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Framework for Bridges Maintenance in Egypt

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ABSTRACT
The traditional approaches for bridges maintenance is proven to be inefficient as they lead to random way of spending maintenance budget and deteriorating bridge conditions. In many cases, maintenance activities are performed due to user complaints. The objective of this paper is to develop a practical and reliable framework to manage the maintenance and repair activities of Bridges network in Egypt considering performance and budget limits. The model solves an optimization problem that maximizes the average condition of the network given the limited budget using Genetic Algorithm (GA).
The main tasks of the system are bridge inventory, condition assessment, deterioration using markov model, and maintenance optimization. The developed model takes into account multiple parameters including serviceability requirements, budget allocation, element importance on structural safety and serviceability, bridge impact on network, and traffic. A questionnaire is conducted to complete the research scope. The proposed model is implemented in software, which provides a friendly user interface. The results of the framework are multi – year maintenance plan for the entire network for up to five years. A case study is presented for validating and testing the model with Data collected from "General Authority for Roads, Bridges and Land Transport" in Egypt.
***Keywords* –** Bridge Maintenance, condition assessment, deterioration, cost optimization, fund allocation.

I. Introduction

Managing bridges maintenance is vital to keep such important infrastructure in healthy condition. In Egypt, bridges suffer major deterioration. Fund scarceness, high traffic, user needs, and other constraints make it difficult to decide which bridge need immediate repair or rehabilitation. That needs effective tools. The consequences of delayed maintenance are higher user costs due to travel delays, accidents, vehicle operating costs, and even bridge failure.

Bridge Management System (BMS) is defined according to the *AASHTO* as "A system designed to optimize the use of available resources for the inspection, maintenance, rehabilitation, and replacement of bridges" [1]. The main components of a typical BMS are (a) Inspection, (b) inventory, (c) The Condition-rating (d) performance prediction, and (e) Cost optimization. [2]. Bridge inspections are conducted to determine the physical and functional condition of the bridge. Successful bridge inspection depends on proper planning, adequate tools and equipment, advanced technology for monitoring systems, and the experienced inspection team. To evaluate the condition of bridges, Performance Measures are used. Bridge inventory data and inspection reports are used to provide the necessary data. Different Performance Measures for BMS includes; Condition Ratings (CR), Condition Index (CI), Sufficiency Rating (SR), Health Index, National Bridge Inventory Rating (NBI), Vulnerability Rating (VR), and load rating [3], [4]. Deterioration prediction of bridges is required to perform Life Cycle Cost Analysis. According to [5], Approaches used in modeling bridge deterioration can be categorized as mechanical, deterministic, stochastic (Markov chain) and artificial intelligence models. Prioritization is used to rank bridges for maintenance activities. Bridges with high priority ranking indicate urgent need for repair actions. A common practice is to rank Bridges and elements in the worst condition first regardless of their effect on the network and costs [6]. Such approach is known as "worst first". However, it fails to account for the level of change in benefit for the funds expended and the network consideration. Another ranking approach is coupling a condition index and a strategic index [7].

Optimization represents the most modern and sophisticated approach for selecting the optimum maintenance schedule for bridges network. Many objectives can be considered in the problem such as minimizing maintenance cost, getting the highest return on the repair budget, and maximizing bridge condition. The constraints that could be considered includes: budget limits, governmental and political constraints, user defined constraints, and performance constraints.

Related work in Egypt was initiated by Abu – Hamd [8] how developed a framework that includes 3 modules; database, structural analysis, and rating model. The framework considered steel bridges only. El-Kafory [9] introduced an approach to estimate the structural condition for the bridge flexural elements by calculating reliability index for shear and flexure failure modes. Abbas [10] introduced EBRMS based on the outcome of BRIME project in Europe, the framework prioritizes concrete bridges for maintenance and provides one-year plan.

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.

II. Description of The Framework

The proposed framework aims to produce simple, Efficient, accurate system for managing bridges in Egypt taking into account the limited budget and target level of performance of the network. Fig. 1 shows the main structure of the proposed E-BMS. The framework contains Database, Condition evaluation, deterioration, and optimization models. The database includes the basic information and documents describing bridge configuration and network characteristics. It also contains the results of inspection reports. It is recommended to perform inspection according to AASHTO standards [3]. Detailed information about the other models are listed below.

III. Condition-Evaluation Model

Condition Evaluation aims to describe the current condition of a structure. According to *AASHTO* (2010) [11], each element has four condition states listed with qualitative descriptions and viable maintenance actions. Elements conditions and quantities are estimated during field inspection. Table I provides a definition of each condition state and feasible actions. Measuring the condition of elements and bridge are determined by calculating Health index, which is a single number ranges from 0 to 100 (0 for the worst possible health). This method is similar to that used in the *Pontis* BMS with some modification in the weighting factor to best suit local conditions and available data in Egypt. The process is accomplished in two steps; Step one calculates the **Element Health Index** (EHI). Step two computes the entire **Bridge Health Index** (BHI) based on the weighted EHI. According to [12], the health index of an individual element (EHI) is calculated according to (1) as:

$$EHI = \frac{\sum_s K_s q_s}{\sum_s q_s} \text{ x } 100\ \% \qquad (1)$$

The health index of the entire bridge (BHI) is evaluated as a weighted average of the health indexes of bridge elements based on element relative importance. It can be calculated by (2) as follows:

$$BHI = \frac{\sum_e H_e\, EIF_e}{\sum_e EIF_e}\ X\ 100\% \qquad (2)$$

Where; ***EHI*** : the health index of an individual element, ***s*** : the index of the condition state (4), q_s : the quantity of the element in the s[th] condition state, k_s : a coefficient corresponding to the s[th] condition state and reflects the level of deterioration. See Table II, ***BHI*** : the health index of the entire bridge, H_e : the health index of an individual element (*EHI*), ***e*** : the number of an element, EIF_e : *Element Importance Factor* of element *e*. It is a weighting factor representing the importance of each element to the structural safety and serviceability of the bridge. EIF_e is determined by a questionnaire where the results are shown in Table III.

TABLE I
CONDITION STATE DEFINITIONS AND FEASIBLE ACTIONS

Level	Condition state			
	1	2	3	4
	Good	Fair	Poor	severe
Condition state Descriptions	No or minor defects; those not Affecting structural safety and serviceability of bridge.	minor defects, but do not weaken structural safety and serviceability of bridges.	failures and defects that currently develop and affect structural safety and serviceability	serious failures and defects that adversely affect structural safety and serviceability
Feasible actions	Do Nothing, Protect	Do Nothing, Protect, Repair	Do Nothing, Protect, Repair, Rehabilitate	Do Nothing, Rehabilitate, Replace Immediately

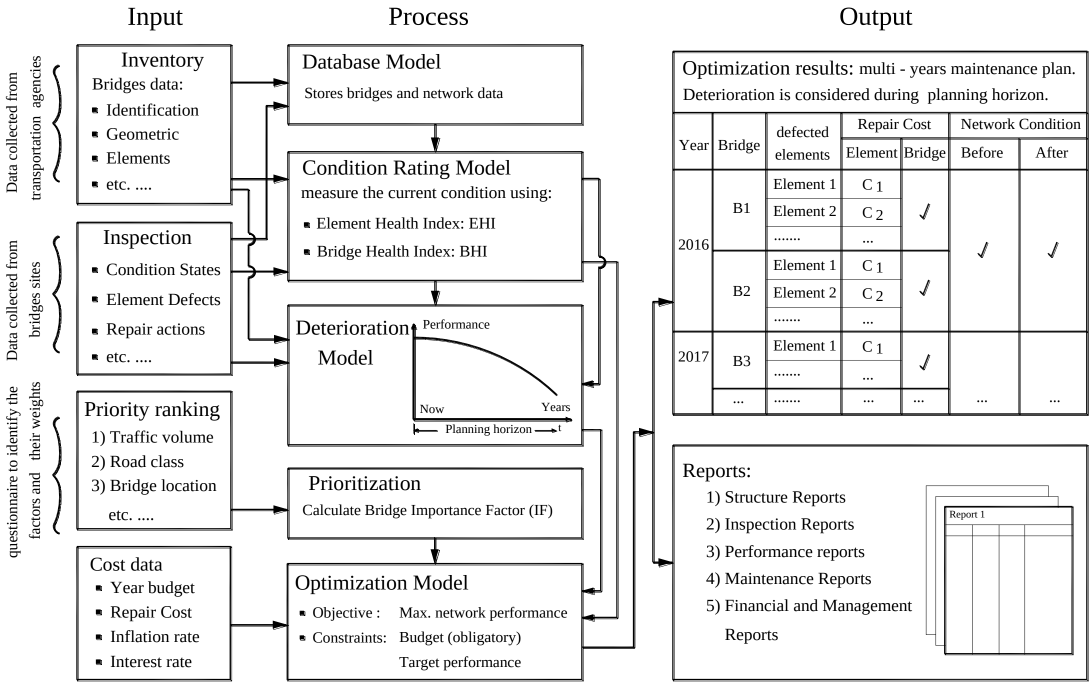

Fig. 1 Main structure of the proposed BMS

TABLE II
VALUES OF K_s COEFFICIENT

Condition State no	1	2	3	4
k_s	1.0	0.67	0.33	0

TABLE III
ELEMENT IMPORTANCE FACTOR (EIF)

Elements	EIF
Columns, abutments	1.0
Piles, pile caps, foundation, columns caps, main girders	0.90
Transversal girders, Floor beams, Slabs, Retaining walls, wing walls, Joints	0.70
Bearings, surface finish, asphalt, Lighting columns	0.60
Drainage system, Parapets, Handrail, Sidewalks, safety barriers, others	0.50

IV. Deterioration Model

This paper considers the deterioration of the bridge element to be a **Markov process**, which is extensively used to forecast the future condition of an element, based on its current condition states and transition probability matrix. Any element can exist in one of four environments **(Benign, Low, Moderate, Severe),** which describe different weather or operating conditions. [3]. Each environmental class has one transition probability matrix. Thus, four matrices have to be feed to the E-BMS for each element. These matrices are obtained from literature.

The general form of a deterioration transition probability matrix (P) is presented in Table IV [13].

TABLE IV
GENERAL FORM OF A TRANSITION PROBABILITY MATRIX

		To state 1	2	3	4
From state	1	P_{11}	P_{12}	P_{13}	P_{14}
	2	*0*	P_{22}	P_{23}	P_{24}
	3	*0*	*0*	P_{33}	P_{34}
	4	*0*	*0*	*0*	*1*

If the initial condition vector $P(0)$ that describes the present condition of a bridge element is known, then the future condition vector $P(t)$ at any year t can be obtained as follows [14]:

$$\sum_{j=1}^{n=4} p_{ij} = 1 \tag{3}$$

$$P\,(t) = p\,(0) \times p^{t} \tag{4}$$

$$P\,(0) = [q_1 \quad q_2 \quad q_3 \quad q_4] \tag{5}$$

Where; $\boldsymbol{q_i}$: the quantity of an element in condition state i, i=1, 2, 3, 4

V. Optimization Model

This section represents the decision – making tool of the proposed that searches for the best solution of maintenance fund allocation.

A. Bridge Importance Factor (IF)

The impact of the loss of bridge service to traffic, are other factors should be considered in deciding which bridges to be repaired. The ***importance factor*** (IF) is developed for this purpose. *IF* is a single indicator ranges from zero for less importance to 100 for the most important bridges. Many parameters are taken into account to determine the bridge importance factor (IF). These factors are collected from literature. Besides, a confirmation is conducted using a questionnaire to determine the factors affecting the importance factor (IF) and their weights in the calculation formula. Table V illustrates these factors.

TABLE V
IMPORTANCE FACTOR MEASUREMENT SUMMARY

Factor	Weight (w_i)	Reference
1) Traffic volume	0.155	[6], [10], [15]
2) Rood class	0.135	[6], [8], [10], [15]
3) Bridge location class	0.127	[10]
4) Possible detours	0.113	[16]
5) Historical importance	0.092	[10], [15]
6) Defense Considerations	0.106	[10], [15]
7) Width condition	0.088	[10], [15]
8) Vertical clearance	0.096	[10], [15]
9) % trucks	0.088	*This study*

$$IF = \sum_{i=1}^{9} w_i * f_i \qquad (6)$$

Where;

$\boldsymbol{w_i}$: weight of factor *i* $\quad \sum_{i=1}^{9} w_i = 1$

$\boldsymbol{f_i}$: Factor Measurement $\quad fi = \{0.25 \text{ to } 1.0\}$

B. Improvement after repair

The conditions of elements after performing specific type of repair improve to certain level. In the real world, some repair actions do not necessarily make the element condition as good as new. The technique used in this study is similar to that used in [17] and. [18]. It is assumed that when doing nothing to a bridge element, no improvement will happen in its condition. Protection or Minor maintenances will enhance the condition to 78% of the initial new condition. Major repairs will raise the element condition to 89% of the initial new condition. Finally, replacement or reconstruction will reset the element to the initial new state (100%). These values of improvement are confirmed by questionnaire. The *Element Health Index* after performing the repair activities (EHI_{After}) is calculated as:

$$EHI_{After} = \frac{100q_1 + 78q_2 + 89q_3 + 100q_4}{q_1 + q_2 + q_3 + q_4} \% \qquad (7)$$

C. Optimization process

The selection of proper maintenance activities for bridges network is modelled as quality maximization of network given the limited annual budget. The following steps summarize the methodology used to get the optimal maintenance plan:

1. Calculate for each element; the values of *Element Health Index* (**EHI**).
2. Calculate for each bridge, the values of *Bridge Health Index* (**BHI**) and *Importance Factor* (**IF**).
3. A reference value is set for ***BHI***; this value represents the target minimum performance of bridges ($BHI_{ref.}$). All bridges with ***BHI*** below this value are considered to need maintenance, repair, or rehabilitation activities and will be included in the optimization process. The remaining bridges are excluded because they satisfy the minimum level of performance specified by transportation agency. However, the not-selected bridges may be selected the next years when excessive deterioration occurs.
4. For bridges selected in step 3, a reference value for element condition is set ($EHI_{ref.}$). All elements with ***EHI*** below this value are considered to need maintenance, repair, or rehabilitation activities and will be included in the optimization process these elements are put into a list called “Eligible elements list”, the remaining not-selected elements are excluded.
5. Operate the Genetic algorithm (GA) optimization process for elements in “Eligible elements list” selected in step 4.

D. Problem Formulation

$$\text{Maximize: } z_1 = H_t \qquad (8)$$

$$\text{Subject to: } C_t \le B_t \qquad (9)$$

$$H_t = \frac{\sum_{i=1}^{N} BHI_{it} * IF_i * BC_i}{\sum_{i=1}^{N} IF_i * BC_i} \qquad (10)$$

Where; $\boldsymbol{H_t}$ = average performance of the entire bridge network at year ***t***, $\boldsymbol{BHI_{it}}$: *Bridge Health Index of bridge i* at year *t* after applying repair actions for the selected elements in that bridge, $\boldsymbol{IF_i}$: *Importance Factor* of bridge *i*, $\boldsymbol{BC_i}$: the estimated Budget cost of bridge *i*, $\boldsymbol{C_t}$: the total repair Cost of the network during year *t*, , ***N*** : the total number of bridges in the network, ***E***: the Total number of elements in bridge *i*, $\boldsymbol{B_t}$: available budget at year *t*.

E. Genetic Algorithm (GA)

A genetic algorithm (GA) is a method for solving both constrained and unconstrained optimization problems based on a natural selection process that mimics biological evolution. The algorithm repeatedly modifies a population of individual solutions. In this study, GA is used to solve the optimization problem.

VI. Validation Using Case Study

A case study of ten real Bridges in Egypt is used to validate the developed framework and test its applicability. The ten bridges have different types, traffic load, size, and location. Table VI provides a description of these bridges. Different scenarios are assumed to test the proposed system as shown in Table VII. Each scenario has its own budget, objective, and target performance.

TABLE VI
GENERAL DATA OF BRIDGES

Bridge ID	Length (m)	Width (m)	BHI (%)	IF (%)
B1	594	16.2	88.1	55.2
B2	600	22	89.9	76.9
B3	1135	22	95.1	77.9
B4	550	11	87.7	77.9
B5	80	24	88.3	68.3
B6	400	18	96.4	52.4
B7	36	16	77.3	54.2
B8	664	26	87.5	72.5
B9	72	38	93.6	65.7
B10	27	9.60	70.3	55.4

TABLE VII
DESCRIPTION OF THE CASE STUDY SCENARIOS

Scenario	Planning year	Target performance (%)		Budget (LE)
		$BHI_{ref.}$	$EHI_{ref.}$	
Scenario 1	2016	95	95	1,000,000
Scenario 2	2016	95	95	2,000,000
Scenario 3	2016	95	95	3,000,000
Scenario 4	2016	95	95	4,500,000
Scenario 5	2016 2017 2018	95	95	1,000,000 1,000,000 1,000,000

The system results are reasonable, acceptable and feasible as they satisfy problem constrains. Selected results are presented. In scenarios 1, 2, 3, and 4, performance maximization problem is solved using different budget limits at each scenario to get one – year maintenance plan. While a multi – year maintenance plan is produced in Scenario 5. The algorithm selects bridge elements that maximize the fitness function; these elements have high *EIF* and are located on more - important bridges. More bridge elements are selected for maintenance and repair works as more fund became available. The current Average condition of the network was 90.55% (before repair); this condition is enhanced when the available maintenance budget has increased as shown in Fig. 2 which provides the average network condition corresponding to different repair costs.

The results of scenario 5 are organized in Fig. 3, which displays the repair cost of each bridge during the three years. Fig. 4 presents sample results of the proposed system.

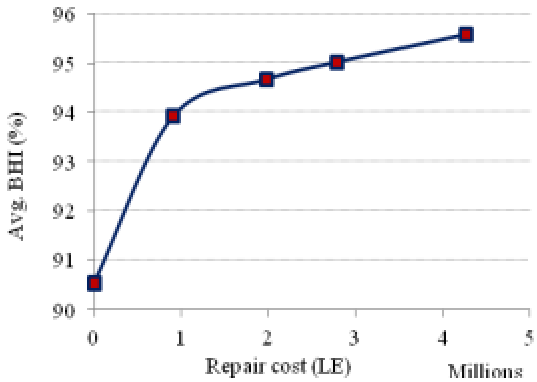

Fig. 2 Results of different budget scenarios

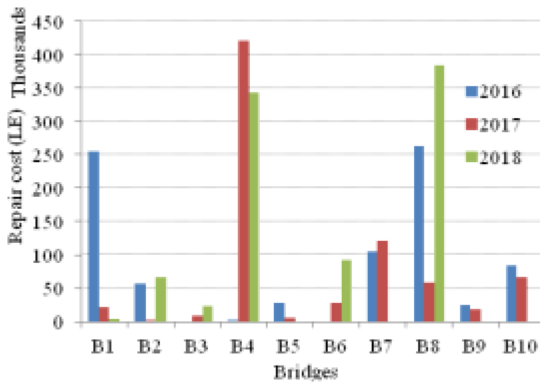

Fig. 3 Repair Costs of each bridge (Scenario 5)

VII. CONCLUSION

The objective of this paper is to allocate optimally the limited maintenance budget to competing bridges in network. The problem is formulated as quality maximization. The impact of the bridge on transportation network is considered by introducing the Importance Factor (IF). Computerized software is developed to implement the model. Validation and verification is accomplished using case study. The study provides a practical tool called **E-BMS** that could be operated within the available data to manage the maintenance of bridges in Egypt. The methodology proposed herein is general, and can be applied to all aspects of concrete bridge management. Future improvements can include; producing Transition Probability Matrices for all elements to best suit the condition in

Egypt, and including user and failure costs in the model.

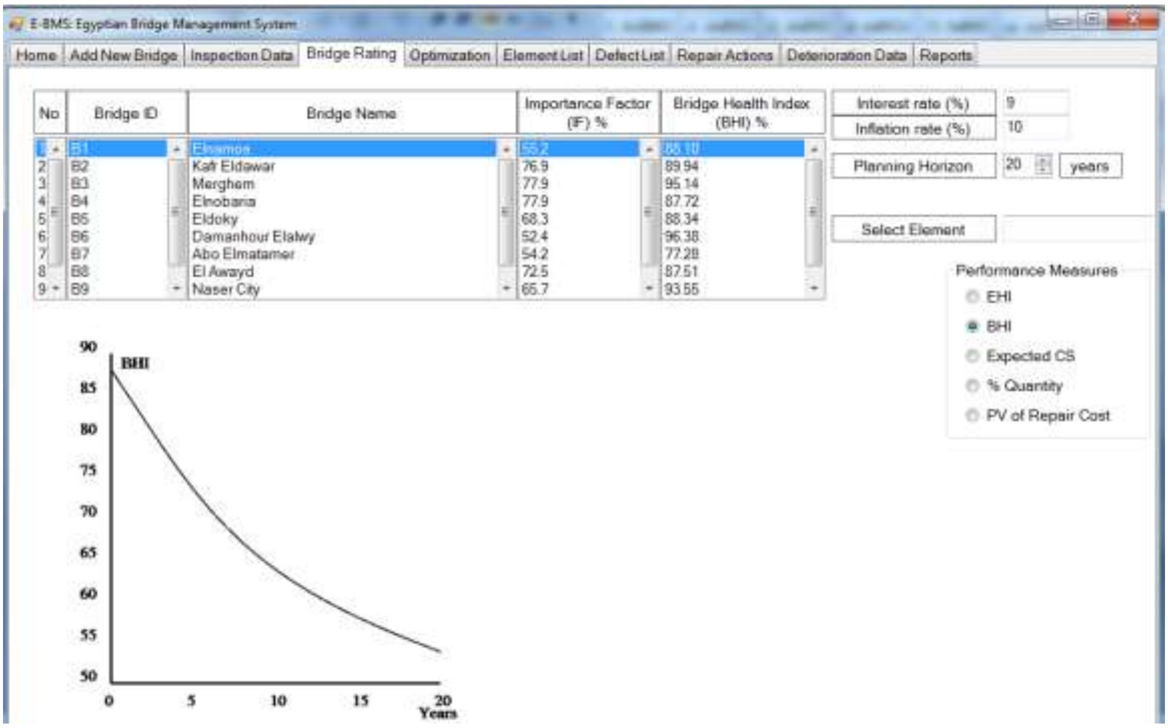

Fig. 4. Sample results of the proposed system

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