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RESEARCH PAPER

Development of a Bridge Maintenance System Using Bridge Information Modeling

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ABSTRACT: Bridges play a critical role in the transportation system network; accordingly, assuring satisfaction with the service level of these structures is vital for bridge maintenance managers. Thus, it is vital to determine the optimum bridge maintenance plan (i.e., the optimum timing and type of repair activities applied to the bridge elements) considering the budget limitations. To optimize the bridge maintenance plan, some researchers have focused on developing optimization models, including the Genetic Algorithm (GA). However, a few studies have employed Bridge Information Modeling (BrIM) to enhance bridge maintenance management. This study focuses on developing an integrated framework based on BrIM and bridge maintenance optimization to utilize visualization capabilities of BrIM to assist maintenance managers in making decisions. The presented framework optimizes the bridge maintenance plan at the sub-element level. The BrIM automatically feeds into the developed GA optimization system. The introduced framework is successfully verified using a real-world case study.

Keywords: Bridge Information Modeling (BrIM), Bridge Maintenance Plan, Genetic Algorithm (GA), Maintenance Optimization.

1. Introduction

Civil infrastructure systems have direct impacts on the sustained economic growth and social development of modern society. The highway transportation system is especially critical within the infrastructure system. Among the many elements of an infrastructure system, bridges are necessary economic and human connectors; their failure, or partial closure, may cause various public or private losses.

Few constructed facilities are genuinely maintenance-free. Most require regular maintenance and occasional repairs to keep them operable and in a good appearance (Nili et al., 2020). Bridges are no exception. Although some structures have a long

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period of usability, overwhelming loads exceeding bridge design and environmental conditions have caused many to perform below their intended function (Miyamoto and Motoshita, 2015). As reported in the literature, the application of effective repair activities is critical for a bridge to reach its expected service life (Chen and Duan, 2014). For instance, in Iran, the national bridge network comprises over 330,000 bridges, and more than 50% of them are more than 30 years old (Sahrapeyma and Hosseini, 2013). Heavy traffic and the absence of a proper bridge maintenance plan have deteriorated many of these bridges (Gholami et al., 2013).

Many researchers have endeavored to develop optimum bridge maintenance plans, including De Brito et al. (1997), Furuta et al. (2004), Hong and Hastak (2007), Elbehairy et al. (2009), and Kim et al. (2013). However, current practices in this area suffer the following limitations:

- Data entry in the developed systems does not enjoy a neat visual interface, even though data visualization facilitates decision making by maintenance managers.
- In current bridge maintenance practices, project life cycle data are scattered over different data sources, which produce a high probability of data loss from one project phase to another.
- Bridge maintenance planning is optimized at the element-level. In other words, all of the bridge elements with a common type are represented by a single element in the optimization process. For instance, in the optimization process, the optimum timing and type of repair activities for a deck element, which represents the full deck of the bridge, is found.

Building Information Modeling (BIM) is one of the most promising developments in the architecture, engineering, and construction (AEC) industries (Eastman et al., 2011). BIM improves upon planning, design, construction, operation, and maintenance processes using a standardized machine-readable information model for each facility. BIM contains appropriate information created or gathered about that facility in a format useable by all stakeholders throughout its life cycle (NIBS, 2008).

The need for BIM in maintenance management has been acknowledged by various researchers and practitioners (Becerik-Gerber et al., 2011). However, BIM is not yet effectively utilized in this phase (Ilter and Ergen, 2015). BIM in bridges, sometimes also called Bridge Information Modeling (Ghadiri Mohghaddam, 2014), is an active topic in bridge maintenance management. The BrIM is not only a geometrical representation of bridges but also an intelligent representation of bridges containing all relevant information throughout their life cycles (Marzouk and Hisham, 2011). BrIM can effectively facilitate the inspection and evaluation of bridges. It can also enable transportation agencies to manage bridge inventories more efficiently. In short, BrIM can lead to a more automated and integrated practice in the design, construction, and operation phases of a bridge life cycle (McGuire et al., 2016). However, developing a framework integrating BrIM and optimization models to enhance bridge maintenance management is neglected in the literature.

This paper utilizes BrIM as a powerful tool to gather data related to the whole life cycle. The obtained data is utilized in maintenance optimization. Moreover, the developed framework provides optimized repair and generates effective visualization of the results to aid bridge managers in decision making. Finally, the optimum bridge maintenance plan is found in the sub-element level. In other words, in the presented framework, instead of finding the optimum timing and type of repair activities for the deck, the deck is divided into some sub-elements. Then, the maintenance plan is optimized for each of the deck sub-elements.

The framework includes an Inspection Module, an Optimization Module, a Visualization Module, and a Maintenance Database. It also incorporates a graphical user interface to facilitate data entry and visualize optimized repair activities in the BrIM model.

2. Literature Review

To determine optimum repair activities for bridges, many researchers have utilized optimization algorithms. De Brito et al. (1997) used single-objective maintenance optimization in a bridge network, maximizing total expected benefits less expected repair and failure costs. They assumed that for each bridge, only one repair type would be implemented. Elbehairy et al. (2009) also proposed a single objective optimization bridge management system utilizing a year-by-year optimization formulation. Their developed system maximizes the benefit/cost of repair activities as well as the overall network condition. Farran and Zayed (2015) developed a multi-objective decision support system (MODSS), which handles two objective functions, including cost and performance, simultaneously, utilizing a normalization technique. Alikhani and Alvanchi (2019) presented a framework to find the optimum bridge maintenance plan at the bridge-level and network-level, which minimizes the ratio of repair costs to repair improvements.

In addition to single-objective optimization, some researchers have developed multi-objective optimization. For example, Frangopol and Liu (2007) optimized maintenance activities, both in an individual bridge and in a bridge network. They considered the objectives of minimizing the maximum condition index, maximizing the minimum safety index, and minimizing lifecycle cost. Kim et al. (2013) proposed a probabilistic framework for optimum inspection and maintenance planning for deteriorating structures, including bridges. The optimum inspection and maintenance types and times are obtained through an optimization, maximizing the expected service life and minimizing the expected total lifecycle cost. Mirzaei and Adey (2018) developed a framework to find the most sustainable bridge maintenance program in a bridge network. The developed model considered agency costs, user costs, and costs related to sound emission, air pollution, and climate change.

An important factor influencing the optimum bridge maintenance plan is bridge deterioration rates. The bridge deterioration is a complex process affected by many factors such as material aging, overload, and aggressive environmental conditions such as chloride contamination, corrosion, and shrinkage. Therefore, calculating the deterioration of elements based on its causes is a complicated task. Thus, the deterioration rate has been modeled in the literature via different statistical techniques, such as linear (Frangopol and Liu, 2007) and nonlinear (Miyamoto et al., 2000) deterioration, or by using the Markov chain (Morcous and Lounis, 2005). Some researchers have utilized a combination of the methods mentioned above (Elbehairy et al., 2009). In some studies, the deterioration model is specific to the deterioration mechanisms, such as chloride-induced corrosion (Frangopol and Soliman, 2016). From another perspective, the effect of repair activities on the elements' PI values is modeled differently in the literature. Some researchers have assumed that repair activities enhance the elements' PI values (Hong and Hastak, 2007), while others have considered a decrease in the deterioration rates (Farran and Zayed, 2015). Table 1 summarizes some of the conducted research in the field of bridge maintenance optimization.

In utilizing BIM to improve maintenance planning, some researchers have introduced BIM to FM practices, mostly focusing on visualization capabilities. Chen and Wang (2009) proposed a 3D visualized approach for the maintenance and management of facilities.

Table 1. Summary of some of the previous research efforts in bridge maintenance optimization

Reference	Optimization level	Deterioration modeling	Improvement effect
De Brito et al. 1997)	Network-level	Chloride corrosion formulation	Enhancing elements' PI values to the best
Furuta et al. (2004)	Bridge-level	Linear	Enhancing elements' PI values, delaying deterioration rates
Frangopol and Liu (2007)	Bridge-level, network-level	Markov	Enhancing elements' PI values, delaying deterioration rates
Hong and Hastak (2007)	Bridge-level	Linear	Enhancing elements' PI values
Elbehairy et al. (2009)	Bridge-level, network-level	Linear, Markov	Enhancing elements' PI values
Huang and Huang (2012)	Bridge-level	Linear	Enhancing elements' PI values
Kim et al. (2013)	Bridge-level	Time-dependent deterioration rates	The extension of bridge service life
Sahrapeyma and Hosseini (2013)	Network-level	Markov	Enhancing elements' PI values to the best
Farran and Zayed (2015)	Bridge-level	Markov	Different Markov deterioration rates are utilized
Alikhani and Alvanchi (2019)	Network-level	Markov	Enhancing the elements' PI values to the best
Mirzaei and Adey (2018)	Bridge-level	Markov	Enhancing elements' PI values to the best

A 3D facility model was provided in the system as the interface for accessing various maintenance-related data intuitively. The 3D model provided users an intuitive understanding of the state of the facility from different aspects. Liu and Issa (2012) focused on automatic bidirectional communications between Computerized Maintenance Management Systems (CMMS) and BIM models on a database level. Lin and Su (2013) proposed a BIM-based Facility Maintenance Management (BIMFMM) system, which helped maintenance staff access and review 3D BIM models to update related maintenance records digitally. Motamedi et al. (2014) utilized BIM visualization capabilities to provide FM technicians with visualizations to utilize their cognitive and perceptual reasoning for problem-solving. Marzouk and Abdelaty (2014) utilized BIM along with a global ranking system to monitor Indoor Environmental Quality (IEQ) in subway stations. In the proposed framework, a Wireless Sensor Network (WSN) is deployed in a subway station and connected to a BIM-based model. WSN readings and particulate matter concentration levels are visualized in the BIM-based model.

Further to FM, some researchers have utilized BIM capabilities for the bridge, which is called BrIM. Most of these studies address the visualization capabilities of BrIM. Hammad et al. (2006) discussed the requirements for developing a Mobile Model-Based Bridge Life-cycle Management System (MMBLMS). The system would link information about the life cycle stages of a bridge (e.g., design, construction, inspection, and maintenance) to a 4D model of the bridge and provide user interfaces that facilitate the use of the 4D models. Marzouk and Hisham (2011) presented a BrIM framework that visualized maintenance information relative to each bridge component. Ghadiri Mohghaddam (2014) proposed a framework to improve bridge maintenance information documentation, storage, and visualization. In their framework, inspection observations are added to the BrIM by the inspector directly interacting with the model at the inspection site.

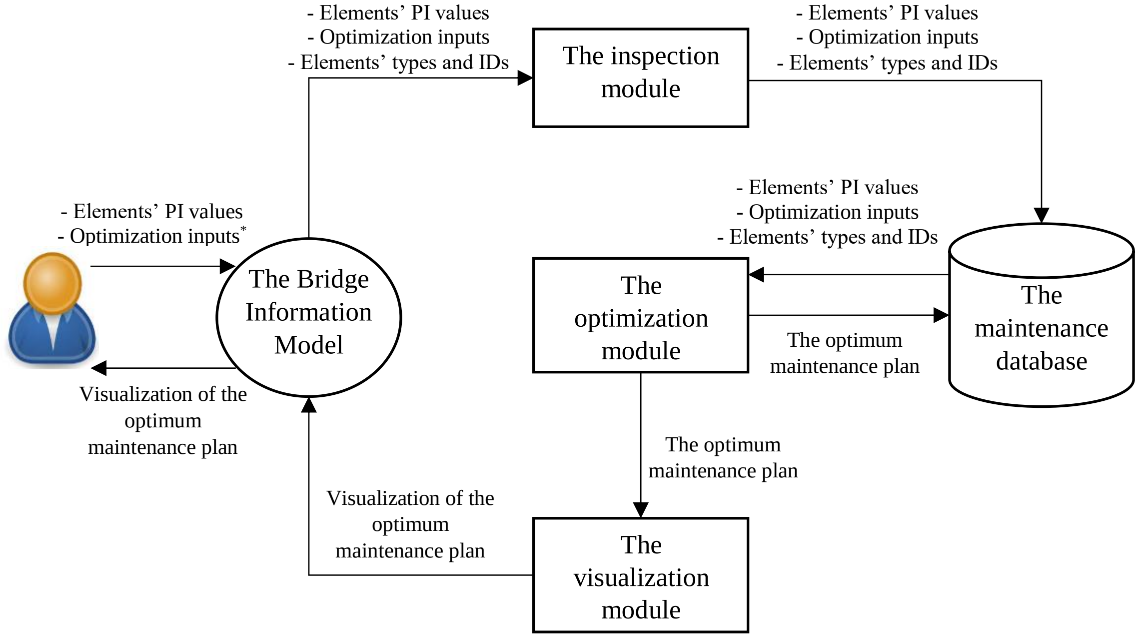
Few papers have explored other benefits of BrIM for bridge maintenance. McGuire et al. (2016) investigated the use of BrIM to link and analyze data related to the inspection, evaluation, and management of bridges. In the proposed method, information on damage type, amount, severity, and location were gathered during bridge inspection by an inspector using a custom software add-in. Next, a custom tool in Microsoft Excel evaluated the structural performance, provided load ratings of the inspected bridge, and offered maintenance recommendations for selected superstructure elements. Also, Chan et al. (2016) integrated BrIM and imaging techniques to detect defects such as cracking, corrosion, or settlement to create a consistent means of inspecting structures by processing images collected from the visual inspection and housed in the BrIM-asset management model.

To conclude, although the use of BrIM in the maintenance phase of bridges is increasing, integration of BrIM and optimization to enhance bridge maintenance planning has been neglected. In the following sections, a framework integrating BrIM and maintenance optimization is proposed and is applied to a real-world case study.

3. General Framework: Integrating BrIM with Maintenance Optimization

3.1. Overview

As discussed above, the integration of BrIM and bridge maintenance optimization should be implemented to economically maintain a bridge at desired performance levels while facilitating bridge maintenance management. Using Autodesk Navisworks Manage and Visual Studio software, the presented framework has been structured to integrate BrIM and bridge maintenance planning. The components of the proposed framework are a maintenance database, an inspection module, an optimization module, and a visualization module (Figure 1). The framework is coded in Visual Basic.NET (VB.NET) programming language utilizing an Application Programming Interface (API). API enables users to create add-ins to tailor and enhance a program-here, the BrIM software. In the following paragraphs, the components of the framework are discussed.



* Optimization inputs include: Elements' weights, available budget, maintenance planning horizon, inflation rate, deterioration rates, repair methods data, GA stop rules, generation length, and chromosome length

Fig. 1. The proposed framework

3.2. The Maintenance Database

The maintenance database acts as a repository in which data required for the proposed framework can be recorded and then retrieved when needed. The input data obtained by the inspection module, and the results of the framework, found by the optimization module, are recorded in the database (Figure 1).

3.3. The Inspection Module

The inspection module obtains the input data required for bridge maintenance planning from the user (Figure 1). For this purpose, this module prepares a graphical user interface by providing a VB form in the BrIM software environment (Figure 2). The provided form allows the user to enter the inspection data for each element in the BrIM environment. Additionally, the entered is saved in the maintenance database automatically through Object Linking and Embedding Database (OLEDB).

The inspection module obtains the bridge elements' types from the user. In this paper, similar to some previous studies in the literature (e.g., Yanev and Testa (1997) as depicted in Table 2), the proposed framework considers a particular weight for each element type. In the bridge maintenance optimization (which is conducted by the optimization module), elements with higher weights get a higher probability of repair. The assigned element type's weight depend on the impact of the element on the overall condition of the bridge.

Table 2. Element types and weights (based on Yanev and Testa, 1997)

Elements	Weight
Road	4
Deck	8
Barrier	1
Railing	1
Abutment	8
Pier	8
Joint	4
Sidewalk	2
Bearing	6

Another input data obtained from the user are elements Performance Index (PI) values. Various methods are utilized to evaluate condition rating in bridge inspection. For instance, the Bridge Condition Index (BCI) demonstrates the overall condition of a bridge, or the Bridge Criticality and Urgency (BCU) demonstrates the risk level of a bridge (Evans, 2018). For the evaluation and condition rating of bridge elements, suitable performance indices are needed to describe the performance of each element over time. One of the most applicable performance indices is a visual condition index. A common type of condition index is the component condition rating published by the National Bridge Inventory (NBI), which classifies the condition of an element on a 0-9 scale. A condition rating of 0, and a condition rating of 9, represent the failure and new status of the element, respectively. The weaknesses of the NBI rating is that it does not consider element condition rating, and it provides the rating only for primary elements such as the deck, superstructure, and substructure. The Michigan Department of Transportation has published a guideline providing NBI ratings within an element-level condition rating (Michigan Department of Transportation, 2016), in which each element condition rating is described qualitatively. A specific condition rating guide is presented for each element type. For illustration, the pier condition rating guide is shown in Table 3. In this study, the condition rating provided by Michigan Department of Transportation (2016) is applied as a performance index.

The maintenance planning horizon is another input parameter of the developed framework. However, various approaches have been adopted in the literature to consider the planning horizon. Some researchers have taken the bridge life as this period (Furuta et al., 2006; Kim et al., 2013). Chassiakos et al. (2005) and Elbehairy et al. (2009) have evaluated maintenance activities over a 10-year and 5-year period, respectively.

In the proposed framework, the optimum bridge maintenance plan is found for a short horizon (e.g., five years). This assumption is fully compatible with environments having high inflation rates. Also, in Iran, visual inspections are not reliable enough to be considered a basis for long-term maintenance planning. However, it should be noted that the proposed framework is flexible enough to be expanded for long-term maintenance planning.

3.4. The Optimization Module

The optimization module obtains the data required for the maintenance database (Figure 1), including the deterioration rates and the repair data. Moreover, the optimization module contains an optimization algorithm to find the optimum bridge maintenance plan. In the following, the main attributes of the optimization module are described in the following paragraphs.

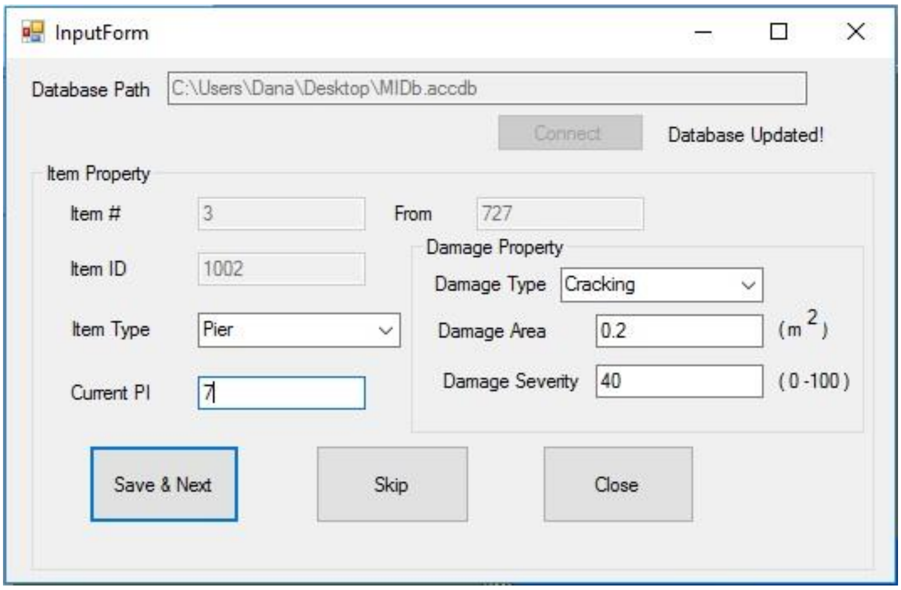


Fig. 2. Sample of Input Form

Table 3. Pier condition rating based on bridge safety inspection NBI rating guidelines

PI	Condition	Description
9	NEW	No deficiency exists in any of the structural components.
8	GOOD	All structural components are sound and functioning as designed. There may be superficial cracking or weathering of components.
7	GOOD	Insignificant cracks or moderate cracks that are sealed have occurred.
6	FAIR	Unsealed moderate-width or map cracks. Minor delamination, spalling, or efflorescence without build-up or rust staining.
5	FAIR	Moderate delamination, spalling, or efflorescence. Reinforcement exposure without section loss.
4	POOR	Considerable cracking, spalling, and efflorescence with massive build-up or rust staining exist.
3	SERIOUS	Considerable areas of spalling exposed reinforcement with section loss, or heavy rust staining.
2	CRITICAL	Deterioration has progressed to the point where the structure will not support design loads and posting emergency repairs.
1	IMMINENT FAILURE	The bridge is closed to traffic due to pier failure, but corrective action may put it back in service.
0	FAILURE	The bridge is closed due to its condition.

Because in Iran, no comprehensive bridge management system is defined and no deterioration rate is developed (Akbari and Maalek, 2017), in this study, a linear function has been employed to model the deterioration rate for each bridge element type. The relation between the current PI and future PI is shown in Eq. (1).

$$\Delta PI = PI_{at\ the\ end\ of\ period} - PI_{current} = a_{type} \times \Delta t \quad (1)$$

where $PI_{at\ the\ end\ of\ period}$: is the PI of the element after Δt period has been elapsed. $PI_{current}$: is the current PI of the element and a_{type}: is the deterioration rate.

The proposed framework assumes that each element is repaired at most one time in the planning horizon (e.g., five years). This assumption is fully compatible because, in most agencies responsible for bridge management, a maximum of one repair activity is applied to an element in a five-year horizon.

Six repair methods have been considered for each element to define repair methods. These have been adapted from Elbehairy et al. (2009) with small modifications, including: “Do nothing;” “Semi-light repair;” “Light repair;” “Medium repair;” “Heavy repair;” and “Replace.” Table 4 shows the defined repair methods for pier elements and their related costs and impact on element PI.

The cost of a repair method applied to an element is calculated as a proportion of the element construction cost. Thus, in the proposed framework, the indirect costs of repair activities, including traffic closure and mobilization costs, are not considered.

Finally, it should be noted that the framework is flexible in considering different input data in the optimization (e.g., other repair methods, repair costs, repair effects, weights, and deterioration rates).

3.5. Optimization Algorithm

The main question in a bridge maintenance optimization is to decide which elements are repaired each year of the planning horizon, and which repair methods are applied. However, a complete mathematical solution does not exist for such a Non-deterministic Polynomial-time Hard (NP-Hard) problem. Thus, a meta-heuristic algorithm is chosen to solve and to optimize the problem.

Recent related studies such as Miyamoto et al. (2000) and Elbehairy et al. (2009) utilized GA to find the optimum bridge maintenance plan. Besides, GA has shown high performance and excellent results in solving assignments and layout optimization problems. Therefore, GA is chosen for the optimization algorithm of this study.

GA performs occasional search techniques to reach optimal solutions based on natural selection, starting with an initial population. This initial population contains random genes used to encode a particular solution to a given problem. These individuals evolve to form a better population through reproduction. New individuals (offspring) are created by merging two individuals as parents using recombination (crossover). Then, some of the offspring are changed by using a mutation operator.

Table 4. The repair cost of the concrete pier (adapted from Elbehairy et al., 2009)

Repair type	Repair option	Cost	Improving PI
1	Do nothing	0%	0
2	Patch	5%	1
3	Cover repair	25%	2
4	RFT. replace	50%	3
5	Rehabilitation	75%	4
6	Replace	110%	5

Individuals are selected to form a new population-based on a tournament selection. Tournament selections sort individuals based on their fitness function and keep the population size constant by removing individuals with low fitness functions. In other words, taking n as the population size, all solutions with an index greater than n are removed after sorting. This procedure is repeated as needed to evolve the population toward the optimum solution. The iteration is stopped when the algorithm converges to an optimal solution with the required accuracy.

In this research, utilizing a single objective GA, repair activities for bridge elements have been taken as the genomes forming individuals. Scheduling and assigning repair activities to each element is conducted based on the current PI of the elements, repair types, repair costs, and available budget. In the proposed framework, the input data for the optimization process are the elements and their PI values. The optimization results are repair activities and the year in which the repair activity is applied to each element.

In the GA optimization in the framework, each chromosome is divided into two categories (Figure 3). In the first category, each genome represents the repair activity for the corresponding element. Since six types of repair activities are considered, each genome has an integer value from 0 to 5. In the second category, each genome shows the repair year of the corresponding element. Since the planning horizon contains five years, each genome has an integer value from 1 to 5.

The objective function for the optimization is adapted from (Elbehairy et al. 2009) with some small modifications, and it is formulated by Eq. (2) as below:

$$F = max\left(\frac{\sum_{i=1}^{n}\Delta PI_i \times (\frac{weight_i}{\sum weight})}{Total\ cost}\right) \tag{2}$$

where ΔPI_i: is the difference between PI of the element i at the end of the maintenance period and its current PI, considering deterioration (Eq. (1)) and repairs, $weight_i$: is the weight of element i. $\sum weight$: is the sum of the weights, $Total\ cost$: is the sum of the cost of the repair activities for all of the elements.

The optimization formulation includes the following constraints:

- The total planned cost should be lower than or equal to the total budget. The total budget is the sum of the available budget for each year based on the Net Present Value (NPV) concept.
- In each year of the planning horizon, the PI value of bridge elements should not be lower than a predefined value, because it would lead to the failure of the bridge or put it in a critical condition. Here, the predefined value is taken as 3.

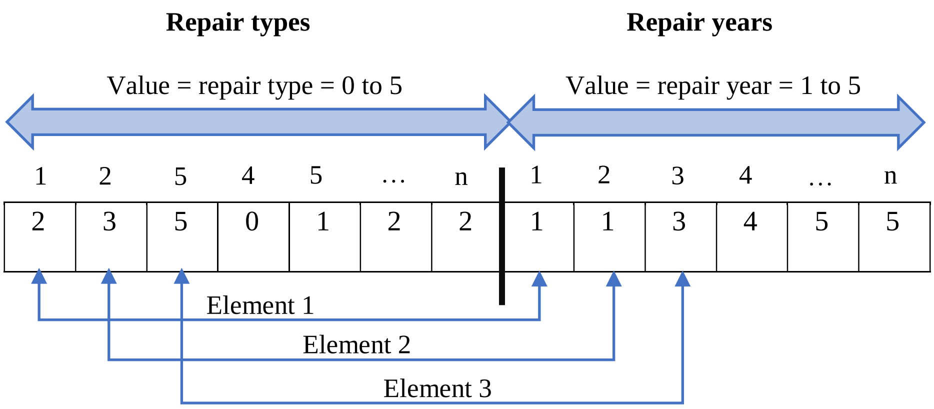


Fig. 3. The structure of the chromosome

A penalty method has been utilized in this study to prevent infeasible chromosomes in the constrained optimization problem. Penalty methods handle the problem to find feasible solutions, as the optimal solution usually happens between the feasible and infeasible regions.

3.6. The Visualization Module

After running the optimization module, the optimized repair activities are recorded in the maintenance database. Then, the PI values of elements are visualized to the user through color-coding in the BrIM environment. Also, the optimum repair method for each element is presented to the user (Figure 4). The prepared visualization tool helps bridge maintenance managers to identify the real condition of the bridge at a simple glance, which is especially beneficial for very long bridges with many elements.

4. Framework Verification

For the sake of validating the optimization module, the optimum repair activities of a hypothetical bridge are found using the provided optimization module and the Microsoft Excel Solver program. Identical inputs were used for both methods. The results obtained from the GA code and Microsoft Excel Solver program are displayed in Table 5, which includes the obtained fitness function and cost related to the optimum repair activities of the bridge. By observing the convergence in the optimization procedure of both of the optimization tools and the closeness of their final answers, it is concluded that the proposed GA code in the optimization module is valid.

5. Case Study

After validating the optimization tool, the framework is applied to a case study in the south-east of Iran. The case study bridge is a concrete bridge with a total length of 700. First, a general in-site visual inspection of the bridge was undertaken. The gathered inspection data for more than 570 identified bridge elements with an average PI value of 5 were recorded in the maintenance database using the inspection module.

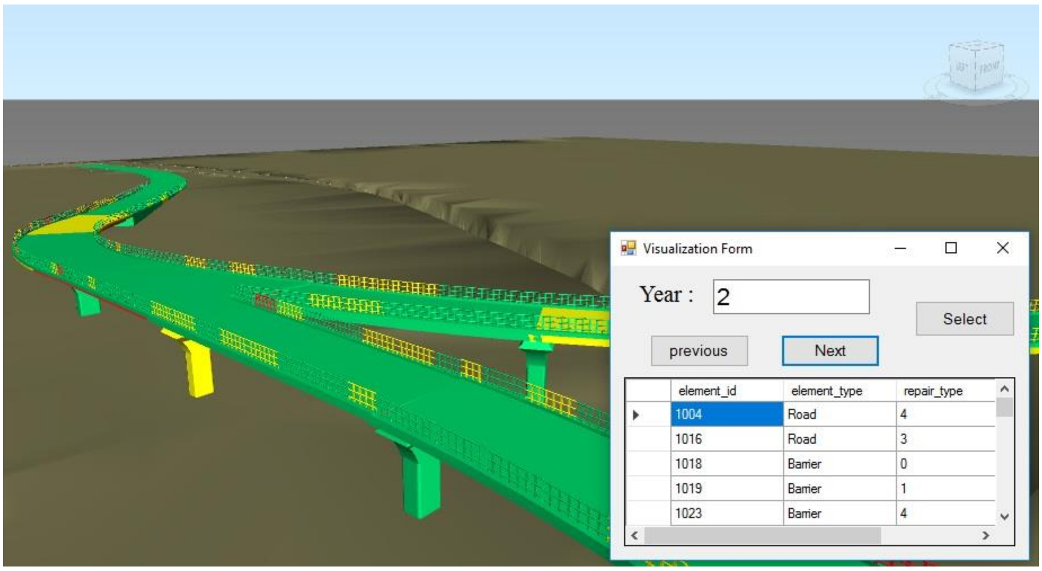


Fig. 4. Display of optimization results

Table 5. Optimization Results

Budget ($)	Optimization tool	Fitness-function	Cost ($)
20,000	API-Code	84	18,623
	Excel-Solver	77.91	19,558
22,500	API-Code	86	21,783
	Excel-Solver	82.87	22,283

Then the optimization module was run for an available yearly budget of $140,000. Maintenance period and an inflation rate are assumed to be a five-year and 20%, respectively. The total available budget was calculated based on the NPV concept, resulting in approximately $500,000 for this case. After running the optimization module, a convergence chart was obtained (see Figure 5a). After the 600th generation, the value of the fitness function converges to 3.47. Thus, the best chromosome of the 600th generation is taken as the optimum bridge maintenance plan.

In the optimization module, the user can apply the “What-if” analysis, e.g., to investigate the optimum bridge maintenance plan related to different available budgets. Figure 5b illustrates the change in the fitness function of the optimum chromosome versus NPV budget. With the increase in budget, the fitness function increases. However, increasing the NPV budget above a specified number (in this example, about $100,000) does not considerably change the fitness function of the optimum chromosome. Thus, the budget of 100,000$ is taken as the maximum required budget for bridge maintenance optimization. Finally, the PI values of bridge elements were visualized using Visualization Module. Figure 6 shows a sample report of repair methods for the case study.

Then, the optimum bridge maintenance plan is evaluated. It was observed that most of the repair activities encompass light repair. Although the average PI value of the elements was 6.8, the elements with higher weights are above the average PI. For example, the average PI of “deck” elements was 7.7, while the corresponding amount for “railing” elements was 6.7. In the end, the optimum repair activities were reported to the bridge maintenance manager, and their rationality was confirmed.

To show the merit of the proposed framework (called scenario #1), the obtained results are compared with a traditional framework (called scenario#2). In the traditional framework, sub-elements with the same type are represented by a single element (i.e., the optimum bridge maintenance plan is found in the element-level). According to Table 6, the optimum plan obtained by the first scenario results in a more excellent fitness function value than the second scenario (about 36%), which means that the current framework finds a more optimum maintenance plan than the traditional frameworks. Moreover, in the first scenario, the average of elements’ PI values does not change drastically compared to the second scenario.

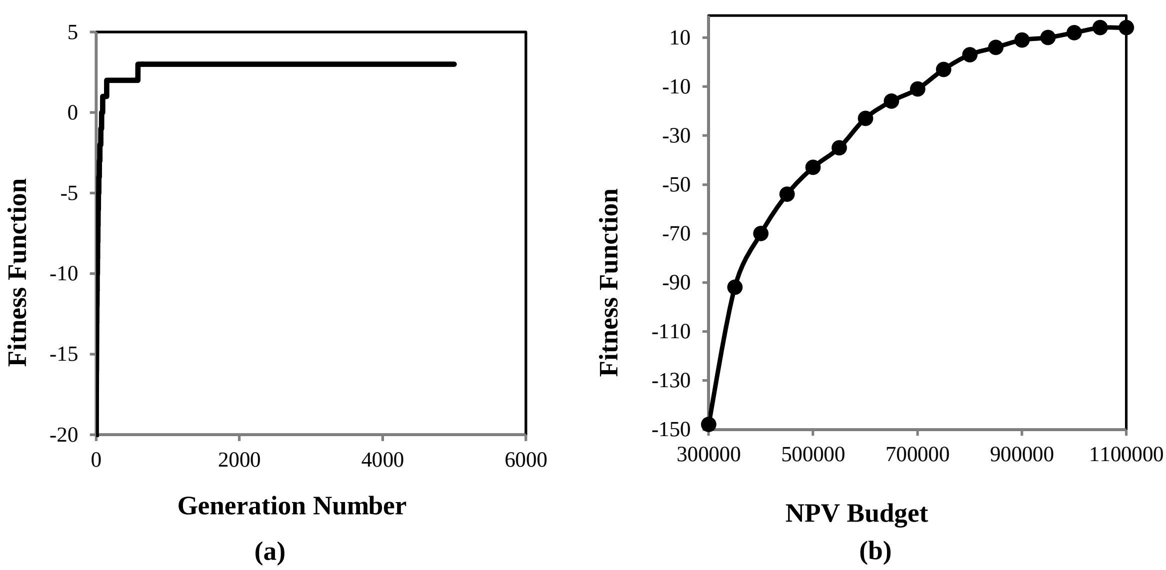


Fig. 5. The process of changing the fitness function: a) The fitness function convergence through generations; and b) Optimized Fitness Function versus different NPV budgets

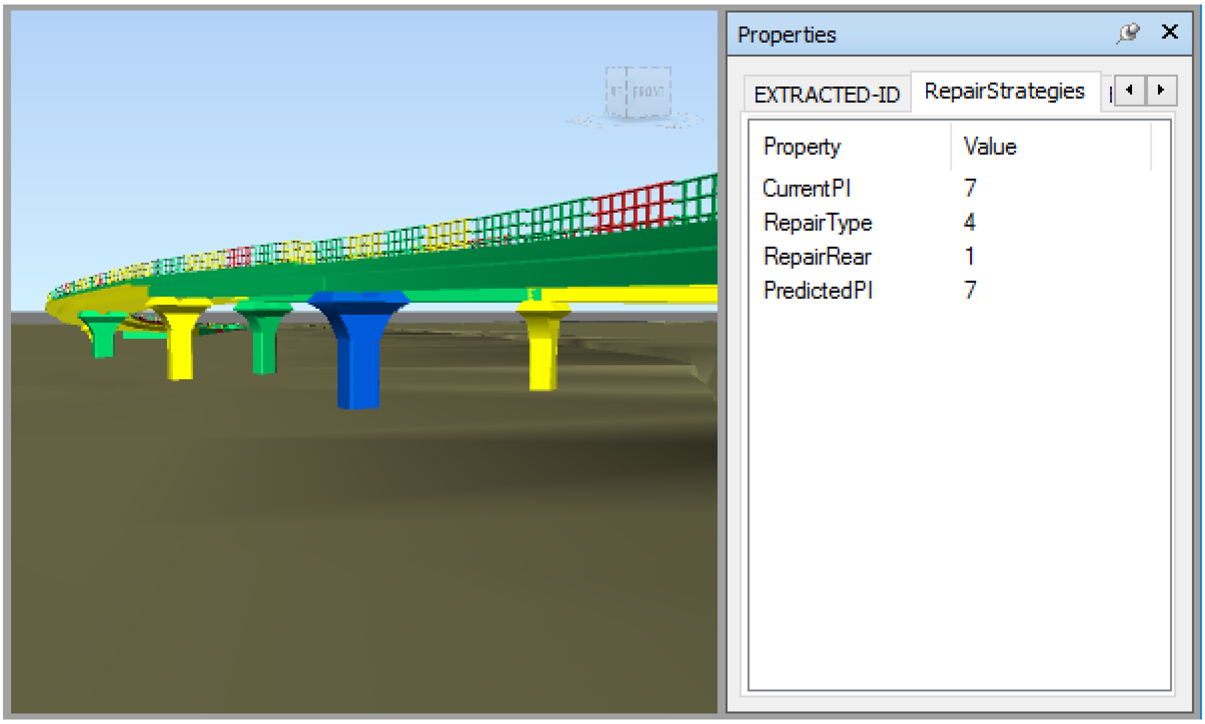


Fig. 6. Sample report of repair strategies

Table 6. Values of the bridge performance index

	Year						Fitness-function
	0	**1**	**2**	**3**	**4**	**5**	
Scenario 1	6.93	7.17	6.97	7	6.99	7.44	3.47
Scenario 2	6.73	6.73	6.23	5.73	5.23	7.76	2.54

6. Conclusions

This paper introduced a framework to enhance bridge maintenance management integrating optimization and BrIM. The proposed framework incorporated four main modules using the developed API: the maintenance database, the inspection module, the optimization module, and the visualization module. The inspection module prepared a graphical user interface, providing a VB form in the BrIM software environment that allows the user to enter the inspection data for each element, and copies the data into the maintenance database. In the optimization module, GA was applied to the information in the database to discover the optimum bridge maintenance plan. The algorithm in the optimization module considered the cost-benefit ratio as the single objective of the optimization.

After optimization, by applying the visualization module, the proposed framework visualized optimum repair activities in the BrIM model to facilitate decision making. Finally, to demonstrate the efficiency of optimization, GA results were compared with results obtained by a code based on the Excel Solver program. Also, to fully validate the proposed framework, it was applied to a real case in Iran. The obtained results were compared with the results obtained by traditional frameworks, and the capability of the developed framework in finding a more optimum bridge maintenance plan was demonstrated. The framework benefits from the use of BrIM in bridge maintenance management, and this result provides a basis for further development in this field.

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