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Strategic Planning for the National Bridge Stock of Iran

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ABSTRACT: The National Bridge Stock of Iran consists of about 330,000 bridges, of which around 50% are older than 30 years. Since 2010, Iran Road Maintenance & Transportation Organization has started implementing a comprehensive Bridge Management System in order to manage this aged stock efficiently. To predict future conditions of bridge stock, a heuristic numerical method is presented. This methodology is based on Markovian process to model deterioration of bridge decks and a multi-objective optimization problem to find the best solutions. The optimization problem involves three decision variables regarding management strategies, and has three objectives regarding cost minimization. Constraints of the problem are the percentage of deficient bridges, the percentage of bridges under MR&Rs (Maintenance, Repair and Rehabilitation) and the average value of condition scores. The results show that to avoid future challenges, the annual budget for bridge maintenance should be increased, the current maintenance strategy should be improved as soon as possible, and national manuals and instructions for inspection, condition rating and maintenance should be developed.

Keywords: BMS, Bridge Deterioration, Markovian Process, Multi-Objective Optimization, National Bridge Stock of Iran, Strategic Planning.

INTRODUCTION

In many countries such as European and North American countries, having older the bridge inventories, investments are shifting from the construction of new bridges to MR&Rs (Maintenance, Repair and Rehabilitation) (Neves and Frangopol, 2005). In Canada, 40% of bridges are older than 35 years, and 42% of the United State National Bridges have been reported to be either structurally deficient or functionally obsolete (Lounis, 2000). There are different estimates of old bridges in different countries. For instance, in Germany, United State and Iran the percentage of bridges that are older than 35 years are 42% (Haardt and Holst, 2008), 50% (USDOT, 2008) and 35% (IRMTO, 2010a), respectively.

In 2005, planning for a Bridge Management System (BMS) has started by IRMTO (Iran Road Maintenance & Transportation Organization) and since 2010 a comprehensive BMS has been implementing on a national scale (IRMTO, 2010a). Moreover, Inventory Specifications

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of Bridges was published by PDSPC, (2007) but it is not mandatory yet. It aims at creating a bridge inventory database. At present, inventory data on about 30,000 out of 330,000 bridges are collected according to (IRMTO, 2010a).

In this study, a heuristic numerical method is presented to predict the future condition of bridges in the Iranian BMS, making maintenance managers aware of the future possible difficulties. This methodology is based on Markovian process to model the deterioration of bridge decks and a multi-objective optimization problem to find the best solutions. The proposed method can be used by maintenance agencies that wish to evaluate the effects of their own maintenance strategies on the future conditions of bridge stock.

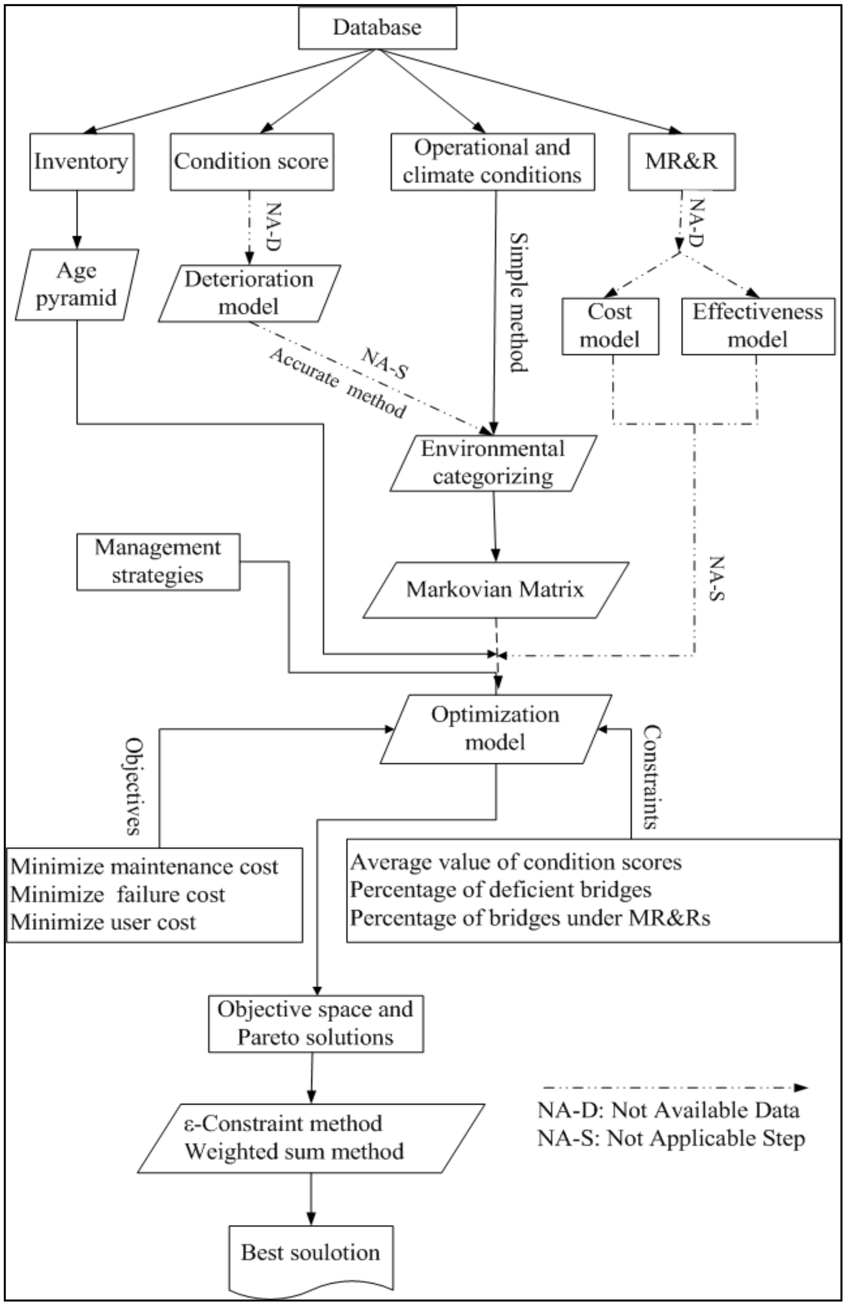


Fig. 1. Flowchart of the proposed methodology.

METHODOLOGY

According to AASHTO (2001), the main parts of an BMS include database and modeling modules (e.g. deterioration, MR&R and optimization models). Figure 1 shows the flowchart of the proposed methodology. The dash-dotted arrows in this figure show that this data or step is not available or applicable in IRMTO yet. So, the required data for these conditions is obtained from the literature.

The major steps in the flowchart are as follows.

Step 1

Analyzing the historical data about inventory, condition score, operation, climate and maintenance, which are usually provided by the BMS database.

Step 2

The age pyramid can be derived from the inventory database. Also, if an appropriate database of condition scores (derived from regular inspections) is available, it is possible to calculate typical deterioration profiles and Markovian matrixes of bridges in terms of environmental categories. Since such a database is not available in IRMTO yet, typical Markovian matrixes suggested in the literature are used. Similarly, the cost and effectiveness models of MR&Rs are not available in Iran yet, so these models are derived from the literature too.

Step 3

An optimization problem is established involving deterioration models, age pyramid, maintenance strategies, cost and effectiveness models of MR&Rs and objectives and constraints.

DATABASE

It is known that database is the heart of a BMS. A database includes inventory, condition score, climate and operational conditions and MR&R data. The data is acquired from historical records, inspections and other measurements. Age pyramid and environmental conditions are two major components of the proposed model as explained in the next sections.

Age Pyramid

Figure 2 compares the bridge age pyramids of Iran (solid bar) (IRMTO, 2010a) and Germany (dashed bar) (Haardt and Holst, 2008). In both countries, a decreasing trend in the construction of new bridges is evident after 1975.

Environmental Condition

Deterioration of bridges depends on many parameters. Zambre (2004) studied the effects of owner type, geographical location, bridge type and district on the deterioration profile of condition scores using the database of Ohio Department of Transportation. Morcous et al. (2003) investigated numerically deterioration profiles in terms of highway type, region, average daily traffic and percentage of truck traffic using the actual data from Ministe´re des Transports du Que´bec database; and suggested four environmental categories for concrete bridge decks. These environmental categories are termed as: benign, low, moderate and severe. In this research, Markovian matrixes, environmental categories and scoring system proposed by Morcous et al. (2003) have been used. According to Morcous et al. (2003), environmental parameters are divided into two major groups, namely climate and operational conditions as discussed below.

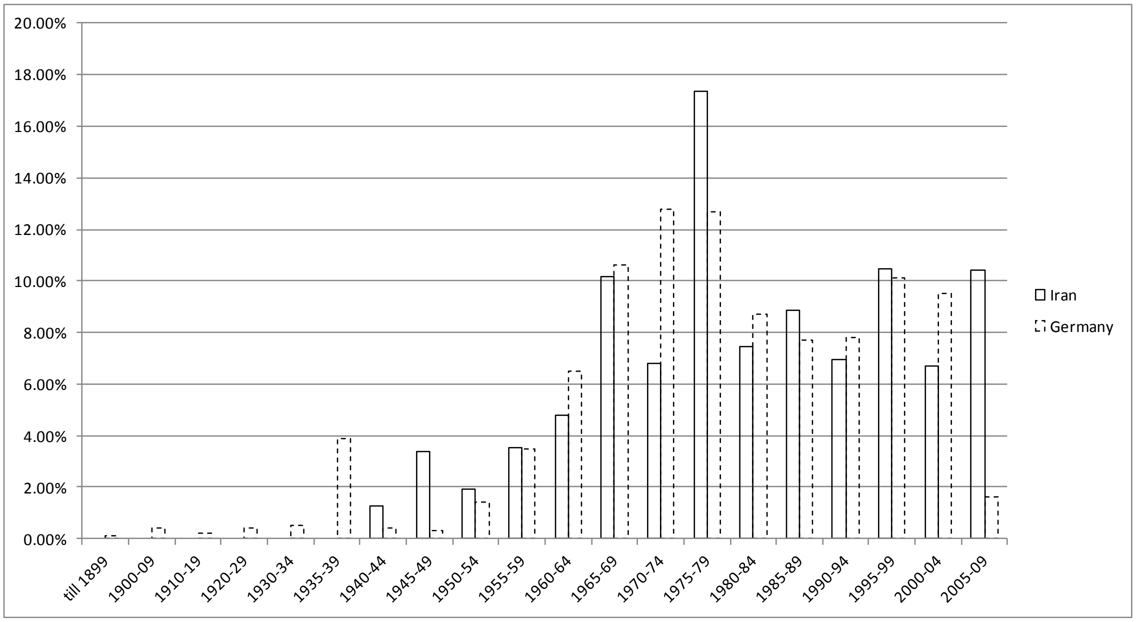


Fig. 2. Bridge age pyramids of Iran (solid) and Germany (dashed).

CLIMATE CONDITIONS

Humidity content, freeze-thaw cycles and de-icing salt (during winters) are the most deteriorating agents related to climate (Morcous et al., 2003). Considering these agents, Iran's provinces are categorized into three climate zones: 1) the low humidity zone, which includes nine provinces with a dry climate mainly located at the center and east, 2) the mountain zone, which includes fifteen provinces located in the Alborz and Zagros mountains, and 3) the high humidity zone, which includes five provinces located on the coasts of the Caspian and Oman seas and Persian Gulf (Figure 3).

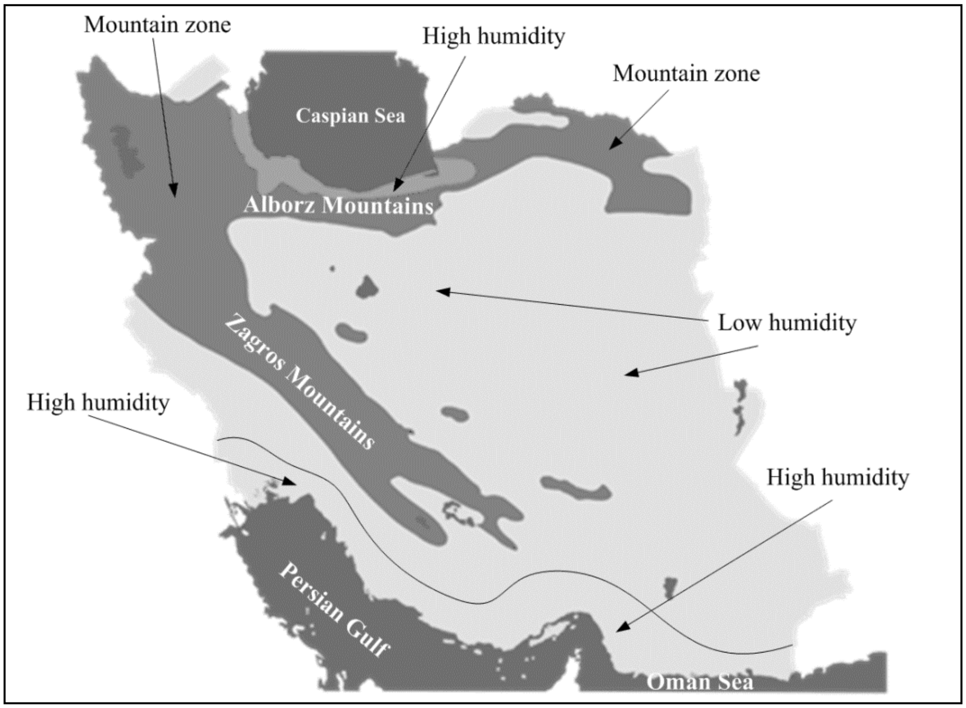


Fig. 3. Climate zones of Iran.

OPERATIONAL CONDITIONS

Traffic volume and loading conditions are the most deteriorating agents of bridges from operational condition. Iran is located in the heart of the North-South, East-West and Trasica Transportation Corridors. Consequently, highways and main roads have relatively a high percentage of truck traffic (IRMTO, 2010b). Also, highways and main roads have higher traffic volume than other roads (IRMTO, 2010b). Due to the absence of detailed inventory data, it is assumed that the number of bridges for each road type (i.e. main or local) is proportional to the corresponding road length.

ENVIRONMENTAL CLASSIFICATION

Based on Morcous et al. (2003), the environmental category of a bridge can be determined in terms of climate and operational conditions. Table 1 presents the environmental category of a bridge in connection with the climate zone that the bridge located in, and the zone and road type share of each zone. For example, a bridge located along a main road in the mountain zone or along a local road in the high humidity zone is classified as the moderate category. According to Table 1, the 15.3%, 45.7%, 32.6% and 6.4% of bridges in Iran are categorized as benign, low, moderate and severe, respectively.

DETERIORATION MODEL

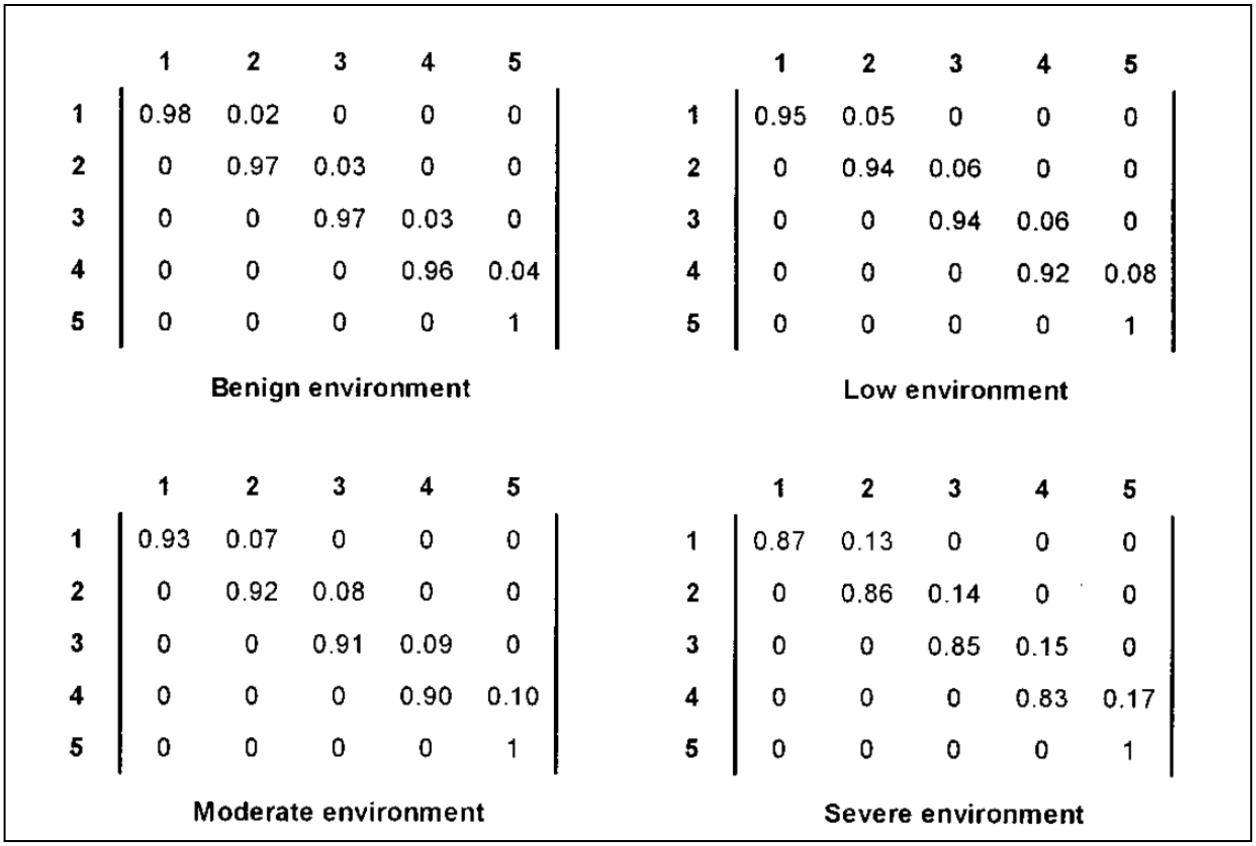
In the literature, there are different methods for modeling the deterioration of infrastructures, such as Weibul-based (Agrawal et al., 2010; Van Noortwijk and Klatter, 2004), reliability-based (Frangopol et al., 2001), Markovian processes and so on. The overall condition of a large scale facility is commonly specified using a condition score. As the condition score is a discrete scale, Markovian process has been broadly used in the modeling of the infrastructures deterioration, especially in highway systems (Morcous et al., 2003). Markovian model is the backbone of the proposed methodology (Figure 1). Morcous et al. (2003) described Markovian models as follows: “these models predict the probability that a given bridge element in a given environmental and a certain initial condition will continue to remain in its current condition state, or change to another condition state, within a one-year period when a particular action is performed”. For further information on Markovian process in bridge engineering, interested readers can refer to Agrawal et al. (2010), Morcous (2006), Morcous et al. (2003), Cesare et al. (1992) and so on.

Table. 1. Environmental categories of Iran’s bridge stock (IRMTO, 2010b).

Main feature of the Zone	Zone share	Road type share	Environmental category
Low humidity	30%	Local road (51%)	benign
		Main road (49%)	low
Mountain	50%	Local road (62%)	low
		Main road (38%)	moderate
High humidity	20%	Local road (68%)	moderate
		Main road (32%)	severe

It is widely accepted that bridge decks are the most vulnerable elements which consume considerable amounts of maintenance efforts and budget. Morcous et al. (2003) published a valuable data set on Markovian matrixes of bridge decks in terms of environmental categories. They collected data from various sources to develop Markovian matrixes, and then compared it with that obtained from the actual data provided by the Ministe´re des Transports du Que´bec databae. They also defined five discreet condition scores, which score 1 represents the best condition (new and undamaged), and score 5 is the worst score (severely damaged).

Figure 4 shows the Transition Probability Matrix (TPM) of structural decks for four environmental categories according to Morcous et al. (2003). For example, consider a bridge located along a main road on the coast of the Caspian Sea. This bridge classified as severe environment (Table 1). If score 3 is assigned to it, the probability that within one year, its condition remains unchanged or drops to score 4 is 85% and 15%, respectively. Also, assume that there are 100 bridges with score 3 in a network belonging to the severe environmental category, consequently, in the next year, 85 bridges (85%×100) remain at score 3, while 15 bridges (15%×100) drop to score 4.



$$\begin{array}{c|ccccc|} & 1 & 2 & 3 & 4 & 5 \\ 1 & 0.98 & 0.02 & 0 & 0 & 0 \\ 2 & 0 & 0.97 & 0.03 & 0 & 0 \\ 3 & 0 & 0 & 0.97 & 0.03 & 0 \\ 4 & 0 & 0 & 0 & 0.96 & 0.04 \\ 5 & 0 & 0 & 0 & 0 & 1 \end{array}$$

Benign environment

$$\begin{array}{c|ccccc|} & 1 & 2 & 3 & 4 & 5 \\ 1 & 0.95 & 0.05 & 0 & 0 & 0 \\ 2 & 0 & 0.94 & 0.06 & 0 & 0 \\ 3 & 0 & 0 & 0.94 & 0.06 & 0 \\ 4 & 0 & 0 & 0 & 0.92 & 0.08 \\ 5 & 0 & 0 & 0 & 0 & 1 \end{array}$$

Low environment

$$\begin{array}{c|ccccc|} & 1 & 2 & 3 & 4 & 5 \\ 1 & 0.93 & 0.07 & 0 & 0 & 0 \\ 2 & 0 & 0.92 & 0.08 & 0 & 0 \\ 3 & 0 & 0 & 0.91 & 0.09 & 0 \\ 4 & 0 & 0 & 0 & 0.90 & 0.10 \\ 5 & 0 & 0 & 0 & 0 & 1 \end{array}$$

Moderate environment

$$\begin{array}{c|ccccc|} & 1 & 2 & 3 & 4 & 5 \\ 1 & 0.87 & 0.13 & 0 & 0 & 0 \\ 2 & 0 & 0.86 & 0.14 & 0 & 0 \\ 3 & 0 & 0 & 0.85 & 0.15 & 0 \\ 4 & 0 & 0 & 0 & 0.83 & 0.17 \\ 5 & 0 & 0 & 0 & 0 & 1 \end{array}$$

Severe environment

Fig. 4. Markovian Transition Probability Matrixes for structural deck (Morcous et al., 2003).

MR&R IMPROVEMENT AND COST MODELS

Since there is no reliable data in IRMTO on repair effectiveness and cost models, attempts have been made to obtain such models from the literature as described below:

In one study, Lounis and Vanier (1998) assumed the following MR&Rs for concrete decks, (i) d1 = do nothing, (ii) d2 = minor repair with a unit cost of US$ 100/m2. (iii) d3= rehabilitation (or major repair) with a unit cost of US$ 250/m2, and (iv) d4 = replacement with a unit cost of US$ 400/m2. In this scoring system, score 7 is the excellent condition, and score 1 is the worst. They assumed that the maintenance decisions d2, d3, and d4 are compatible with scores (5, 4), (3, 2) and 1, respectively. It is assumed that the abovementioned repairs pick a bridge up to score 7 (best score). For example, if repair d2 is conducted on a bridge with score 4 or more, its score improves to score 7. However, this repair is not effective on a bridge with a score below 4.

In another study, Morcous and Lounis (2005) assumed three MR&Rs for a concrete deck, including: i) do nothing, ii) repair and iii) replace, where in their scoring system, scores 6 and 1 represent the best and worst conditions, respectively. In that research, the repair scenario is compatible with scores (6, 5), (4, 3) and (2, 1) improving the condition of the deck to scores 6, 5 and 4, respectively. In addition, the replacement scenario is applicable to all scores improving the score to 6 (i.e., best score). For example, if the repair scenario is carried out on a bridge with score 4 or 3, its score is improved to score 5. Cesare et al. (1992) assumed a repair effectiveness model in which after repair, the bridge score reaches the best.

With respect to repair considerations, Moscow Bridge Management System has defined a five-level rating for the deck condition, namely good, not very good, poor, very poor and unacceptable. These ratings are compatible with the following repair actions: cleaning and scheduled maintenance, preventive maintenance, repair, major repair, and replacement or restoration repair (Elbehairy, 2007).

Considering the abovementioned effectiveness models as well as differences in the scoring systems of this research, a simple model is used, as described below. In the proposed model, three MR&Rs are considered, namely minor, major (e.g. strengthening) and extensive repairs (e.g. replacement), which are compatible with scores 3, 2 and 1, respectively. These improve the before-repair score to the best score (i.e. 5). In addition, their associated costs are considered Ʉ 0.28, Ʉ 0.65 and Ʉ 1.0, respectively (Elbehairy, 2007). These values are in conformance with values used by Lounis and Vanier (1998) (Ʉ 0.25 =US$ 100/ US$ 400; Ʉ 0.63=US$ 250/ US$ 400; and Ʉ 1.0=US$ 400/ US$ 400).

It is noted that Ʉ 1.0 is an imaginary currency which is equal to the average spending on the replacement of an average-sized deck. In Iran, average deck area is 40 m2 (IRMTO, 2010a), so Ʉ 1.0 =40× US$ 400= US$ 16000= US$ 16000×IRR10960= IRR 175 million (currency exchange rate is based on CBI (2012) in year 2011, and IRR denotes the Iranian Rial).

OPTIMIZATION MODEL

Problem Formulation

Figure 5 illustrates the framework of the deterioration model. In Figure 5, (1) i and j denote the scores of a bridge in years y and $y+1$, respectively, (2) e denotes the environmental category (e.g., benign, low, moderate and severe), and $n_e(y)$ =the number of new bridges which start operating in year y and belong to the environmental category e, (3) $n_e^i(y)$ =the number of total bridges with score i in year y which belong to the environmental category e, and $T(i,j)$ = the percentage of $n_e^i(y)$ which deteriorate from score i in year y to j in year $y+1$ (see Figure 4), and (4) $R(i,j)$ is the percentage of bridges with score i in year y which improve to score j in year $y+1$ due to a MR&R, $C(i,j)$ =the cost which is spent on improving a bridge condition from score i to j (i.e., $i > j$), and herein $C(3,1) =$ Ʉ0.28, $C(4,1) =$ Ʉ 0.65 and $C(5,1) =$ Ʉ 1.00. If no repair is conducted (i.e., $i \le j$), this term is equal to zero.

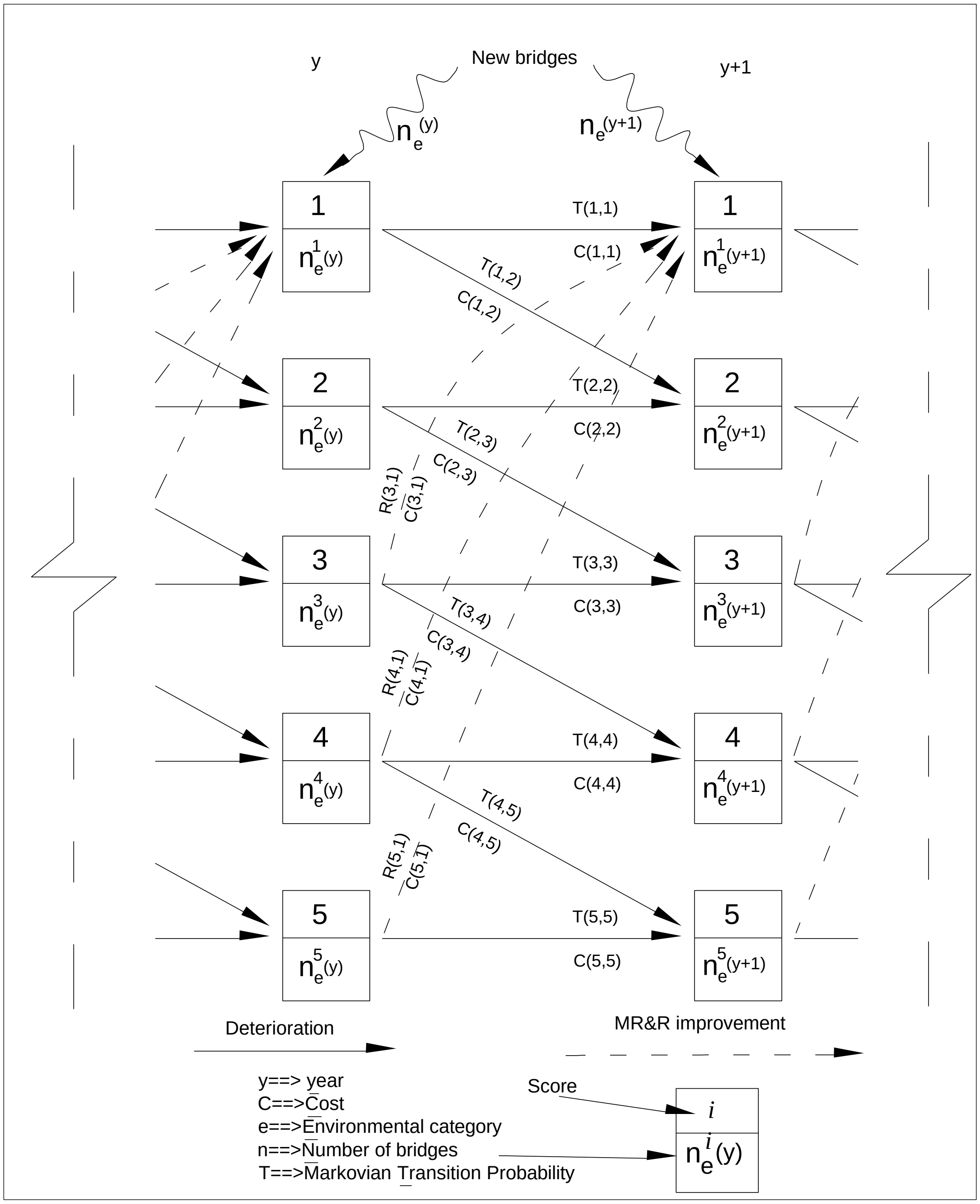


Fig. 5. Framework of deterioration model of bridge stock.

$n_e(y)$ is calculated as follows:

$$n_e(y) = w_e \times n(y) \tag{1}$$

in which, w_e = the percentage of bridges which belong to the environmental category *e*, and $n(y)$ = the number of new bridges which go into operation in year y (see the age pyramid).

As seen in Figure 5, for example, $n_e^1(y+1)$ and $n_e^4(y+1)$ are calculated as follows:

$$n_e^1(y+1) = n_e(y+1) + T(1,1) \times n_e^1(y) + R(3,1) \times n_e^3(y) + R(4,1) \times n_e^4(y) + R(5,1) \times n_e^5(y) \tag{2}$$

$$n_e^4(y+1) = (1 - R(3,1)) \times T(3,4) \times n_e^3(y) + (1 - R(4,1)) \times T(4,4) \times n_e^4(y) \tag{3}$$

$n_e^2(y+1)$, $n_e^3(y+1)$ and $n_e^5(y+1)$ are calculated in a similar way.

The annual cost of maintenance, $C(y)$, is calculated as follows:

$$C(y) = \sum_e [C(3,1) \times R(3,1) \times n_e^3(y) + C(4,1) \times R(4,1) \times n_e^4(y) + C(5,1) \times R(5,1) \times n_e^5(y)] \tag{4}$$

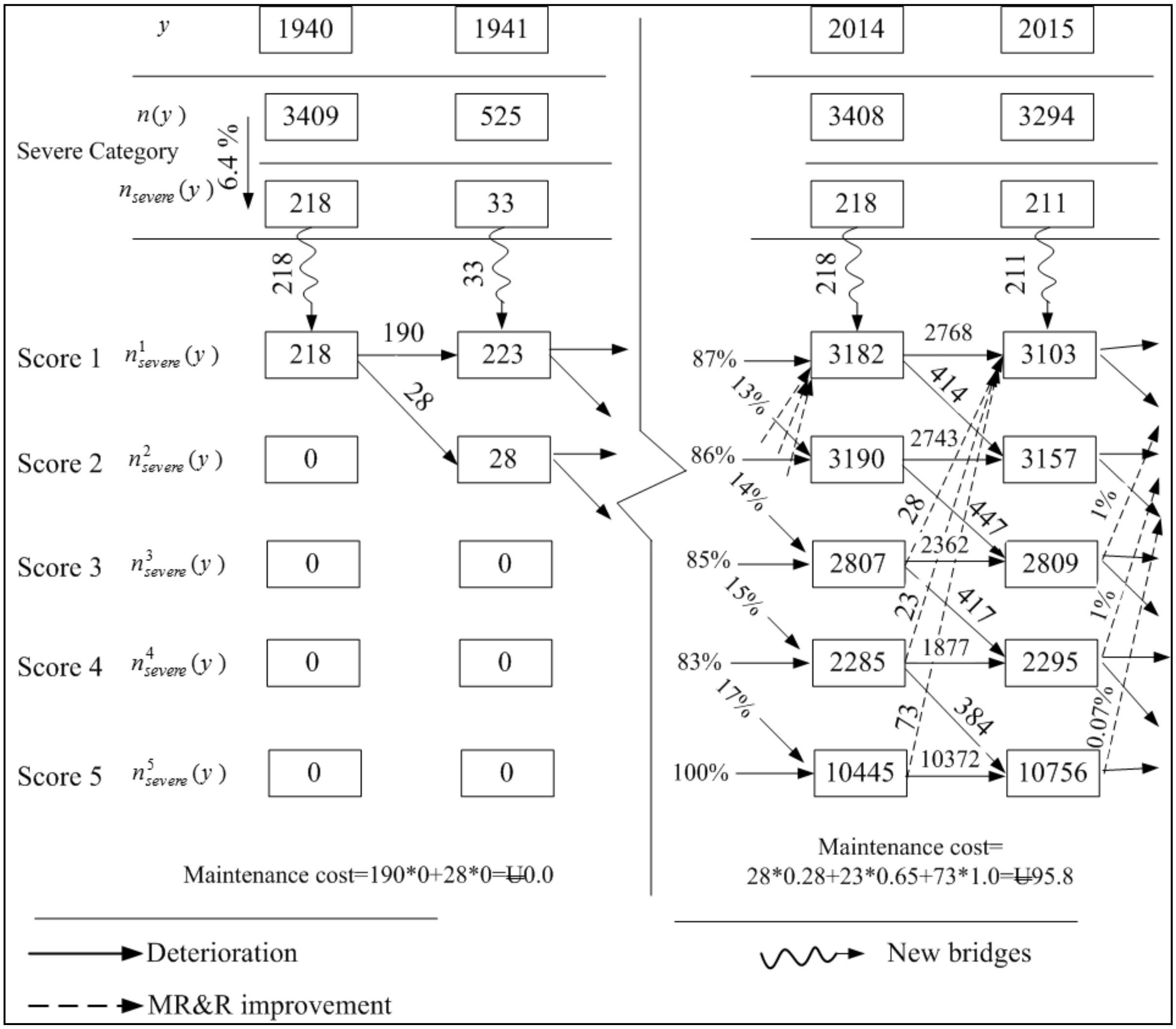


Fig. 6. A numerical example for deterioration modeling process.

Problem Formulation Example

To have a better understanding of the deterioration formulation, an example for the severe environmental category (e = severe) is shown in Figure 6. The procedure starts in 1940, when there were totally 3409 bridges (i.e. n (1940) = 3409) in Iran, and it is assumed that all of them had score 1. So, the number of new bridges belonging to the severe category would be n_{severe} (1940) = 218 (6.4%×3409). In the next year, 525 bridges (n (1941) = 525) were added to the stock, and n_{severe}(1941) = 33 (6.4%×525). Also, 87% of the bridges that had score 1 in the previous year would remain at that score (87%×218 = 190), while 13% would drop to score 2 (13%×218 = 28). Therefore, in 1941, there would be 223 (33+190) bridges with score 1 and 28 bridges with score 2. The procedure is continued in a similar manner for the next years. The results for 2014 are demonstrated in Figure 6. As seen, in 2014, 2807 bridges will have score 3, of which 1% (28 bridges) will be improved to the best score by applying Minor Repairs. This repair type costs Ʉ0.28. Also, 85% of the remained bridges i.e., 0.85*(2807-28) =2362 will remain in score 3, while 15% i.e., 0.15*(2807-28) = 417 will drop to score 4 in the next year. Based on this figure, the number of bridges with score 1 in 2015 will be equal to 3103 (211+2768+28+23+73). It is noted that before completion of Iran's BMS (i.e., 2015), $R(3,1)$, $R(4,1)$ and $R(5,1)$, which show level of maintenance activities, are 1%, 1% and 0.07% , but after 2015, various strategies are examined to find the optimum value for R.

Optimization Model

Iran's BMS is expected to be completed in 2015, and after 2015, previous maintenance strategies will be changed. Maintenance strategies may be quantified by decision variables, namely $R(3,1)$, $R(4,1)$ and $R(5,1)$ (see Figure 5). In this research, a 50-year time horizon after 2015 (i.e. the target year is 2065) is assumed. The optimization processes try to minimize maintenance, failure and user costs. The problem constraints include the percentage of deficient bridges, the percentage of bridges under MR&Rs and the average condition score. The average condition score must be equal to or less than 3. Other constraints and objectives are explained below.

*M*inimizing *M*aintenance *C*ost

The average annual maintenance cost, $\bar{C}$, is calculated by:

$$\bar{C} = \frac{\sum_{2016}^{2065} C(y)}{50} \tag{5}$$

where, $C(y)$ is calculated by Eq. (4).

*M*inimizing *F*ailure *C*ost under the *C*onstraint of the *P*ercentage of *D*eficient *B*ridges

It is clear that the safety of a road network is directly related to the percentage of deficient bridges, D. A deficient bridge needs major repair or rehabilitation or even replacement (USDOT, 2008). In other words, they are known as probable failure sources. Failure consequences impose cost on society called failure cost. Using this definition, scores 4 and 5 are considered as deficient conditions. Therefore, the average percentage of deficient bridges, $\bar{D}$, should be minimized in order to minimize the failure cost. $\bar{D}$ is calculated as follows:

$$\begin{cases} D(y) = \dfrac{\sum_{e} [n_e^4(y) + n_e^5(y)]}{\sum_{1940}^{y} n(y)} \\ \bar{D} = \dfrac{\sum_{2016}^{2065} D(y)}{50} \end{cases} \tag{6}$$

After the implementation of BMS in the United States in 1992, the percentage of deficient bridges reduced from 20.6% to 12.6% in 2006 (Elbehairy, 2007; Morcous et al., 2003; USDOT, 1999 ; USDOT, 2008). The average value of deficient bridges during 1992 -2006 is 16%. Consequently, $\bar{D}$ is assumed to be below 16%.

Minimizing User Cost under the Constraint of the Percentage of Bridges under MR&Rs

It is usually necessary to close a bridge totally or partially to perform an MR&R. This causes problems such as traffic and business disturbances, which indirectly impose cost on society called user cost. This subject is taken into account by a variable termed the percentage of bridges under MR&Rs, denoted by *M*. The average of *M* denoted by $\bar{M}$ is defined by:

$$\begin{cases} M(y) = \sum_{e} [R(3,1) \times n_e^3(y) + R(4,1) \times n_e^4(y) \\ + R(5,1) \times n_e^5(y)] / \sum_{1940}^{y} n(y) \\ \bar{M} = \dfrac{\sum_{2016}^{2065} M(y)}{50} \end{cases} \quad (7)$$

To minimize user cost, $\bar{M}$ should be minimized. On average, annually 2.1% of bridges in 16 OECD's (Organization for Economic Co-operation and Development) countries are under repair and strengthening (Lounis and Vanier, 1998). So in this research, the maximum allowable value of $\bar{M}$ is considered to be 2.1%.

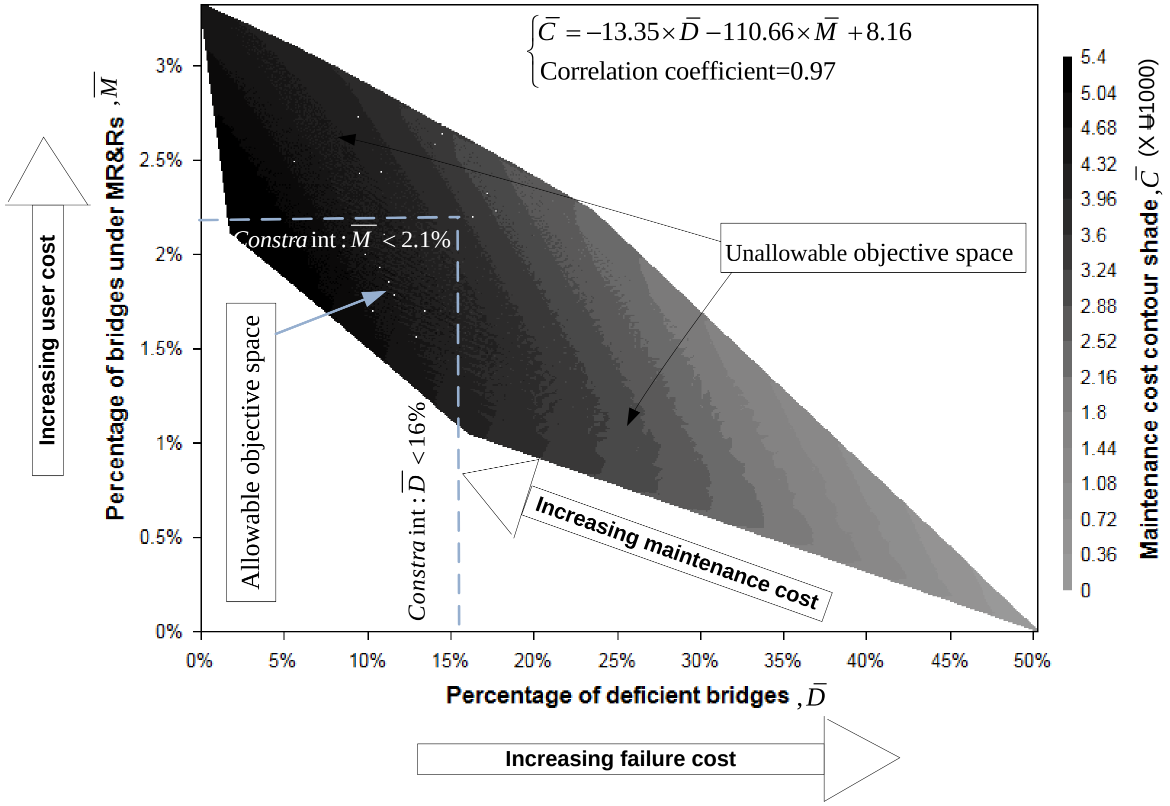


Fig. 7. Contour shade bands of the objective space (no constraint is applied).

RESULTS AND DISCUSSIONS

A maintenance strategy can be defined by a specific decision variable point as ($R(3,1)$, $R(4,1)$, $R(5,1)$). Before completion of the Iran's BMS, the values of $R(3,1)$, $R(4,1)$ and $R(5,1)$ are assumed to be 1%, 1% and 0.07% ,respectively. These values have led to outputs that are more consistent with the previous maintenance performance of IRMTO. For example, the average number of bridges under extensive repairs during 2009 - 2011 is predicted to be 216 cases using the above values for R, while the actual number of bridges funded for MR&Rs have been 234 cases. To estimate the best maintenance strategies in future (i.e. after the completion of Iran's BMS), various strategies are simulated by trying different values for the decision variables (i.e. *R*). It is possible to assign any value between 0% and 100% to each decision variable. Indeed, the feasible space is a cube of side 1 (unit cube). For simplicity, the space has been divided with increments of 1%, and for each decision point, the corresponding objective point is calculated.

Analysis of Objective Conflicts

Figure 7 shows a 3D visualization of the objective space (of the feasible decision space) with contour shade bands. As is clear, a plane could be fitted to the space with a high correlation factor. In this figure, the third dimension is the average maintenance cost as shown by contour shade bands, where, darker shade means higher maintenance cost. Based on this figure, if maintenance cost is decreased, the percentage of deficient bridges increases. Consequently, the network safety decreases, and likely there will be many incidents of bridge failure. Such unexpected failures impose socio-economic costs, such as fatalities, extensive damages, reconstruction and demolishing costs and traffic disturbance. Although an increase in maintenance activities improves the network safety, it increases user costs. Higher user cost is due to the fact that in MR&Rs, a bridge is completely or partially closed and this causes traffic and business disturbances. In this figure, the allowable and unallowable objective space is also illustrated. An unallowable objective point is one that does not satisfy the constraints of the optimization problem.

Determination of the Best Strategy

A multi-objective problem usually yields many solutions. But the maintenance managers can choose only one solution (i.e., strategy) to implement. In this section, the steps of refining feasible solutions to obtain the best solution are presented.

Step 1

In this step, the objective space is determined by using the deterioration and optimization models. As mentioned before, the decision space has been divided with increment of 1%. So, the feasible decision space is separated to 101×101×101 =1030301 data points. Each feasible point in the decision space yields a specific objective point (Figure 8.a).

Step 2

In this step, the constraints are applied to the problem. As it is obvious from Figure 8.b, a considerable number of points (about 97%) not satisfying the constraints are ignored.

Step 3

Some allowable solutions may be dominated by at least one or more solutions. In this step, the dominated solutions are ignored by using Pareto set concept. A Pareto set includes all the non-dominated solutions (Konak et al., 2006). Consider points 1 and 2 in the allowable objective space (Figure 8.b), point 1 dominates point 2, if (a) $\bar{D}_1 \le \bar{D}_2, \bar{M}_1 \le \bar{M}_2$, $\bar{C}_1 \le \bar{C}_2$, and (b) at least for one objective the sign $\le$ changes to < (Konak et al., 2006). For example, points (0%, 1%, 58%) and (0%. 2% 39%) in the allowable decision space correspond to points (15.96%, 1.10%, Ʉ 4102) and (15.99%, 1.11%, Ʉ 4118) in the objective space. The first point dominates the second, since the second point consumes higher maintenance cost, while the two remained objectives have not improved. In this step, 77% of the allowable points are omitted (Figure 8.c).

Step 4

Although a considerable percentage of the feasible space is ignored (about 99.35%), there are still many solutions (6493 points), making it hard to select a specific solution to execute. Decision maker can select each solution from the Pareto set considering its organizational and environmental requirements. Some recommendations are provided below to select the best solution(s). The recommendations are based on the ε-Constraint and Weighted sum methods (Marler and Arora, 2004).

ε - Constraint Method

In this method, the primary objective is selected and other objectives are constrained (Marler and Arora, 2004). In this study, the maintenance cost is the primary objective; and the constraints of the problem are applied on the secondary objectives in Step 2. Therefore, the best solution in Pareto set (Figure 8.c) is one that needs the minimum maintenance cost. Therefore the point (17%, 0%, 8%) is the best strategy which corresponds to the objective point (16%, 2%, Ʉ 3630).

Weighted Sum Method

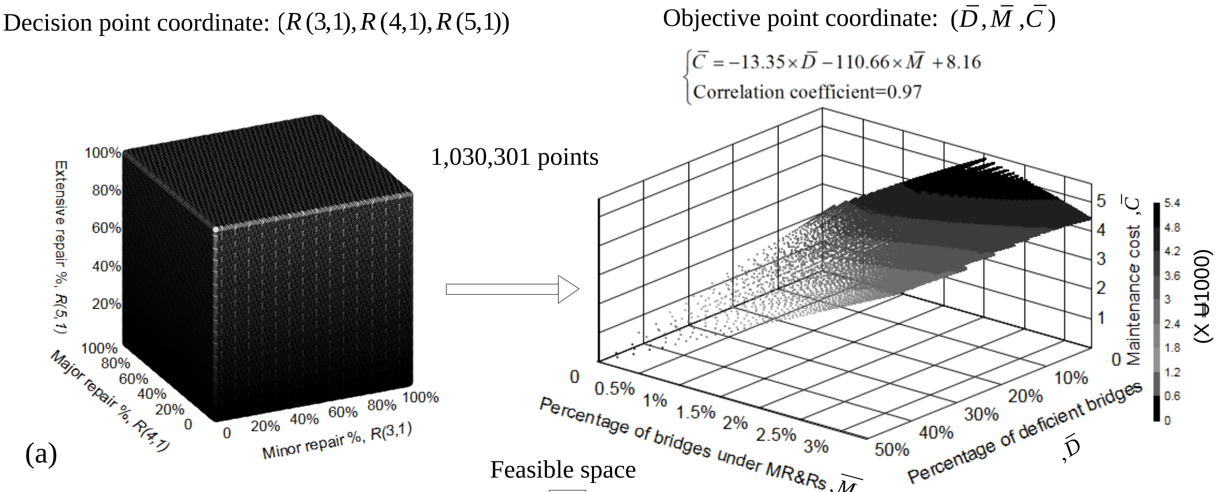
In this method, the decision maker should assign an importance weight to each objective. Since each objective may have different magnitude, normalized values should be used. So the optimization problem is formulated as (Konak et al., 2006):

Minimize

$$z = W_{deficient} \times \left(\frac{\bar{D} - \bar{D}_{\min}}{\bar{D}_{\max} - \bar{D}_{\min}}\right) + W_{MR\&R} \times \left(\frac{\bar{M} - \bar{M}_{\min}}{\bar{M}_{\max} - \bar{M}_{\min}}\right) + W_{\cos t} \times \left(\frac{\bar{C} - \bar{C}_{\min}}{\bar{C}_{\max} - \bar{C}_{\min}}\right) \tag{8}$$

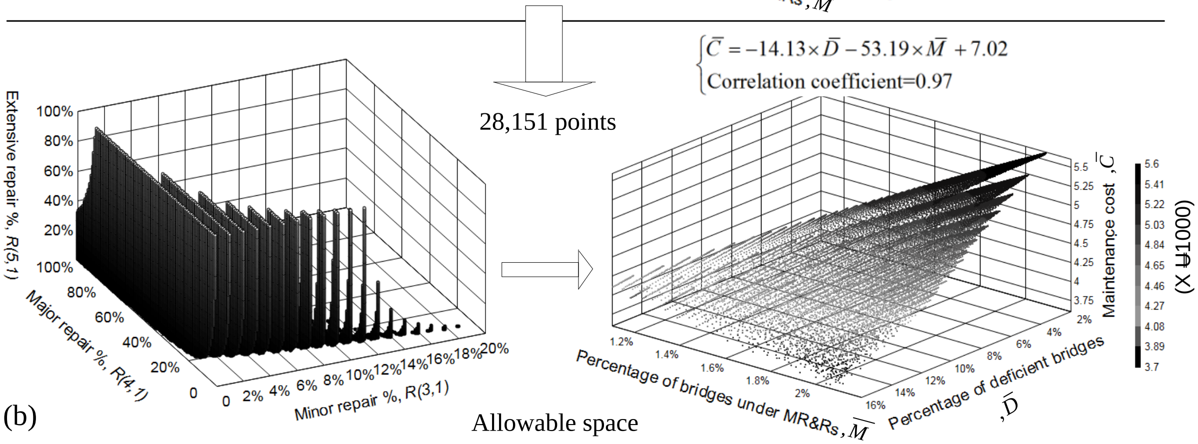
where, z and W denote the objective score and objective importance weight; the subscripts *max* and *min* denote the maximum and minimum values of the relevant variable in the allowable space, respectively; and $W_{deficient} + W_{MR\&R} + W_{\cos t} = 100\%$.

Three marginal weight assignments and three top ranking solutions for each assignment are presented in Table 2. When the concern is only about the failure cost i.e. $W_{deficient} = 100\%$, the solutions with the minimum deficient percentage win. In this state, the best solutions do not recommend minor repairs, but recommend a high percentage of major and extensive repairs, which are associated with high maintenance cost. The weight assignment based on user cost (i.e. $W_{MR\&R} = 100\%$) does not recommend minor and major repairs, but only recommends a high percentage of extensive repairs. Finally, the weight assignment based on maintenance cost ($W_{\cos t} = 100\%$) does not recommends major repairs, but recommends a higher percentage of minor repairs and relatively a low percentage of extensive repairs. The last assignment gives strategies that recommend minor repairs rather than other repair types. Minor repair is a preventive action. Based on the opinion that "Prevention is better than cure", the preventive action are more rational and acceptable by bridge managers.



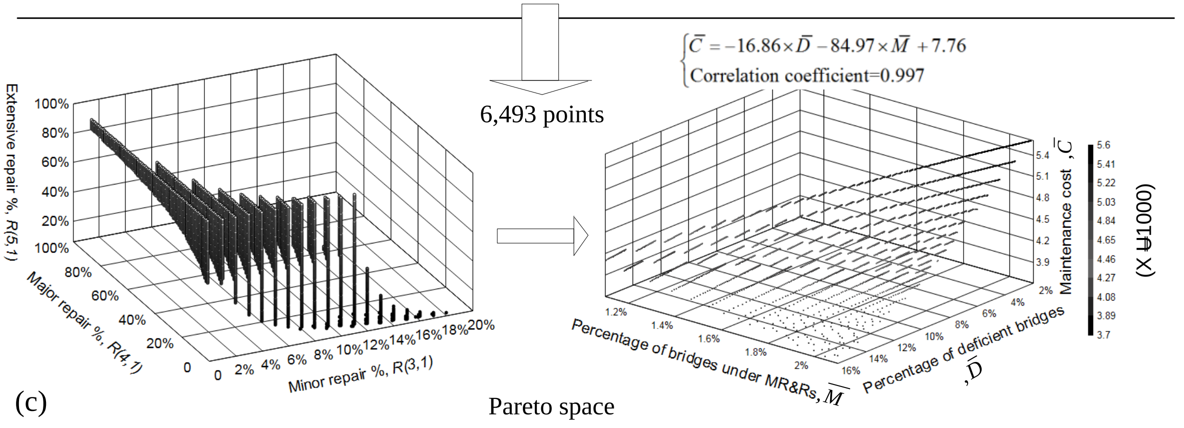
(a)

Feasible space



(b)

Allowable space



(c)

Pareto space

Fig. 8. Decision and objective spaces of feasible, allowable and Pareto solutions.

Table. 2. Comparison of various weight assignments.

Objective weight assignments		Ranking	Maintenance strategy			$\bar{C}$		$\bar{D}$	$\bar{M}$
			$R(3,1)$	$R(4,1)$	$R(5,1)$	Ʉ	Milliard IRR		
Failure cost-based	$W_{deficient}$=100%	1	0%	86%	100%	5603	980	2.050%	2.0990%
	$W_{MR\&Rs}$=0%	2	0%	86%	99%	5602	980	2.054%	2.0989%
	W_{cost}=0%	3	0%	86%	98%	5602	980	2.058%	2.0988%
User cost-based	$W_{deficient}$=0%	1	0%	1%	58%	4102	718	15.96%	1.1038%
	$W_{MR\&Rs}$=100%	2	0%	1%	59%	4106	719	15.92%	1.1049%
	W_{cost}=0%	3	0%	1%	60%	4110	719	15.89%	1.1060%
Maintenance cost-based	$W_{deficient}$ =0%	1*	17%	0%	8%	3630	635	15.91%	2.0407%
	$W_{MR\&Rs}$=0%	2	18%	0%	8%	3649	639	15.58%	2.0772%
	W_{cost}=100%	3	15%	0%	9%	3662	641	15.83%	1.9901%
			Continuation of the prior strategy						
-			1%	1%	0.7%	983	172	43.0%	0.4%

*This is ε-Constraint solution, too.

The Best Proposed Strategy for the National Bridge Stock in Iran

The best strategy is very sensitive to the importance weights (Table 2). In addition, the importance weights depend on the owner/operator organizational and environmental requirements. For example, municipal owners are concerned firstly about user cost and secondly on failure costs, since inaccessibility of a bridge in a municipal imposes a considerable socio-economic cost. In contrast, for railway owners, failure costs are more important than user costs. Because failure of a railway bridge under train passage leads to a catastrophic event. In addition, inaccessibility of a railway bridge disables a considerable part of the network and imposes considerable user costs. In this research, the National Bridges of Iran is mainly located in the interprovincial and local road networks, which are not as sensitive as railway and municipal bridges to failure and user costs. So, the importance weight of maintenance cost is more than those of failure and user costs. In addition, as discussed before, the constraint on $\bar{D}$ (i.e. failure cost concern) and $\bar{M}$ (i.e. user cost concern) are based on the conditions of United States and 16 OECD's countries, respectively. Hence, the Pareto solutions are safe and efficient enough with respect to failure and user costs, and consequently in order to find the best solution in the Pareto space, it is enough to optimize the maintenance cost. Based on the above, we, therefore, propose $W_{deficient} = 0\%$, $W_{MR\&R} = 0\%$ and $W_{\mathrm{cost}} = 100\%$. Finally, similar to the ε-Constraint method, the point (17%, 0%, 8%) is suggested by the authors as the best strategy corresponding to the objective point (16%, 2%, ~~U~~ 3630).

Maintenance cost vs. IRMTO Budget

Table 2 compares the average annual cost of the optimum solutions with condition that if the previous strategy will continue in the future only for the maintenance of deck. Table 3 compares the cost predicted by the proposed model with the budget funded or predicted by IRMTO (IRMTO, 2010a). Since the cost of the deck maintenance is only considered in this research, and the IRMTO funds are for the whole bridge maintenance, it is necessary to make consistency between them. The portion of fund consumed for the deck maintenance is about 30%-50% of the whole bridge maintenance fund (Elbehairy, 2007). The total annual budget predicted by IRMTO is a little (6%) more than the average annual maintenance cost predicted by the proposed model. However, the funded value (IRR 300 Milliards) is lower than the model predictions (IRR 459 Milliards). This relatively high difference more likely comes from the fact that the funded value is for 2011 and the proposed model predicts the average annual cost over the 2015-2065 period.

Deficient Profile Comparison

Figure 9 compares the percentage of deficient bridges of Iran's National Bridge Stock for two possible maintenance strategies after 2015. The strategies include the continuation of the previous strategy or the implementation of the best solution. Also, in this figure, the deficiency percentage profile of the United State bridges is presented. The U.S. deficiency profile has a decreasing trend after the implementation of BMS in 1992. The U.S. deficiency trend shows good conformance with the best solution trend. The largest value of the percentage of deficient bridges in the U.S. is about 21% when the U.S. was experiencing socio-economic difficulties induced by recurring incidents of bridge failure. At present, more than 21% of the Iranian bridges are deficient, which is a warning for Iranian bridge owners/operators.

Table. 3. Maintenance cost vs. IRMTO budget.

	Model[1] (Milliard IRR)	**IRMTO[2] (Milliard IRR)**	**IRMTO/ Model**
Deck	635 (best solution)	720* predicted	1.13
	172 (prior strategy continuation)	120* funded	0.70
Total	1694* (best solution)	1800 predicted	1.06
	459* (prior strategy continuation)	300 funded	0.65

[1] 50 years time horizon; [2] Funded in year 2011; * total/deck conversion

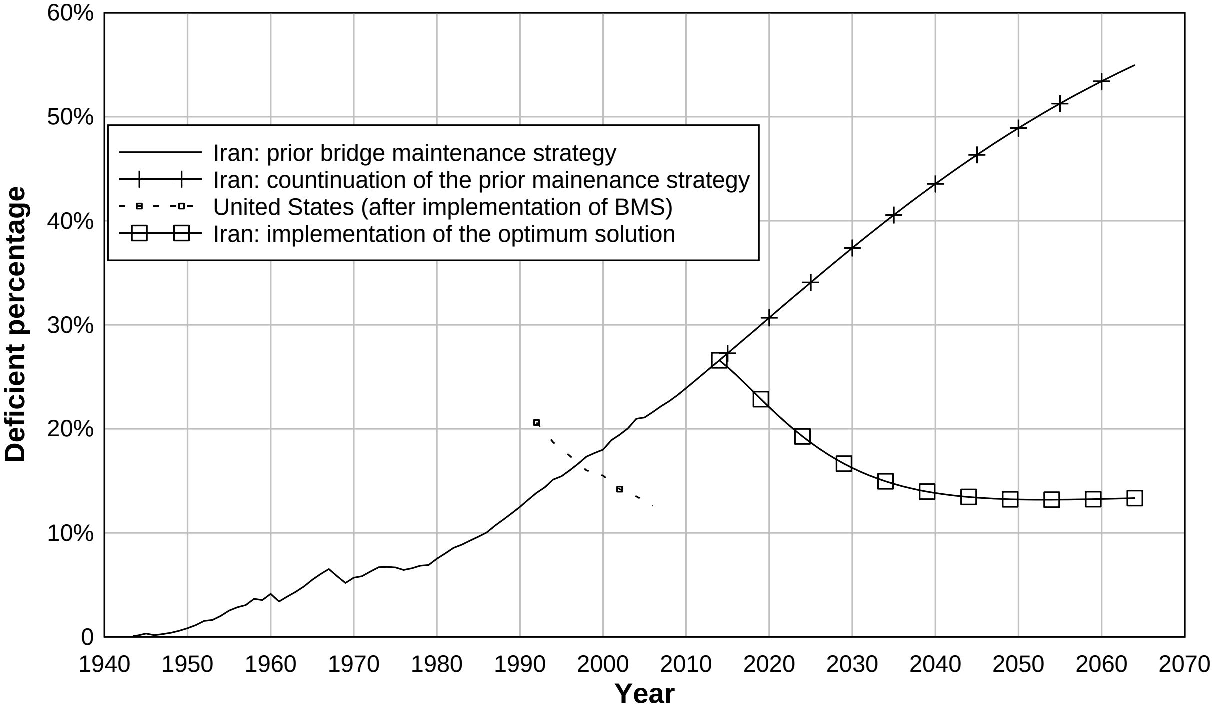


Fig. 9. Profiles of percentage of deficient bridges in Iran and United States.

CONCLUSIONS

INBS consists of about 330,000 bridges, of which 50% are older than 30 years. To efficiently manage this bridge stock under limited maintenance fund, Iran Road Maintenance & Transportation Organization (IRMTO) has started implementing a comprehensive Bridge Management System (BMS) since 2010. Because of insufficient maintenance during past years, the overall conditions of INBS are not acceptable at present, and an efficient maintenance strategy should be implemented to compensate the past poor performance. To find the best strategy for future, a simple methodology has been proposed in this paper. This methodology is based on Markovian process to model the bridge deck deterioration and a multi-objective optimization problem to find the best solution. The optimization process involves three decision variables with regard to maintenance strategy, and tries to minimize maintenance, failure and user costs. The constraints of the problem are identified as the percentage of deficient bridges, the percentage of bridges under MR&Rs and the average condition score.

Using the proposed model, the main findings of this research include: 1) the annual budget to implement the optimum solution for the bridge maintenance in Iran is IRR 1694 Milliards, 2) using the best maintenance strategy, 17%, 0% and 8% of the bridges respectively specified for minor, major and extensive repair should go annually under MR&Rs, 3) the current maintenance strategy should be improved, and at the same time the BMS should be completed sooner rather than later, and 4) national manuals and instructions for inspection, condition rating and maintenance should be prepared, published and mandated.

Finally, it should be noted that there is not still a complete database for strategic planning of maintenance activities in Iran, and the data used in this research is from the literature and the scarce data available in IRMTO. Therefore, the outputs of this research should be updated after the completion of Iran's BMS.

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