Decision Making Model for Bridge Maintenance Planning in Egypt

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ABSTRACT
The maintenance of bridges as a key element in transportation infrastructure has become a major concern due to increasing traffic volumes, deterioration of existing bridges and well-publicized bridge failures. Therefore, bridge maintenance planning should accommodate multiple performance goals that need to be quantified by various performance indicators. The main goal of this research is to develop a decision support model for maintenance of bridges in Egypt within acceptable limits of safety, serviceability and sustainability. The General Authority for Roads, Bridges, and Land Transport (GARBLT) was chosen for the study of the current research as it represents the biggest governmental organization responsible for planning, operating and maintaining of bridges in Egypt. To achieve the research objective, structured interviews were conducted with bridge engineers/ inspectors and top managers of GARBLT using a pre-designed questionnaire to explore the main factors affecting bridge performance and the major risk constraints affecting decision making. In this research, an application of Multi-Attribute Utility Theory (MAUT) for bridge maintenance planning is illustrated with two case studies of bridges in Egypt. Bridge prioritization on the network and maintenance strategy decision for each bridge are the major outcomes of this study. This study provides a systematic approach to enhance the decision making of maintenance planning by making use of available data, accommodating multiple performance goals, their uncertainty, preferences and risk attitude of infrastructure managers.
Keywords: Bridge maintenance strategy, bridge prioritization, condition assessment,, decision making, Multi-Attribute Utility Theory (MAUT).

1. Introduction

Infrastructure projects are crucial to the economy of any country, especially developing ones such as Egypt and most African countries. There are many aspects to consider when dealing with infrastructure projects such as unique characteristics, complexity, risk, public safety, financial difficulty etc. [1].

Traditional management systems in developing countries are inefficient, costly, and a hindrance in their nations' attempt for development. In such a situation, the key element of enhancing management systems is maximizing the efficiency of the existing infrastructure, and exploring the opportunities for cutting down the unnecessary costs in infrastructure asset management. [2]

Egypt has currently a road network of more than 64,000 km across the country, on which more than 3,000 bridges are in service. Statistics shows that 98 % of its domestic cargo depends on this road network so that no doubt the road network plays a significant role to the national economy and people's daily activities. [3].

The importance of bridge maintenance is highlighted when discussing infrastructure, because of the loss of life and property, and the social and economic effects caused by the damage or collapse of bridges.

Decision Making

Decision-making in infrastructure asset management field is more complicated than it was in the past due to two governing reasons. Firstly, expanding technology and communication systems have spawned a greater number of feasible solution alternatives from which a decision-maker must choose. Secondly, the increased level of structural complexity and design competition typical of today's problems can result in a chain reaction magnification of costs if an error should occur. Deficiencies related to aging bridges have become a major concern for asset managers and society globally.[4]

Bridge Maintenance Planning

Bridge maintenance planning is a process of deciding the scope, timing, costs and benefits of future maintenance activities on a specific bridge while taking into account the relative importance of the bridge with respect to the overall road network. Multiple bridge performance aspects widen the scope of maintenance planning where a number of related performance goals other than minimizing owner cost must be considered. The example of such performance aspects are structural performance of the bridge, safety and security of users and workers, environmental impact, economic impact on the users, and impact on agency's and officials' reputation(political aspect). Considering the large number of bridges on the network, it is intractable for an infrastructure manager to quantify the performance goals for each bridge and systematically perform the trade-offs among them in order to select those bridges that optimize the various performance goals. Moreover, at times, an infrastructure manager is uncertain of his preferences due to incomplete or unavailable data and due to lack of experience. So, the need to optimize multiple and/or conflicting performance goals based on the preference uncertainty marks maintenance planning a complex decision-making problem. [5].

According to [6], the main ranking procedures currently used by transportation agencies and proposes an alternative innovative ranking method for bridge networks, based on the Multi-Attribute Utility Theory (MAUT) is presented. The theory enables the decision makers to include multiple and conflicting criteria and to incorporate qualitative and quantitative measurements in the ranking process. In addition, the theory provides flexibility for the decision makers in expressing their degree of satisfaction with each bridge attribute and captures the decision makers' attitude toward risk. The framework includes the development of a hierarchy structure, defining the objectives and the decision criteria, and presenting an innovative technique to develop the necessary utility functions.

The development of a knowledge-based decision support model for bridge remediation in Australia is presented by [4]. The working model includes a procedure for condition assessment in order to priorities bridges in a network for maintenance fund allocation. The next step is classifying all the viable courses of action, and finally finding the best remediation strategy using Multi Attribute Utility Theory (MAUT).The working framework for bridge remediation comprises the process which provides the system inputs(Condition Index, maintenance alternatives and decision constraints), the inference engine (Decision Analysis Tool) and the system output (Remediation Plan).

An application of Multi-Attribute Utility Theory (MAUT) for bridge maintenance planning with a case study of bridges from the Netherlands road network is developed by [5]. MAUT seeks to optimize multiple objectives by suggesting a trade-off among them and finally assigns a ranking to the considered bridges. Moreover, utility functions of MAUT appropriately account for the involved uncertainty and risk attitude of infrastructure managers.

Related work in Egypt was initiated by [7] that developed a framework that includes 3 modules; database, structural analysis, and rating model. The framework considered steel bridges only. Then [8] introduced an approach to estimate the structural condition for the bridge flexural elements by calculating reliability index for shear and flexure failure modes. Then [9] introduced EBRMS based on the outcome of BRIME project in Europe, the framework prioritizes concrete bridges for maintenance and provides one-year plan

A practical framework to manage the maintenance and repair activities of Bridges network in Egypt considering performance and budget limits is developed by [10]. This research introduces a bridge management tool called *E-BMS* to best allocate the limited maintenance fund on bridges in transportation network to keep all bridges in the target level of performance within the available budget.

All previous researches in Egypt doesn't focus on risk constrains. This research takes risk attitude and preference of infrastructure managers into account in the development of decision support model for bridge maintenance . In Egypt the major risk factors in infrastructure arise from owner side as the owner in the majority of construction project in Egypt is the governmental sector. Government focus on economic development through raising efficiency of roads network but with limited resources so the need to use a model taking risk into consideration was essential to minimize the burden on government.

2. Methodology

The main goal of this research is the development of decision support model for bridge maintenance in Egypt. To achieve the research objective, structured interviews were conducted with bridge engineers/ inspectors and top managers of GARBLT using a pre designed questionnaire. The first step is to prioritize bridges in a network for maintenance and this includes condition assessment of bridges taking into account six major factors chosen from literature review and from experts interviews. The next step is classifying all the viable courses of action considering risk assessment, and finally finding the best maintenance strategy using Multi Attribute Utility Theory (MAUT). The outcome will provide the decision of maintenance strategies for bridges based on the trade-offs of multiple performance goals. The last step is the model validation using two case studies. The research methodology is shown in fig. 1.

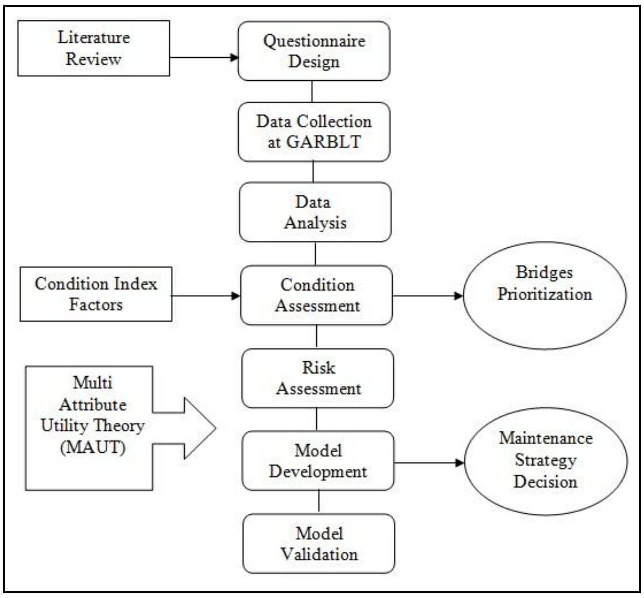

Figure 1: Research Methodology

3. Data Analysis

3.1 Data Collection

In order to explore the main factors affecting bridge performance and the major risk constraints affecting decision making at GARBLT, a questionnaire has been developed as the basis for data collection. It was applied through personal interviews with bridge engineers/ inspectors and top managers to maximize quality and credibility of the questionnaires' results. The questionnaire is divided into two parts: 1. Condition Index Factors. 2. Risk Constraints affecting decision-making.

3.2 Data Results

a- Bridge condition assessment based on field inspection is a fundamental step for providing the appropriate inputs for any condition rating system. The condition index factors addressed based on the interviews with GARBLT experts are structural deficiency (S.D.F.), serviceability potential (S.P.F.), bridge age (A.F.), bridge type (T.F.), client impact (C.I.F.) and historical value (H.F.)**.** The weight of different factors affecting condition index are as shown in Table 1 depending on the expert judgment. The calculation of each of these factors were also addressed in the questionnaire and are described in the following sections. A weighting of zero means that a specific condition factor is judged to have no effect on the decision making, whilst a rating of 4 means that the factor is extremely important.

Table 1: Weight of Condition Index Factors

	S.D.F.	S.P. F.	A.F.	T.F.	C.I.F	H.F.
w_i	4	3	2	2	3	0

b- Bridge risk evaluation serves as the basis for bridge priority ranking for maintenance. It is conducted for the purpose of functionality, sustainability, safety and political. For each purpose, risk constraints are identified and a weighting for each risk constraint and purpose is determined through the interviews with top managers at GARBLT. The weighting is shown in Table 2.

Table 2: Purpose and Risk Constraints Weights

Purpose (w_k)	Risk Constraints	Weight (w_{ki})
Functionality (w= 0.4)	Low level of service	0.6
	Closure of a major route	0.4
Sustainability (w=0.25)	Excessive cost	0.6
	Delay	0.25
	Environmental damage	0.15
Safety and Political (w=0.35)	Damage to property	0.65
	Change in standards or political strategies	0.35

4. Bridges Prioritization

Bridge prioritization depend on the condition assessment of bridges. Bridges having higher condition index (CI) are considered to take priority of actions in the network. For calculating condition Index, we must calculate the six factors affecting it as mentioned before. Numbers from 1 to 4 have been included which demonstrate the potential level of severity.

1-Structural Deficiency Factor (S.D.F): This refers to the rate of deterioration of constituent bridge material (e.g. cracking, corrosion, etc…). According to [11], each element has four condition states listed in Table 3.

Table 3: Description of Condition Rating

Description of Defects	Condition Rate (Ci)
No / minor Defects	1
Minor Cracks	2
Corrosion, Spalls	3
Spalls and Corrosion , deterioration may affect serviceability	4

To describe the overall condition status of structural elements, the Element Structural Condition Index (ESCI) is introduced as in (1):

$$ESCI = \Sigma(q_i * C_i) / \Sigma q_i \qquad \text{(Equation 1)[4]}$$

Where: q_i: : quantity of elements reported in condition index C_i

C_i: condition of sub-element c_i €(1,2,3,4)

It should be clearly understood that some elements require more attention than the others in terms of material vulnerability and/or structural significance. In this research, the element structural significance (Si) and the material vulnerability factor (Mi) have been investigated through the interviews and from literature review. The outcome of the processed expert judgments is summarized in Table 4 and Table 5 respectively. The higher Si represents the superior structural importance and the greater Mi reflects the higher material vulnerability.

Table 4: Element Structural Significant Factor

Element	Structural Significant Factor (S_i)
Columns, abutments, Piles, pile caps, foundation, columns caps, main girders	4
Transversal girders, Floor beams, Slabs, Retaining walls, wing walls, Joints	3
Bearings, surface finish, asphalt, Lighting columns	2
Drainage system, Parapets, Handrail, Sidewalks, safety barriers, others	1

Table 5: Material Vulnerability Factor

Material	Material Vulnerability Factor (M_i)
Steel	1
Reinforced Concrete	2
Precast Concrete	3
Pre stressed Concrete	4
Other Material	3

The overall structural importance of concrete bridges can be estimated through (2) as follows:

$$S.D.F. = \sum_{i=1}^{n} \lfloor (S_i * M_i * ESCI_i) / 16n \rfloor \quad (Eq.\ 2)[4]$$

Where S_i: element structural significance factor
-M_i: material vulnerability factor
-$ESCI_i$: element structural condition index
-n: number of elements

2- Serviceability Potential Factor (S.P.F.)
This parameter indicates the potential level of service and operation efficiency of a bridge. Five main deficiencies that can seriously affect bridge safety and serviceability are: load bearing capacity, vertical clearance, width, barriers and the drainage system.

3-Age factor(A.F.)
Age is a useful parameter in structural condition assessment. Generally, bridges in the last quarter of their design life (typically 100 years) require more serious actions than in previous quarters.

4- Bridge Type Factor (T.F.)
This factor is based on usage and importance of bridge to network.

5- Client Impact Factor (C.I.F.)
The nature of a bridge site and the extent of the bridge treatment may cause decision makers to close bridge lanes or create alternative routes or bypasses to control the traffic flow. This represent the social implications of treatment in the risk assessment process.

6- Historical Factor (H.F)
Some bridges have historical value but some bridges with noted historical significance may need to remain in service.

The rating of these factors is summarized in Table 6.

Table 6: Rating of the Condition Index Factors (F_i)

Factor	Rating			
	1	2	3	4
S.D.F.	0< S.I≤ 1	1< S.I≤ 2	2< S.I≤ 3	3< S.I≤ 4
S.P.F.	Excellent	Good	Fair	Poor
A.F.	Recently build	New	Old	V. Old
T.F.	Minor	Local	Collectors	Arterials
C.I.F.	Low	Medium	High	V. High
H.F.	Low	Medium	High	V. High

Calculating the Condition Index (CI)

The relevant weighted condition index is calculated in (3) as follows:

$$CI = \sum_i (w_i * F_i) / 24 \quad (Equation\ 3)[4]$$

Where: w_i is the weight of the i th factor
F_i is the assigned value of the condition index factor

5. Decision Making Model For Bridge Maintenance Strategy

5.1 Risk Assessment

In Egypt, government focus on raising efficiency of roads network but with limited resources, so the need to use a model taking risk into consideration was essential to minimize the burden on government. As mentioned in Table 2 risk constraints are identified and a weighting for each risk constraint is determined through the interviews with top managers at GARBLT. Each risk constrain for bridge maintenance are described as client constrain. Table7 illustrates the different cases.

Table 7: Risk and Client Constraints

Purpose (Criteria)	Risk Constraints	Client Constraints (Sub Criteria)
Functionality	Low level of service	Maximize Service Level
	Closure of a major route	Minimize Traffic Disruption
Sustainability	Excessive cost	Minimize cost
	Delay	Minimize time
	Environmental damage	Minimize Environmental Impact
Safety and Political	Damage to property	Minimize Damage
	Change in standards or strategies	Minimize Political Pressure

5.2 Decision Analysis Tool

The ranking method in this research is based on Multi Attribute Utility Theory (MAUT). The advantages of the MAUT approach are that the implicated judgments are made explicitly and the value information can be used in many ways to help simplify a decision process. Through the MAUT process, the problem is broken down into a hierarchy as shown in fig. 2. A four level hierarchy structure which consider all the main aspects of the problem is introduced. The first level of the structure is the overall goal of the ranking (Bridge Maintenance Plan). The second level contains the purposes (criteria) defined to achieve the main goal. The third level holds the constraints (sub criteria) for assessing the objectives. The last level is for the maintenance strategies alternatives. Weights of the criteria and sub criteria are previously defined based on the expert's judgments and shown in table 2.

In order to choose which alternative is more suitable for bridge circumstances, risk avoided and goals achieved by this alternative is determined by using scores that take into consideration weight of achieved criteria and sub criteria for this alternative and the relative importance of it.

The overall ranking value of each alternative X_j is expressed in (4) as follows:

$$X_j = \sum_{i=1}^{m} W_k W_{ki}\, a_{ij} \qquad j= 1, \ldots,m \qquad \text{(Eq. 4) [4]}$$

Where W_k and W_{ki} are the weights of criteria and sub criteria as shown in Table 2,

a_{ij} is the importance level of j^{th} alternative in respect to the i^{th} sub criterion and k^{th} criterion.

The chosen alternative is normally the option with the highest overall score.

Maintenance Strategy Decision

Strategies for bridge maintenance are defined as follows: Preventive maintenance, Repair and Replacement. However, in Egypt Preventive and routine maintenance action is very rare due to budget constraints.

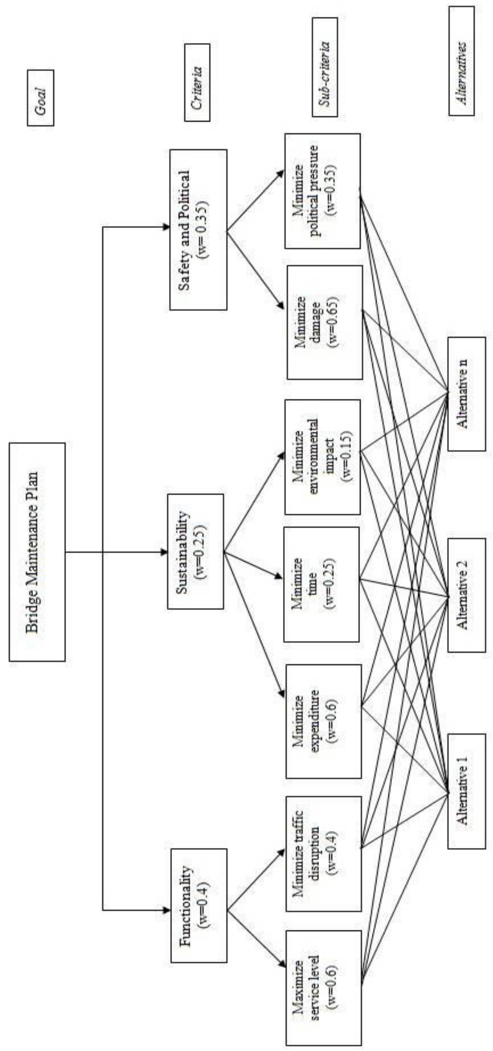

Figure 2: Hierarchy of Bridge Maintenance Plan

6. Model Implementation

The developed decision support model provides a systematic approach to improve the decision making of maintenance planning for bridges in Egypt by making use of available data, accommodating multiple performance goals, their uncertainty, preferences and risk attitude of infrastructure managers.

The study outcomes are

- First bridge prioritization for maintenance in the whole network and this is done through condition assessment calculation (equation 3). The bridge having the higher the Condition Index (CI), will take the priority of actions in the network.
- Second is choosing the maintenance strategy for bridge taking risk assessment into consideration using MAUT as decision analysis tool. The chosen alternative is normally the option with the highest overall score

7. Model Validation

In order to verify the application of the proposed model, two case studies located in international coastal road have been chosen. Required data was extracted from reports provided by The General Authority for Roads, Bridges, and Land Transport (GARBLT).

Bridge (1) description:

The first bridge is Ananeia bridge located at kilo 50 Portsaid- international coastal road Port said Damietta . It is 400 m long twin bridges consisting of three sections. The middle section is a Bowstring arch steel bridge with a span of 40 m provided with inclined crossing two layers of cables. The second section is a steel bridge with a simply supported multi-girder of span 30 m identical for both of the left and right sides. The 25 cm reinforced concrete slab decking connected to steel beams by shear connectors is used to cover the floor of the two steel parts. The third section is a multi box girder concrete bridge that extends for a total length of 300 m. The occurrence of cracks and separation of the steel at the upper joints connection of the tensile members with the bottom panel of the box section in the upper arch of the bridge. They are in different areas in both directions of the bridge. This is due to occurrence of the bridge near the port of Damietta and Port Said and the passage of cargo with high loads without any control.

Bridge (2) description:

The second bridge is Bostan bridge (located at international coastal road Bostan- Damietta). It consists of box section of reinforced concrete and steel beams crossing railways and waterways. The box section consists of two separate cells for each direction, which are based on pillars, columns, piles capes, as well as earthworks at beginning and end from and to Damietta city. The condition of the bridge was as follows:

- Transverse joints between spans were damaged, no concrete cover and steel corrosion in transverse beams.

- Steel corrosion at longitudinal joints in upper slab between the two directions.
- Corrosion in diaphragms at joints, discoloration at concrete surface.
- No concrete cover in some slabs.
- Cracks in box section webs and corrosion of its steel
- No openings in lower slabs of the box section so rain water was there and so corrosion.
- Little corrosion in steel beams
- Bad condition and corrosion of some columns capes.
- Corrosion and no concrete cover at column joints
- Corrosion and cracks in pile caps

Model implementation

1- The overall condition index has been evaluated for the two bridges considering the six parameters being addressed. The assigned value (F_i) for different factors are estimated based on the bridge inspection reports and are shown in Tables 8 and 9. Then calculating CI for each bridge using equation 3.

Table 8: Condition Index For Ananeia Bridge

	S.D.F.	S.P. F.	A.F.	T.F.	C.I.F.	H.F.
F_i	2	3	1	4	3	1
w_i	4	3	2	2	3	0
w_iF_i	8	9	2	8	9	0

For Ananeia Bridge , CI = $\sum w_iF_i/24 = 1.5$

Table 9: Condition Index For Bostan Bridge

	S.D.F.	S.P.F.	A.F.	T.F.	C.I.F	H.F.
F_i	3	4	1	4	3	1
wi	4	3	2	2	3	0
wiFi	12	12	2	8	9	0

For Bostan Bridge, CI = $\sum w_iF_i/24 = 1.79$

Bostan Bridge has higher CI so it should be considered for priority of actions in the network.

2- The second step was to find the best maintenance strategy using the developed model. For each of the observed defects some treatment options are proposed.

Bridge 1

Span shortening, surface coating and recast with concrete are the alternatives taken into consideration for repairing of joints of Ananeia bridge. According to decision support model using equation 4, the results are presented in Table 10, Span shortening had the highest overall score in the proposed system , and in fact it was the decision taken for repair of the bridge which demonstrate the validity of the model.

Bridge 2

For Bostan bridge, some treatment options are proposed for each of the observed defects. Span shortening, surface coating and recast with concrete are the alternatives taken into consideration for repairing of column caps. Following same procedure, results are presented in Table 11, recast with concrete had the highest overall score. The decision taken for repair of this bridge was recast with concrete as corrosion has been removed and steel is treated with corrosion inhibitors before patching, each crack is injected with epoxy before the section is recasted with concrete. This also demonstrate the validity of the model.

Table 10: Ananeia Bridge

Criteria	w_i	Sub Criteria	w_{ij}	Span shortening a_{ij}	Span shortening x_{ij}	Surface coating a_{ij}	Surface coating x_{ij}	Recast with concrete a_{ij}	Recast with concrete x_{ij}
Functionality	0.4	Maximize Service Level	0.6	4	0.96	2	0.48	3	0.72
		Minimize Traffic Disruption	0.4	3	0.48	3	0.48	4	0.64
Sustainability	0.25	Minimize cost	0.6	3	0.45	3	0.45	2	0.3
		Minimize time	0.25	2	0.125	3	0.188	2	0.125
		Minimize Environmental Impact	0.15	2	0.075	3	0.113	2	0.075
Safety and Political	0.35	Minimize Damage	0.65	4	0.91	2	0.455	2	0.455
		Minimize Political Pressure	0.35	2	0.245	2	0.245	2	0.245
Overall score				3.25		2.41		2.56	

Table 11: Bostan Bridge

Criteria		Safety and Political		Sustainability			Functionality	
wi		0.35		0.25			0.4	
Sub Criteria		Minimize Political Pressure	Minimize Damage	Minimize Environmental Impact	Minimize time	Minimize cost	Minimize Traffic Disruption	Maximize Service Level
wij		0.35	0.65	0.15	0.25	0.6	0.4	0.6
Span shortening	aij	2	3	1	2	2	3	3
	xi	0.245	0.683	0.038	0.125	0.3	0.48	0.72
surface coating	aij	2	2	2	3	3	3	2
	xi	0.245	0.455	0.075	0.188	0.45	0.48	0.48
Recast with concrete	aij	2	3	2	3	3	4	4
	xi	0.245	0.683	0.075	0.188	0.45	0.64	0.96

Alternative	Overall score
Span shortening	**2.59**
surface coating	**2.373**
Recast with concrete	**3.24**

8. Conclusion

A Decision Support model for maintenance planning of bridges is developed. The major outcomes of this study are:

- Firstly, bridge prioritization through the Condition assessment (CI) of the bridge. The main factors addressed for calculating CI are Structural deficiency, serviceability potential, bridge age, bridge type, client impact and historical value. CI is used to rank and prioritize bridges with the highest concern.
- Secondly, maintenance strategies alternatives are ranked through Multi Attribute Utility Technique (MAUT) that the decision criteria should be drawn from risk assessment process.

In Egypt, Functionality and safety criteria have the higher effect on decision rather than the other factors; as the risk of having low level of service and damaging the property are the most important concern. In achieving sustainability, minimizing the expenditure has the highest weight and that assures the importance of the economic side on the decision and so minimizing the burden on government.

In this research, model verification is accomplished through two bridges located at the international coastal road. The analysis of the case studies reveals that the developed model is applicable and has the ability to evaluate the possible alternatives and suggests valid decisions regarding selecting an alternative for bridge improvement.

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