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BrDSS: A decision support system for bridge maintenance planning employing bridge information modeling

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Abstract. Effective bridge maintenance reduces bridge operation costs and extends its service life. The possibility of storing bridge life-cycle data in a 3D parametric model of the bridge through Bridge Information Modeling (BrIM) provides new opportunities to enhance current practices of bridge maintenance management. This study develops a Decision Support System (DSS), namely BrDSS, which employs BrIM and an efficient optimization model for bridge maintenance planning. The BrIM model in BrDSS extracts basic data of elements required for the optimization process and visualizes the inspection data and the optimization results to the user to help in decision makings. In the optimization module of the DSS, the specifically formulated Genetic Algorithm (GA) eliminates the chances of producing infeasible solutions for faster convergence. The practicality of the presented DSS was explored by utilizing the DSS in the maintenance planning of a bridge under operation in the southwest of Iran.

Keywords: bridge maintenance management; maintenance optimization; Decision Support System (DSS); Genetic Algorithm (GA); Bridge Information Modeling (BrIM)

1. Introduction

Bridges deteriorate due to natural causes and increasing traffic volume (Chan *et al*. 2015, Huang *et al*. 2016, Zambon *et al*. 2018). The tragic collapses of bridges all over the world, from Silver Bridge in USA in 1967 to the I-35 W bridge in Minnesota in 2007 and Polcevera Bridge in Italy in 2018, have highlighted the importance of bridge maintenance planning (Darbani and Hammad 2007, Deng *et al*. 2015, Bazzucchi *et al*. 2018). Proper maintenance and repair are pre-requisite for a bridge to reach its planned service life (Chen and Duan 2014, Boller *et al*. 2015, Jung *et al*. 2019). Considering huge numbers of bridges and limited available budgets for maintenance of these complicated structures, bridge managers must monitor bridge element condition states continuously and prioritize maintenance activities properly, so that the required level of a bridge performance throughout its service can be ensured.

Various researchers have addressed applications of optimization tools for determining the optimal timing and the type of required repairs for bridge elements. Recent developments of 3D bridge models have provided new opportunities to visualize inspection data to the bridge managers (Adhikari *et al*. 2014). However, in current practice, the inputs of the maintenance optimization are obtained through database forms, and the obtained outputs are presented in the forms (Brenner *et al*. 2018). Moreover, manual data exchange among the bridge design and construction phases and the operation phase is challenging (Jeong *et al*. 2017).

Building Information Modeling (BIM) can be used to address some of the challenges mentioned above. BIM is one of the most promising developments in Architecture, Engineering and Construction (AEC) industries and has been introduced as a technology to improve efficiency in the project life cycle (Eastman *et al*. 2011, Akhoundan *et al*. 2018, Xue *et al*. 2018). Bridge Information Modeling (BrIM), defined as the application of BIM to bridges (Maier and Brinckerhoff 2012, Marzouk *et al*. 2014), is a digital representation of physical and functional characteristics of a bridge. BrIM can be used in various phases of the bridge life cycle, including design, construction, operation and maintenance, rehabilitation, and demolition (O'Keeffe 2014, Mawlana *et al*. 2015, Rashidi and Karan 2018). BrIM not only provides an extensive database that can contain all information about a bridge throughout its life cycle (Marzouk and Hisham 2011, Chipman *et al*. 2016, Costin *et al*. 2018) but also facilitates the data exchange between the bridge life cycle phases. Visualization capabilities through the Application Programming Interface (API) is the other advantage that BrIM offers to bridge maintenance practices.

The main objective of this study is to demonstrate the potential of BrIM in improving the efficiency of bridge maintenance planning. For this purpose, BrDSS, which is a Decision Support System (DSS) for bridge maintenance planning, is developed. In BrDSS, a customized Genetic Algorithm (GA) optimization model specially formulated for bridge maintenance optimization, namely BrGA, is linked to BrIM. BrIM feeds the optimization model with the

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necessary data, and along with the Graphical User Interface (GUI) of BrDSS, assists the user in evaluating the bridge inspection data and optimization results visually. BrGA employs a new method for generation and evaluation of new chromosomes that eliminates infeasible solutions, leading to a more efficient optimization process with less computational effort for achieving convergence.

2. Literature review

2.1 Bridge maintenance optimization

Bridge managers have developed tools to find the optimum bridge maintenance plan taking into account the concept of the Life Cycle Cost (LCC) (Park *et al.* 2008). Various optimization techniques, such as linear programming (Chassiakos *et al.* 2005) and dynamic programming (Seyed-Hosseini and Khoshkish 2003), have been used for bridge maintenance optimization. However, GA has been used more frequently due to its computational efficiency as well as its flexibility for solving non-linear optimization problems (Morcous and Lounis 2005, Frangopol and Liu 2007). For example, Elbehairy *et al*. (2009) developed an integrated multiple-element Bridge Management System (BMS) that determines efficient maintenance types for bridge elements through a single objective function maximizing improvement in bridge condition rating and minimizing repair costs simultaneously. Zhu and Liu (2011) introduced a method for optimizing bridge maintenance activities. Their proposed method utilizes a multi-objective GA that optimizes performance indicators, service life, and life-cycle maintenance costs, simultaneously (Zhu and Liu 2011). Huang and Huang (2012) introduced a new method called "concurrent element maintenance" to perform maintenance activities on bridge elements at the same time to minimize life-cycle costs. Finally, Farran and Zayed (2015) developed a multi-objective decision support system to optimize infrastructure maintenance planning. They utilized a single objective optimization handling cost and performance objective functions, simultaneously (Farran and Zayed 2015).

Optimization methods developed in most of the previous research efforts produce infeasible solutions, which significantly slows down the convergence of the optimization procedure. Also, in the aforementioned research efforts, all parts of a bridge element type are represented as a single element in the optimization process. For instance, for a 10-span bridge, only one overlay element is taken into account. However, each part of an element type (called an element in this study) may have a specific Condition Index (CI) value and need to be repaired sooner or later than other bridge elements with the common type. Moreover, although some of the data required for the optimization process (e.g., types and quantities of bridge elements) is inherent in the documents produced in the design and construction phases, this data must be re-entered for maintenance optimization due to the lack of data exchange among project life cycle phases. Furthermore, data entry and the format of presenting optimization results are mostly handled by tables and forms, which do not provide a visual understanding of the bridge elements for the user, resulting in the possibility of mistakes and misunderstandings. Visualization facilitates data interpretation and analysis and helps bridge managers acquire a better sense of priorities of maintenance activities (Kyle *et al*. 2002, Davila Delgado *et al*. 2016).

As a result, it is necessary to develop a bridge maintenance optimization tool that takes into account the CI values of various bridge elements and provides faster convergence by eliminating infeasible solutions. Moreover, such a tool should utilize data related to bridge elements generated throughout the bridge life cycle and visualize the inspection data and optimization results to the user to assist him/her with more accurate decision making. Presenting a bridge maintenance decision support system with these functionalities, namely BRDSS, is the primary goal of this study.

2.2 Bridge information modeling (BrIM)

A few methods have been developed to consider different aspects of the application of BrIM in bridge management. In a pioneering work, Hammad *et al*. (2006) developed a prototype of a mobile model-based bridge life-cycle management system. Developed by Java language, their prototype system records inspection information in a bridge 3D model, and a rule-based expert system supports decision making (Hammad *et al*. 2006).

Some researchers in recent years have utilized BrIM to enhance bridge inspection along with structural analysis. Marzouk and Hisham (2011) presented a BrIM framework to integrate BrIM with BMS modules by connecting a 3D bridge information model, inspection sheets, and structural condition assessment modules. McGuire *et al*. (2016) used BrIM to link and analyze the data related to the inspection, evaluation, and management of bridges. They designed a Damage Location Tool (DLT) to generate element-level bridge inspection forms that capture information on damage type, amount, severity, and location. Further, they designed a Damage Evaluation Tool (DET) to evaluate structural performance and provide load ratings of the inspected bridge (McGuire *et al*. 2016). Sacks *et al*. (2018) proposed an integrated bridge inspection system that produces semantically rich BIM models for inspected bridges. The method utilizes remote sensing technologies to capture the state of the bridge in the format of point cloud and to generate the BrIM automatically (Sacks *et al*. 2018).

BrIM has also been used as a database to house the bridge data collected through its life cycle phases. Davila Delgado *et al*. (2016) proposed an approach to visualize structural health monitoring data in a BrIM. Chan *et al*. (2016) employed advanced imaging techniques to process the images collected from visual inspections of bridges to detect the structural damages. In their presented framework, image processing results, as well as condition ratings of bridge elements, photos, and design drawings, are represented in the BrIM (Chan *et al*. 2016). Shim *et al*. (2017) developed a data schema for a maintenance information management system to store bridge life cycle data in the BrIM model. To visualize bridge defects, Hüthwohl *et al*. (2018) presented a method to convert bridge defect information into BrIM. Xu and Turkan (2019) developed a technique to identify bridge defects using image processing techniques automatically and to assign them to the bridge elements in BrIM. Adibfar and Costin (2019) integrated Intelligent Transportation System (ITS) data and BrIM to utilize the traffic data in the assessment of bridge deterioration.

Reviewing literature shows the potential of BrIM to improve bridge inspection and structural analysis and to integrate different sources of data. However, none of the aforementioned research efforts utilized the capabilities of BrIM in bridge maintenance optimization. This study uses BrIM to provide BrDSS with bridge elements data required as the maintenance optimization inputs as well as visualizing inspection data and optimization results to the user for better decision making.

3. Methodology

The methodology consists of the following modules and tools:

a. Database

i. Direct import of bridge elements' basic data through BrIM, which includes bridge elements' IDs, types and quantities

ii. Direct import of inspection data by the user, which includes bridge elements' defect types, severities, amounts, photos, and CI values.

iii. Direct import of optimization inputs by the user, which includes repair-types, costs, improvements and durations, and elements' deterioration rates along with BrGA settings.

iv. Optimization results obtained from BrGA and exported to be visualized by BrIM, which includes the optimum maintenance plan (i.e., the optimum timing and type of repairs)

b. Model base: BrGA

c. GUI: BrIM

Fig. 1 shows BrDSS structure and its interaction with BrIM. BrDSS is developed using Visual Basic.Net (VB.Net). Data exchange between the user, BrIM, and BrDSS is provided using API. API enables users to develop new BrIM applications by creating new features and capabilities (Marzouk and Hisham 2011). The BrIM software here is Autodesk Navisworks manage, which is selected due to its high interpretability capabilities. All of

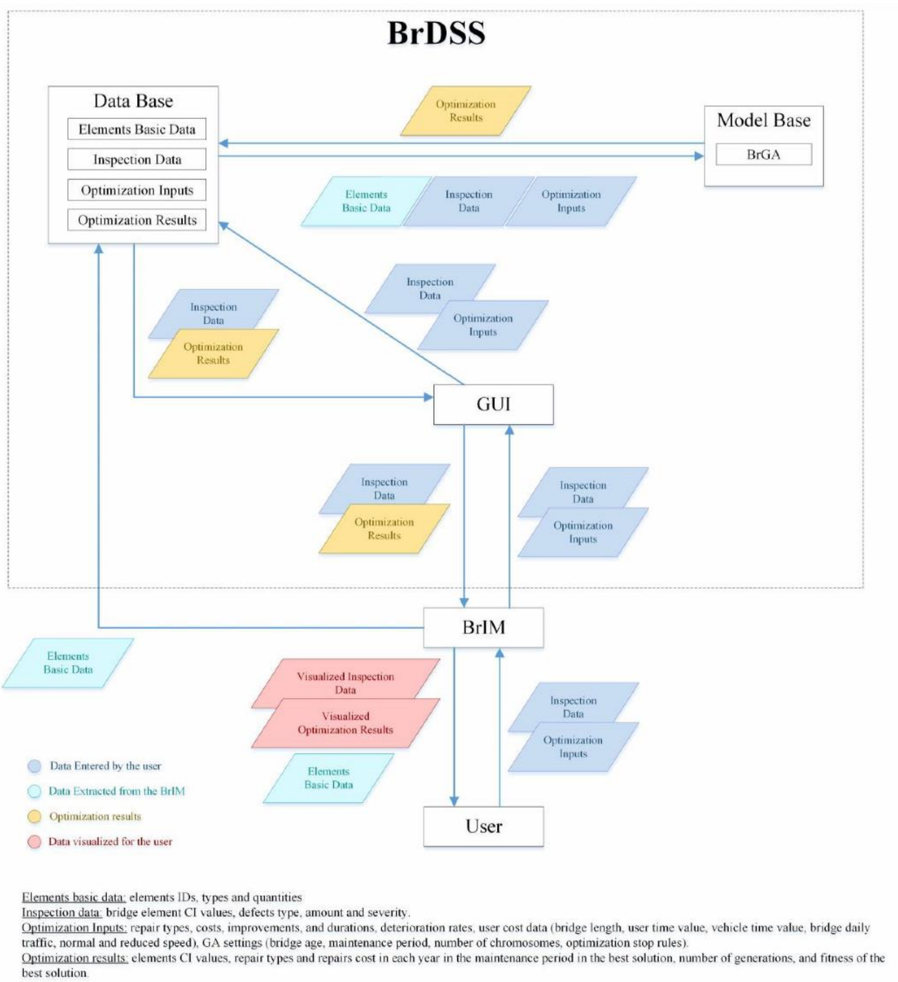
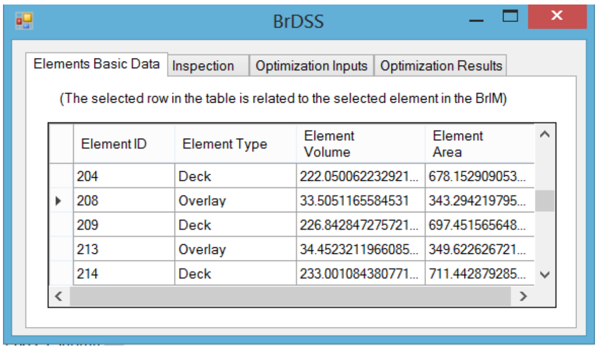
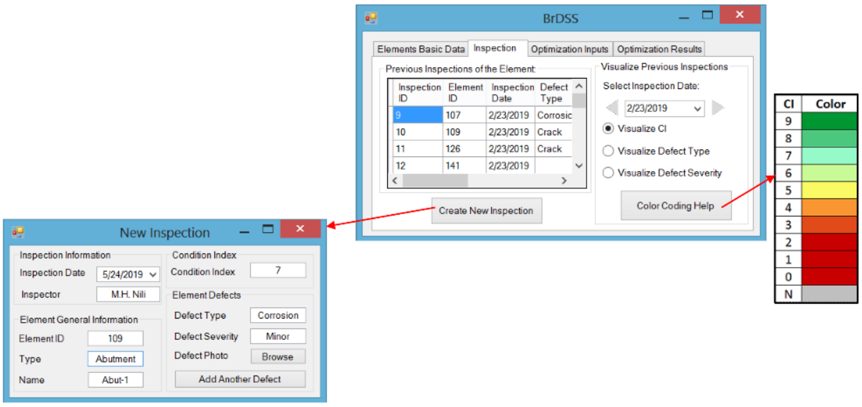


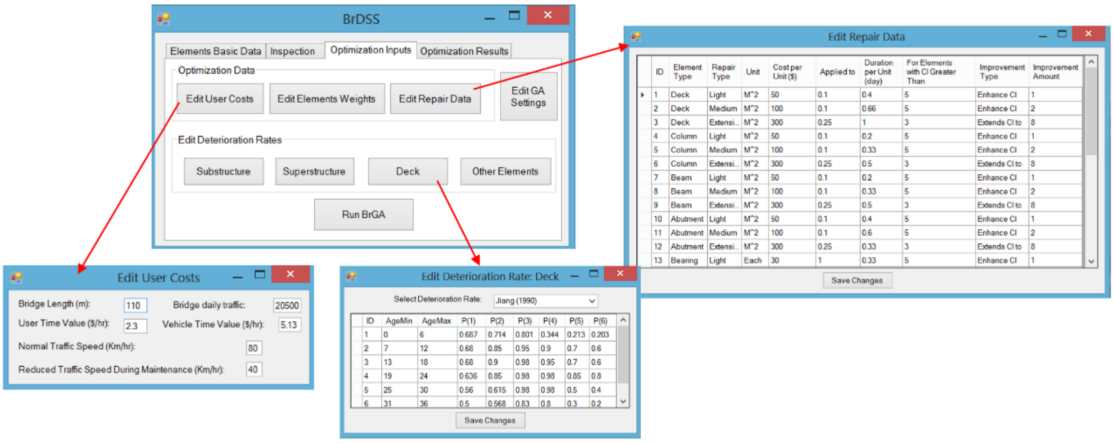
Fig. 1 BrDSS structure and its interaction with BrIM



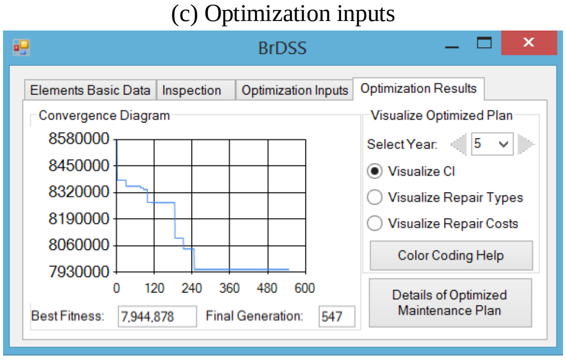
(a) Elements basic data



(b) Inspection data



(c) Optimization inputs



(d) Optimization results

Fig. 2 BrDSS GUI

the data collected from the user and those managed by BrIM, as well as optimization inputs and results, are stored in the database and can be retrieved by the user and visualized in the BrIM if needed.

Table 1 Repair-methods for different bridge elements' types

Element type	Repair type	Repair-method	Unit	Local cost per unit	Repair duration per unit (day)	% of the element the repair is applied to	Available for elements with	CI improvement
Deck, column, girder, beam and abutment walls	Light repair	Surface repair: Applying mortar on the surface of the concrete	M^2	\$100	0.05	10%	CI $\geq$ 5	CI = CI + 1
	Medium repair	In-depth repair: Removing deteriorated concrete and applying mortar	M^2	\$200	0.1	10%	CI $\geq$ 5	CI = CI + 2
	Extensive repair	Epoxy injection: Removing deteriorated concrete, epoxy injection, applying mortar	M^2	\$600	0.2	25%	CI $\geq$ 3	Extends CI to 8
Bearing	Light repair	Lubricate bearing	each	\$60	0.05	100%	CI $\geq$ 5	CI = CI + 1
	Medium repair	Replace bearing	each	\$200	0.1	100%	CI $\geq$ 5	Extends CI to 8
	Extensive repair	Replace bearing and pedestal	each	\$300	0.2	100%	CI $\geq$ 3	Extends CI to 9
Bituminous overlay	Light repair	Asphalt spray	M^2	\$100	0.01	10%	CI $\geq$ 5	CI = CI + 2
	Medium repair	Sealing	M^2	\$140	0.01	25%	CI $\geq$ 5	Extends CI to 8
	Extensive repair	Replace overlay	M^2	\$200	0.01	100%	CI $\geq$ 3	Extends CI to 9
Expansion joints	Light repair	Remove debris	M	\$40	0.05	100%	CI $\geq$ 5	CI = CI + 1
	Medium repair	Repair expansion joint	M	\$500	0.1	25%	CI $\geq$ 5	Extends CI to 8
	Extensive repair	Replace expansion joint and adjacent concrete	M	\$1000	0.2	100%	CI $\geq$ 3	Extends CI to 9
Railing	Light repair	Repair damaged section of parapet mounted metal rail	M	\$60	0.01	10%	CI $\geq$ 5	CI = CI + 2
	Medium repair	Repair damaged section of parapet mounted metal rail and adjacent concrete	M	\$100	0.01	25%	CI $\geq$ 5	Extends CI to 8
	Extensive repair	Replace damaged section of parapet mounted metal rail and adjacent concrete	M	\$200	0.02	100%	CI $\geq$ 3	Extends CI to 9
Drainage system	Light repair	Remove debris in front of deck drains	each	\$20	0.05	100%	CI $\geq$ 5	CI = CI + 1
	Medium repair	Repair bridge deck cross slope and profile	each	\$100	0.1	100%	CI $\geq$ 5	Extends CI to 8
	Extensive repair	Replace the drainage system	each	\$200	0.2	25%	CI $\geq$ 3	Extends CI to 9

The bridge elements' basic data (e.g., bridge elements' IDs, types and quantities), covers the data created in the bridge design and construction phases. Among this data, the bridge elements' quantities (containing side surface and volume for each element) are required to assess repair costs and durations. In BrDSS, if the elements' quantities have been stored in the BrIM model, the quantities are extracted from the BrIM software directly through the "properties tab" in Navisworks software. Otherwise, the quantities are estimated utilizing the bounding boxes of the elements. A bounding box is a 3D rectangular box that surrounds a BIM element and can be called through the Navisworks API (Han 2017). Although a bounding box indicates rough dimensions of an element, BRDSS considers the element type to increase the accuracy of quantities estimation. For instance, BRDSS estimates the value of the side surface of railings, as shown in Eqs. (1)-(3)

$$Element\ height = Z_{max} - Z_{min} \quad (1)$$

$$Element\ length = \sqrt{(X_{max} - X_{min})^2 + (Y_{max} - Y_{min})^2} \quad (2)$$

$$Element\ surface = Element\ height \times Element\ length \quad (3)$$

where X_{max}, Y_{max} and Z_{max} are maximum values of X, Y, and Z in the element bounding box and X_{min}, Y_{min} and Z_{min} are minimum values of X, Y and Z in the element bounding box.

The GUI in BrDSS facilitates data transfer between the user and the database through BrIM software (Fig. 2). The GUI shows the elements' basic data extracted from the BrIM to the user (Fig. 2(a)). Moreover, it depicts the results of the previous inspections of the bridge elements (including types, severities and the amounts of the defects and the CI values of the elements) to the user visually through the BrIM model of the bridge. BrDSS also assists bridge inspectors in entering the data related to a new conducted inspection to the database visually, hence the probability of making mistakes in data entry is reduced (Fig. 2(b)). Furthermore, the GUI provides the user with the ability to enter and edit optimization inputs (Fig. 2(c)). Finally, it demonstrates the optimization convergence diagram and represents the optimization plan to the user visually (Fig. 2(d)). It should be noted that among the inspection data obtained from the user, only the bridge elements CI values are taken into account in the optimization algorithm, and the other data is utilized for visualization purposes. Visualizing the inspection data (by the color-coding feature in this study) assists in recognizing critical trends in bridge elements condition over time quickly.

3.1 BrGA model

The BrGA algorithm developed in this study finds the best maintenance plan given the CI values of various bridge elements, expected deterioration rates, repair costs, Driver Delay Costs (DDC), Vehicle Operating Costs (VOC) and the available budget (Fig. 3). In this research study, the definition by the Michigan Department of Transportation (MDOT 2016) for CI rating between 0 (failed condition) to 9 (excellent condition) was used.

The primary decision variables in BrGA are "repair years" (years in which repairs are performed on the elements) and "repair-types" of the elements in the repair years. Repair-types are selected among four categories of "no repair," "light repair," "medium repair" and "extensive repair" for each element in the specified maintenance period. The application of a specific repair-type to a particular element type is called a repair-method in this study. For instance, the "deck light repair method" is the application of the "light repair-type" to the deck element type. Moreover, the application of a repair-method to a specific element is called a "repair-activity" in this study. The single objective optimization model is formulated to minimize the ratio of the sum of the user costs and repair costs to the weighted average of CI values of the bridge elements throughout the maintenance planning horizon.

Taking into account the relative importance of the element types, BrGA formulation is as follows:

Objective:

$$F = Minimize\ \left(\frac{\sum_{i=1}^{n}\sum_{j=1}^{m} RC_{ij} + \sum_{j=1}^{m} UC_j}{\frac{\sum_{i=1}^{n}\sum_{j=1}^{m} CI_{ij} \times W_i}{\sum_{i=1}^{n} W_i}}\right) \quad (4)$$

Subject to:

$$UC_j = DDC_j + VDC_j \quad (5)$$

$$DDC_j = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times ADT \times N_j \times w \quad (6)$$

$$VDC_j = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times ADT \times N_j \times r \quad (7)$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} RC_{ij} \leq B_j \quad (8)$$

$$CI_{ij} \geq 3 \quad \forall i, j \quad (9)$$

$$RC_{ij} = f(R_{ij}) \quad (10)$$

$$R_{ij} = g(CI_{ij}) \quad (11)$$

where: F, the fitness function of the chromosome; RC_{ij}, repair cost of element i in year j; UC_j: user cost in year j; CI_{ij}: CI value of the element i in year j; W_i: weight of element i; N: number of the bridge elements; M: maintenance planning horizon; DDC_j: driver delay costs in year j; L: length of the bridge; S_a: the reduced traffic speed during the repair intervention; S_n: normal traffic speed; ADT: average daily traffic; N_j: the duration of the repair intervention in year j, which is the maximum duration of repair-activities in year j; w: hourly value of the drivers time; VOC_j**:** vehicle operating costs in year j; r: hourly cost of a vehicle; B_j: available budget for year j; R_{ij}: selected repair-type for element i in year j.

To consider the user costs in the optimization process, *DDC* and *VDC* are calculated using the Eqs. (6)-(7) provided by Ehlen (2003). The duration of repair intervention in year j (i.e., N_j) is determined based on the assumption that repair-activities on the elements in year j are applied at the same time. The duration of a repair-activity applied to an element is calculated based on the element quantity, the percentage of the element that the repair-activity is applied to, and the duration of the repair-activity per unit of the element.

Eq. (8) ensures that in each year, the overall elements' repair costs are lower than or equal to the available budget for that year. Based on Eq. (9), the elements' CI value should be greater than 3. If the CI value of an element is dropped to 3 or less (i.e., it requires a very urgent repair), that element gets the highest priority for receiving repair. Eq. (10) shows that repairs cost of each element is a function of repair-type selected for that element and Eq. (11) shows that available repair-types for each element depend on the CI value of that element. For instance, for deck elements, the light repair is applicable only if the CI is equal to or greater than 5.

The BrGA model input data includes the followings:

• repair data
• deterioration rates
• cost data imported by the user
• GA model settings
• elements' weights

Table 1 depicts the durations and the local costs of the repair-methods per unit. Each repair-method improves CI to a certain level. The data displayed in Table 1 were gathered

Table 2 Deterioration rate of bridge elements

Bridge element	Annual deterioration rate
Deck	0.05
Column	0.05
Beam	0.05
Abutment	0.05
Bearing	0.1
Overlay	0.1
Expansion joint	0.1
Railing	0.1
Drainage system	0.06

Table 3 Elements' weights

Element type	Weight
Deck	7
Column	8
Girder and beam	8
Abutment	7
Bearing	7
Bituminous overlay	5
Expansion joints	5
Railing	3
Drainage system	3

through studying some bridge repair projects and interviews with some bridge managers in Iran, while the user can also modify them. It should be noted that the costs are calculated based on the current currency in Iran (Rial) and then converted from Iran Rial to US dollar according to the exchange rate of 4200 (Rial per Dollar) reported by Central Bank of the Islamic Republic of Iran in September 2019.

Since local deterioration rates have not been developed for Iran yet (Alikhani and Alvanchi 2017), evaluating deterioration history of about 300 bridges in Iran, the writers developed linear deterioration rates for this study based on the average life span of bridge elements (Table 2). The developed deterioration rates can be modified by BrDSS user, as well as the bridge elements' weights shown in Table 3.

In the GA optimization models, the chromosome structure has a significant impact on the optimization convergence speed. Due to the constraints of BrGA, if the repair-type is utilized directly in the chromosome structure as the decision variable, the optimization procedure develops many infeasible solutions resulting in a too slow convergence rate. To avoid this issue, BrGA represents the repair-type for each element in each repair year by two random variables; Priority Index (PI) and Repair Index (RI).

The RI index indicates the selected type of repair among the available repair-types for the element. For example, Table 4 depicts the RI for a deck element with CIs equal to 4 and 6. PI and RI are assigned to each bridge element in each repair year by a function called "Create Chromosome"

Table 4 Selection of repair-type for a deck element

CI = 4		CI = 6	
Condition	Repair-type	Condition	Repair-type
RI < 0.5	0	0.5 ≤ RI < 0.67	1
0.5 ≤ RI < 1	3	0.5 ≤ RI < 0.83	2
		0.83 ≤ RI < 1	3

(Fig. 3). Repair-types are assigned to each bridge element in each repair year by a function called "Analyze Chromosome," based on the values of the element PI and RI (Fig. 3).

The PI index indicates the priority of the element to be repaired. In a repair year, elements are prioritized to be repaired based on their PI values (part 1-2 of Fig. 3) as the following:

• At first, the element with the highest PI is repaired.

• If there is any available budget, the element with the next highest PI is repaired.

• The procedure continues until the available budget finishes, or all of the elements are repaired.

Fig. 4 shows the proposed structure of the chromosome for a case in which there are *k* repair years in the maintenance period, and the bridge contains three elements. In the first repair year in the maintenance planning horizon, because of its highest PI, first "element 2" is selected to be repaired. Assuming "element 2" is deck type with CI = 6, repair 1 (light repair) is selected for "element 2". The repair cost and available budget is recalculated. If there is any available budget, "element 3" will be repaired. Then, if there is still any available budget, "element 1" will be repaired. This procedure continues for all of *k* repair years so on.

By the proposed chromosome structure, the budget constraint is satisfied. However, it is still possible that a chromosome does not satisfy the CI constraint (Eq. (2)) because it is possible that in a year in the maintenance planning horizon, the CI of a bridge element drops below 3 and no repair-work is conducted on the element in that year. To overcome this problem, a function called "improve chromosome" is applied to the chromosomes (Fig. 3). This function tries to repair elements with CI < 4 in the nearest repair year before the year in which CI gets lower than 4, by increasing PI value of the element in the nearest repair year. If there is no available budget in the nearest year, or the period between the two repair years is equal or greater than four years, "improve chromosome" adds the year that the element CI gets lower than 4 to the repair years. After applying "improve chromosome" to the chromosome, "analyze chromosome" is used again to assign repair-types to the chromosome. This cycle is repeated until a feasible chromosome is obtained. Functions "analyze chromosome" and "improve chromosome" are applied to the chromosomes obtained from the crossover and the mutation operators, too, to ensure the production of feasible chromosomes by the GA operators (Fig. 3).

The optimization algorithm stops if it reaches the maximum number of generations, or no improvement occurs in the fitness function after a particular number of

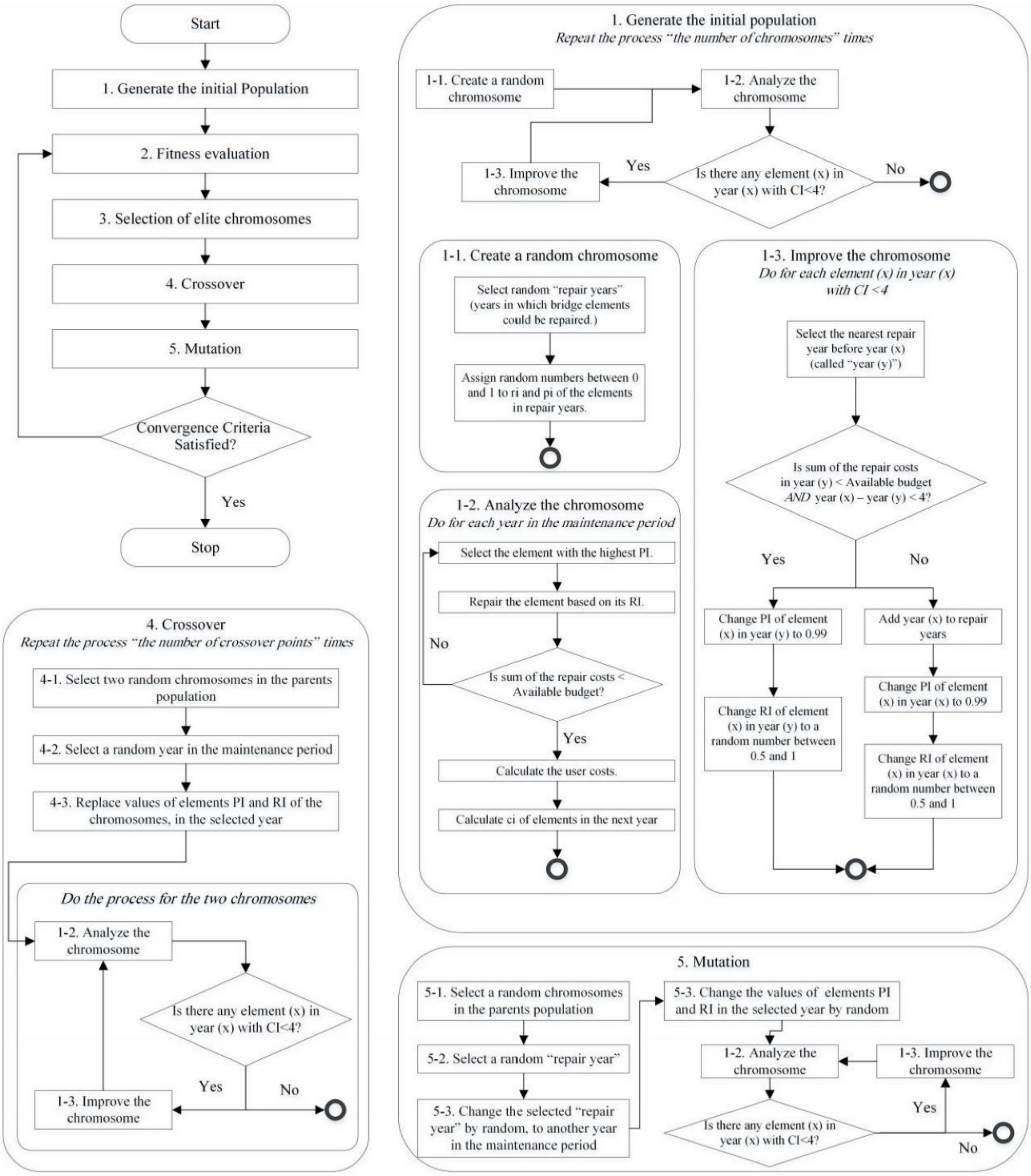


Fig. 3 BrGA algorithm

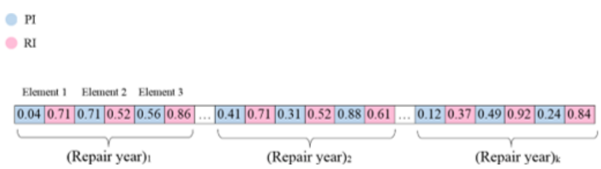


Fig. 4 Structure of the chromosome in BrGA in an example

generations. After the optimized maintenance plan is obtained, the optimized solution is recorded in the database. Also, the user can consider the solution visually by the optimization tool. Elements' CI values, repair-types, and repair costs are visually presented to the user by BrDSS through the maintenance planning horizon.

4. Case study

To demonstrate the applicability of BrDSS to enhance bridge maintenance optimization, this section presents the results of the application of BrDSS in a real case study, located in the southwest of Iran. The concrete case study bridge is under operation since 2014 with the 470 meters length and the box-girder structural system. The BrIM model of the bridge was developed during the construction phase, with Level of Detail (LOD) of 200 to 300, and was first created in Autodesk Civil3D and Autodesk Revit and then exported to Navisworks Manage.

Each part of the deck, pier, overlay, and railing located in a span is considered as an element. Thus, the bridge

Table 5 The GA settings

Bridge age	Five years
Maintenance period	30 years
Available budget in each year	$510,000
Population size	17,400
Mutation rate	5%
Crossover rate	40%
Stop rule 1: Maximum number of generations	5,000
Stop rule 2: Stop GA if the fitness value does not change over generations	300

Table 6 User cost data

Bridge daily traffic	20,000 vehicle
Driver time value	16.6 $/hr
Vehicle time value	12.26 $/hr
Normal traffic speed	80 km/hr
Traffic speed during bridge repair intervention	40 km/hr

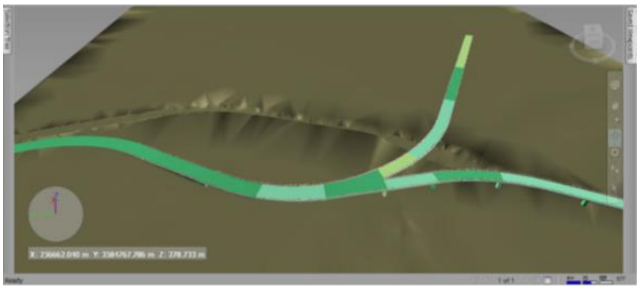


Fig. 5 Visualization of the elements' CI values in year 10 of the maintenance planning horizon in the BrIM

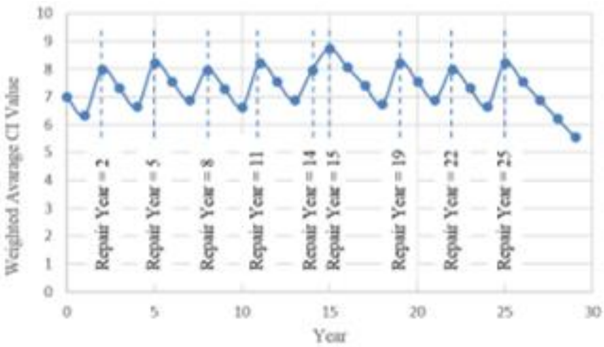


Fig. 6 The weighted average of the elements' CI values and the repair years in the maintenance planning horizon

contains 58 elements, including 12 columns, 13 decks, 14 ailings, 16 overlays and three abutments. Bearings and expansion joints are not modeled in this study.

Previous conducted inspections data, including the bridge elements' CI values in the NBI 0-9 scale and the defects' types, amount, severities, and photos, were

Table 7 The repair costs and user costs in the repair years

Repair year	Repair cost ($)	User cost ($)
2	508,760	75,400
5	508,760	75,400
8	417,290	43,650
11	508,760	75,400
14	417,290	43,650
15	190,370	43,650
19	508,760	75,400
22	417,290	43,650
25	508,760	75,400
Sum ($)	3,986,040	551,600

recorded in the database. The maintenance period was assumed to be 30 years. Thus, the size of the solution space of the case study is $4^{58\times30}$ considering four repair-types available for each of the 58 bridge elements in each year in the planning horizon. Thus, it would not be possible to evaluate all possible solutions and using an optimization model is necessary. The GA settings and user costs parameters are shown in Tables 5-6, respectively. BrDSS visualized the optimized maintenance plan data, including elements' CI values, repair-types, and repair costs through the maintenance planning horizon for the bridge maintenance managers. For instance, Fig. 5 depicts bridge elements' CI values in year 10 of the maintenance planning period, based on the optimized maintenance plan.

5. Results and discussion

The optimization model in BrDSS converged after 422 generations for the case study bridge. The developed model took about 22.25 hours to run entirely, while it took about 2.5 minutes to evaluate a single generation (i.e., 0.008 seconds to evaluate a single chromosome). The system utilized was a hardware configuration of Intel Core i5-3230, 2.60 GHz and 6 GB RAM. Fig. 6 depicts the weighted average of CI values in each year in the 30-year maintenance horizon in the optimum plan, with an average of 7.34.

Table 7 shows the repair costs and the user costs in the repair years in the optimum plan. As it is clear, the total repair costs in the planning horizon are $3,986,040, the overall user costs are $551,600, and the sum of the costs is $4,537,640. The low ratio of the total user cost to the total repair costs (about 14%) is due to the low value of each hour of a driver's time and the low cost of each hour of a vehicle in Iran. As Table 8 shows, most of the repair-types in the optimized solution are repair-type 2 (light repair), and no repair-type 3 (extensive repair) is considered in the solution because of its high cost.

Table 9 demonstrates the total repair costs allocated to each bridge element type in the optimum plan. As it is clear, elements with the "overlay" type utilize most of the maintenance budget due to the high deterioration rate of this element type.

Table 8 Frequency of the repair-types in the optimized maintenance plan obtained from BrGA

Repair-type	Frequency
1 (Light repair)	148 (22%)
2 (Medium repair)	536 (78%)
3 (Extensive repair)	0 (0%)
Sum	684 (100%)

Table 9 The total repair costs allocated to each bridge element type in the optimized plan

Element type	Total repair costs ($)
Deck	609,490 (30%)
Column	30,800 (2%)
Abutment	48,600 (2%)
Overlay	1,132,160 (57%)
Railing	171,970 (9%)
Sum	684 (100%)

The results obtained from BrGA were compared with a model in which the “improvement function” was not applied in the optimization process. The results show that the optimization convergence time is ten times the optimization convergence time in BrGA, which shows the effectiveness of “improvement function” in producing faster convergence and better solutions.

BrDSS was presented to bridge managers working in the municipality of Isfahan in Iran, and the optimization results and visualization of the maintenance plan were admitted. The bridge managers mentioned that the visualization provided by BrDSS helped them better and faster understand the deterioration of bridge elements over the planning horizon.

6. Conclusions

Efficient bridge management plays a crucial role in minimizing bridge operation costs and extending its service life. Although commercial BMS software packages exist in the market, the proposed BrDSS complements the capabilities of available BMS software applications by utilizing data collected in the BrIM for the optimization process. Aside from the interoperability enhancement, the main benefit of BrIM is providing an integrated approach for the bridge life cycle data management to employ data in the design, construction, operation, and maintenance phases thoroughly. The developed system also visualizes the inspection data and optimization results efficiently. The main features of BrDSS are:

• Enabling automatic data exchange between project life cycle phases through extracting bridge elements’ data from BrIM model to be used in BrDSS

• Presenting an efficient bridge maintenance optimization with a fast convergence speed

• Taking into account various bridge elements in the optimization process, instead of considering a single element for all bridge elements with a common type

• Enabling the user to record the bridge inspection data in the 3D BrIM environment

• Visualizing the bridge inspection data and the optimum maintenance plan throughout the maintenance planning horizon

It is also worth mentioning that the proposed DSS can serve as a complement to commercial BMS software packages such as AASHTOWare Bridge (e.g., Pontis). BrDSS structure can extend available BMS structures to utilize data inherent in the BrIM for the optimization process, to receive the inspection data in a 3D environment, and to visualize the inspection data and optimization results through the 3D BrIM model. Also, the proposed formulation for BrGA can also be utilized in available BMS for faster convergence.

While the efficiency of utilizing BrIM in bridge maintenance planning was demonstrated in the present study, some drawbacks remain. An important issue is the costs and efforts required to produce BrIM models, particularly for existing bridges. Many bridges currently under operation, especially in developing countries, do not have any BrIM model available, although providing BrIM is becoming a mandate in many developing and developed countries. Another limitation is that in the presented DSS, the duration of a repair intervention is estimated based on the maximum duration of repair-activities. In other words, it is assumed in BrDSS that repair-activities on bridge elements are performed at the same time. However, if the limitations of crews and workspace (i.e., resource limitations) are considered, more realistic results are obtained.

The presented system can be further developed in some aspects. To use BrIM as a host for bridge life-cycle data, all valuable data related to design, construction, and operation phases should be stored in the BrIM model of the bridge. Also, the presented optimization model could be extended from the current project-level planning to the network level-planning.

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