads	4.00	1.00	3.00	2.00	2.00	2.00
Expansion Joint	4.00	0.33	1.00	3.00	2.00	2.00
Abutment Walls	1.00	0.50	0.33	1.00	0.50	0.50
Pier Columns	2.00	0.50	0.50	2.00	1.00	0.50
Foundations	0.50	0.50	0.50	2.00	2.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.570013	0.114003	1.24	0.091938	Yes	

Table 49 R7 Responses for AHP of Components

R7	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	0.25	0.25	1.00	0.50	2.00
Bearing Pads	4.00	1.00	1.00	3.00	3.00	3.00
Expansion Joint	4.00	1.00	1.00	3.00	2.00	3.00
Abutment Walls	1.00	0.33	0.33	1.00	0.50	0.50
Pier Columns	2.00	0.33	0.50	2.00	1.00	0.50
Foundations	0.50	0.33	0.33	2.00	2.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.371266	0.074253	1.24	0.059882	Yes	

Table 50 R8 Responses for AHP of Components

R8	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	0.25	5.00	0.33	0.33	0.33
Bearing Pads	4.00	1.00	4.00	1.00	1.00	1.00
Expansion Joint	0.20	0.25	1.00	0.33	0.33	0.33
Abutment Walls	3.00	1.00	3.00	1.00	1.00	1.00
Pier Columns	3.00	1.00	3.00	1.00	1.00	1.00
Foundations	3.00	1.00	3.00	1.00	1.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.347011	0.069402	1.24	0.05597	Yes	

Table 51 R9 Responses for AHP of Components

R9	Bridge Deck and Parapet	Bearing Pads	Expansion Joint	Abutment Walls	Pier Columns	Foundations
Bridge Deck and Parapet	1.00	2.00	1.00	2.00	2.00	2.00
Bearing Pads	0.50	1.00	2.00	0.50	0.50	0.50
Expansion Joint	1.00	0.50	1.00	0.33	0.33	0.33
Abutment Walls	0.50	2.00	3.00	1.00	0.50	1.00
Pier Columns	0.50	2.00	3.00	2.00	1.00	1.00
Foundations	0.50	2.00	3.00	1.00	1.00	1.00
# of Comparisons	Average Consistency	CI	RI	Consistency	Consistent? Less than 0.1	
6	6.46634	0.093268	1.24	0.075216	Yes	

APPENDIX E: MAUT UTILITY VALUE

Table 52 Utility Values for Condition Factors

Item	Condition Factor				
	0.00	0.25	0.50	0.75	1.00
Respond 1	9	6.75	4.5	2.25	0
Respond 2	9	6.375	4	1.875	0
Respond 3	1	1.5	2	3	4
Respond 4	2	2.5	3	4	5
Respond 5	9	7.125	5	2.625	0
Respond 6	1	2	2.333333333	2.666666667	3
Respond 7	1	1.25	2	3.25	5
Respond 8	9	6.75	4.5	2.25	0
Respond 9	1	1.5	2.25	3	4

Table 53 Utility Values for Age Factor

Item	Age Factor				
	0.00	0.25	0.50	0.75	1.00
Respond 1	0	10	20	30	40
Respond 2	0	10	20	25	30
Respond 3	0	10	20	25	30
Respond 4	10	20	30	40	50
Respond 5	10	15	21.66666666	30	40
Respond 6	0	8.75	17.5	26.25	35
Respond 7	0	5	10	16	33
Respond 8	0	5	10	15	20
Respond 9	0	15	26.66666667	35	40
	2.5	10.97222222	19.53703704	25.90625	34.75

Table 54 Utility Values for Location Factor

Item	Location Factor				
	0.00	0.25	0.50	0.75	1.00
Respond 1		Residential	Commercial	Industrial	Military/Political
Respond 2		Residential	Commercial	Industrial	Military/Political
Respond 3		Residential	Commercial	Industrial	Military/Political
Respond 4		Residential	Commercial	Industrial	Military/Political
Respond 5		Residential	Commercial	Industrial	Military/Political
Respond 6		Residential	Commercial	Industrial	Military/Political
Respond 7		Residential	Commercial	Industrial	Military/Political
Respond 8		Residential	Commercial	Industrial	Military/Political
Respond 9		Residential	Commercial	Industrial	Military/Political

Table 55 Utility Values for Previous Maintenance

Item	Previous Maintenance				
	0.00	0.25	0.50	0.75	1.00
Respond 1	0	10	20	30	40
Respond 2	0	10	15	20	25
Respond 3	5	10	15	20	25
Respond 4	5	15	25	30	40
Respond 5	5	15	25	30	40
Respond 6	5	10	15	20	30
Respond 7	0	8.25	16	23.25	30
Respond 8	0	5	10	15	20
Respond 9	5	15.625	25	33.125	40
	2.777777778	10.98611111	18.44444444	24.59722222	32.22222222

Table 56 Utility Values for Scheduled Maintenance

Item	Scheduled Maintenance				
	0.00	0.25	0.50	0.75	1.00
Respond 1	25	20	15	10	5
Respond 2	25	20	15	10	5
Respond 3	25	20	15	10	5
Respond 4	20	20	15	10	5
Respond 5	25	20	15	10	5
Respond 6	30	20	15	10	5
Respond 7	30	22.5	15	7.5	0
Respond 8	20	15	10	5	0
Respond 9	0	5	10	15	20
	22.22222222	18.05555556	13.88888889	9.72222222	5.55555556

Table 57 Utility Values for Traffic Factor

Item	Traffic Factor				
	0.00	0.25	0.50	0.75	1.00
Respond 1	A	B	C	D	E
Respond 2	A	B	C	D	E
Respond 3	A	B	C	D	E
Respond 4	A	B	C	D	E
Respond 5	A	B	C	D	E
Respond 6	A	B	C	D	E
Respond 7	A	B	C	D	E
Respond 8	A	B	C	D	E
Respond 9	A	B	C	D	E

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