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INTEGRATED SUPER-STRUCTURE AND ASPHALT DECK SCHEDULING AND OPTIMIZATION FRAMEWORK FOR BRIDGES

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Abstract: North America's bridges are aging and deteriorating. According to the Canada's infrastructure report, around 40% of the existing bridges are in fair and below condition state, which increases their risk of failure and requires further attention. Furthermore, Canada's infrastructure deficit is estimated between $110 billion to $270 billion and is annually increasing by $2 billion. Given the tight municipal operating budgets coupled with the pressure of maintaining an acceptable level of service, efficient utilization of the maintenance expenditures is becoming of paramount important not only for bridges, but for all the deteriorating assets. Even though, several scholars developed bridge management systems to schedule the maintenance of the bridge concrete deck. Yet, scholars have not considered the spatial proximity between the concrete structure and the asphalt surface. In the lights of those issues, this paper proposes an integrated bridge super-structure and asphalt deck scheduling and optimization framework to ensure proper expenditures utilization, while maintaining the super-structure condition and asphalt level of service. The framework revolves through five core models: (1) bridges' inventory that contains information about the bridge components, condition state, etc., (2) condition deterioration and future prediction model that simulates the super-structure deterioration across the planning horizon; (3) level of service model that calculates the degradation of the asphalt, represented by the international roughness index; (4) bridge super-structure assessment model that computes a bridges' super-structure combined index for both the concrete deck's condition and the asphalt's level of service; and (5) optimization model that relies on evolutionary algorithms and integer programming using genetic algorithms optimization engine to schedule the corridor interventions across the planning horizon. To demonstrate the framework's functionality, it will be applied to a bridge across 50 years planning horizon. The results resulted in an extension of 45 years in the service life as opposed to the no repair scenario. The bridge superstructure experienced three major rehabilitation and three minor repairs for the concrete superstructure. The age of the bridge superstructure was 78 years, which is 3 years more than the expected design life according to the code. Furthermore, it resulted in an average IRI of 140 in/mi. For the costs, the EUAC of the structural actions was $18,175. However, the EUAC of the asphalt deck IRI enhancement actions was $7,765, which is 40% of the structural actions. The overall EUAC of the combined superstructure was $25,940. In summary, the developed framework is an integrated bridge management solution that assists municipalities in taking informed and coordinated bridge super-structure maintenance decisions, while maintaining an acceptable condition and level of service.

1 INTRODUCTION

The infrastructure is at risk. Canada's aging municipal infrastructure is placing tremendous pressure on the government through steeply growing deficits to repair/replace the failing assets. The fact that one-third of municipal infrastructures in Canada fall in fair, poor and failing states (FCM 2016) points to high risk of service disruption. This situation requires corresponding corrective maintenance measures. Recent studies estimated Canada's infrastructure deficit at a range between $110 billion to $270 billion. Furthermore, urbanization represents another challenge for asset managers. According to the United Nation Population, the world is undergoing the largest wave of urban growth. In 2008, more than 50% of the world's population was living in towns and cities and the figures are expected to exponentially swell throughout the upcoming years (Moir et al. 2014). Moreover, the climate change and the extreme cold weather represents another challenge for managing the assets. Therefore, there is an urgent need to develop innovative and effective asset management approaches that minimize the expenditures and maintain the safety of public infrastructures including highway bridges. In Canada, almost half of the bridge superstructures are of steel reinforced concrete type. Those structures are exposed to severe deteriorating conditions in cold regions with harsh corrosive environment. This is due to the aging, fatigue, corrosion, inadequate maintenance and special loading patterns (i.e. increasing load spectra). Furthermore, the corrosion of the steel reinforcement is increasing because of the use of salt-based de-icing materials (Bisby 2006). The preventive measures for maintaining and rehabilitating the bridges are too costly. In the United States, the cost for undertaking necessary bridge interventions is estimated at $100 billion (McDaniel et al. 2010). Therefore, building future performance prediction models and cost optimization platforms is of paramount importance in the Bridge Management Systems (BMS).

BMS apply either Bridge Condition Index (BCI) or Bridge Health Index (BHI) to monitor the structural health of the bridges. Those indicators compute the bridge condition based on element-level condition assessment determined from visual inspection results. Given the lack of available funds to frequently inspect the elements, reliability-based condition can be applied in BMS to indicate the system level condition. The application of the system reliability considers the uncertainty of structural parameters, correlation between structural elements, load redistribution and redundancy of the structure (Ghodoosi et al. 2015). Condition and reliability indices are interrelated given that both (1) define the health and safety of a structure; (2) have maximum values for a newly constructed structure; and (3) decrease over time as the structure deteriorates (Grussing et al. 2006). Ghodoosi et al. 2016 developed system reliability-based deterioration models to predict the time for potential interventions in a more precise and rational approach for the conventional and innovative bridge superstructure systems. Similarly, El-Behairy et al. 2009 built markov-based deterioration to predict the degradation of the bridge elements and sequential optimization to optimize the expenditures across the planning horizon. Table 1 summarizes the most representative research efforts in the BMS and their corresponding optimization formulation.

Research	Scale of application	Optimization type	Optimization tool	Objective(s)
Ghodoosi *et al.* (2018)	Project level	Single objective	GAs	Minimize the equivalent uniform annual cost over the bridge life-cycle
Frangopol *et al.* (2017)	Network level	Multi-objective	Integrated probabilistic life-cycle optimisation, MAUT, and risk	Maximize the network performance and minimize the costs
Kim and Frangopol (2017)	Network level	Multi-objective	Weighted sum method and GAs with pareto optimization	Minimize the damage detection delay, probability of failure, life-cycle cost, and maximize the service life

Research	Scale of application	Optimization type	Optimization tool	Objective(s)
Sabatino *et al.* (2016)	Network level	Multi-objective	GAs	Maximize performance, minimize cost and failure consequences
Barone and Frangopol (2014)	Project level	Multi-objective	GAs	Maximize structural performance and minimize maintenance costs
Deco and Frangopol (2013)	Network level	Single objective	Integrated fragility analysis, latin hypercube sampling, and weibull	Minimize the network life-cycle risks
El-behairy *et al.* (2009)	Network level	Single objective	Sequential optimization and Markov chain	Maximize the network performance
El-behairy *et al.* (2006)	Network level	Single objective	GAs and Shuffled Frog Leaping (SFL)	Minimize the life-cycle costs
Elbeltagi *et al.* (2005)	Network level	Multi-objective	GAs, memetic algorithms, particle swarm, ant colony systems, and SFL	Maximize performance and efficiency and minimize time, resources, and cost
Morcous and Lounis (2005)	Network level	Single objective	Markov chains and GAs	Minimize the life-cycle costs
Hegazy *et al.* (2004)	Phased project and network level	Multi-objective	GAs	Maximize the performance and minimize the cost
Miyamoto *et al.* (2000)	Project level	Single objective	GAs with ε-constraint method	Maximize performance (capability and durability)

Table 1: Summary of bridges management systems and their corresponding optimization formulation

As shown in Table 1, scholars utilized different deterioration mechanisms, optimization engines, objective functions to formulate the optimization problem. For instance, Frangopol et al. 2017 integrated the life-cycle costs, risk, and condition to optimize the expenditures utilization for a network of bridges. Barone and Frangopol used GAs to maxmmize the structural performance and minimize the maintenance costs of one bridge. Similarly, Sabatino et al. 2016 expanded the previous model and used goal optimization integrated with genetic algorithms (GAs) to maximize the performance and minimize the costs and consequences of failure for a network of bridges. Other scholars used different evolutionary algorithms to either maximize the performance or minimize the life-cycle costs. The performance was used to represent several aspects such as; condition, capability, durability). Even though scholars exerted considerable efforts to predict the deterioration of the bridge deck, they lacked the interdependency of the concrete structure and the asphalt deck. Thus, this paper aims at developing an integrated bridge super-structure and asphalt deck scheduling and optimization framework to ensure proper expenditures utilization, while maintaining the super-structure condition and asphalt level of service.

2 METHODOLOGY

The research methodology functions through three phases as shown in Figure 1. Those phases are: (1) asset inventory; (2) performance models; and (3) optimization model. The 1st phase, asset inventory, includes all the relevant information to build a BMS. That information includes but not limited to; year the bridge was originally built, age, last major repair, last minor repair, number of lanes, length, location, structural capacity, average annual daily traffic, cost of minor and major repairs, replacement cost, interest rate, etc. Thenceforth, the 2nd phase takes place to build performance models to measure the bridge structural condition, asphalt deck level of service, and compute the life-cycle costs. The bridge structural condition indicates the condition of the structural elements after being exposed to aging, severe weather conditions, traffic, etc. However, the asphalt surface degradation model represents the level of service of the asphalt deck. Similar to the roads, the asphalt deck is exposed to cycles of freeze and thaw, high traffic density. Those factors increase its' deterioration and thus impacts the level of service of the bridge superstructure. Hence after, those two models are integrated into an overall bridge super-structure index that represents the condition of the structural elements as well as the asphalt deck. On the financial side, the financial model computes the life-cycle costs including the minor and major repair and the replacement costs. Finally, the 3rd phase, optimization, takes place to optimize the expenditure across the planning horizon. Given the conflicting in nature objectives, goal optimization is used to minimize the deviations for the thresholds (i.e. available budget, asphalt IRI threshold, and unacceptable structural condition). Further details on each model will be highlighted in the upcoming subsections.

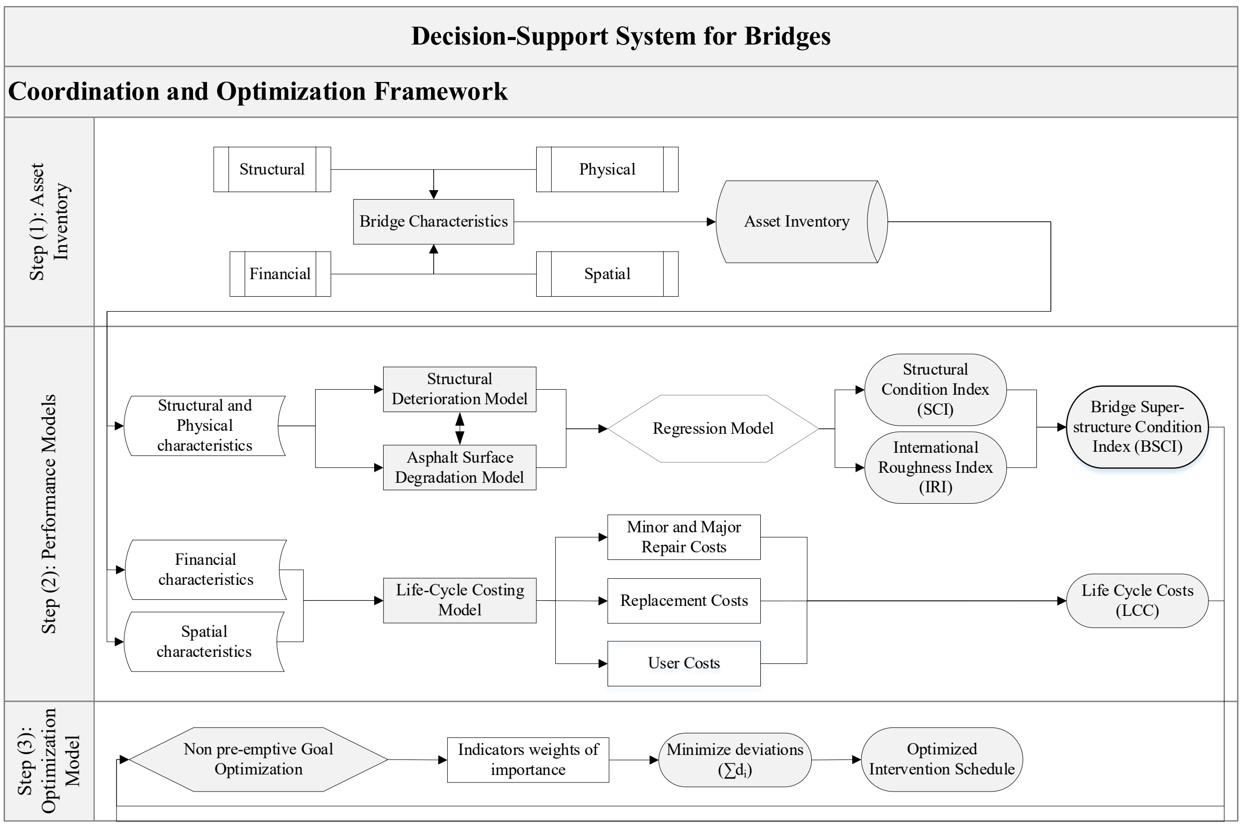


Figure 1: Methodology

2.1 Asset inventory

The bridge inventory data contains the bridges characteristics such as; structural, financial, physical, and spatial. The structural and physical characteristics includes number of lanes, lane width, bridge length, condition ratings, year of last repair, age, construction year, etc. The condition ratings are measured and inspected at an element-level, which are usually assigned based on routine visual inspections. There are different guidelines for the bridges inspections such as; Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges published by the U.S Federal Highway Administration (FHWA). The element-based condition data together with the results of corresponding visual and non-destructive evaluations can be helpful in developing bridge structural and asphalt deterioration models (Bolukbasi et al. 2004). The main parameters that affect the capacity of concrete bridge superstructure are the reinforcing steel yield strength F_y), modulus of elasticity of reinforcing steel (E_s), compressive strength of concrete (f_c'), cast in-situ concrete specific weight (γ_c), deck slab cast in-situ concrete thickness, beam web thickness, beam concrete overall thickness and cover for bottom and top reinforcements in a concrete slab and beam. These statistical parameters are required to build an accurate deterioration model (Ghodoosi et al. 2015). The financial and spatial characteristics include but not limited to the cost of minor and major repairs, replacement cost, user costs, interest rate, bridge location. That information is used in estimating the life-cycle costs for maintaining the bridge across its service life. It is worth noting that this paper does not develop any data acquisition protocols but existing protocols could be used to feed the inventory with the necessary information.

2.2 Performance models

2.2.1 Structural deterioration model

The structural deterioration model features a biquadratic deterioration curve for concrete bridge members. The deterioration equation was adopted from Miyamoto et al. 2000 as shown in Equation 2. The structural condition index (SCI) varies with time and ranges between 0 and 100. An SCI of 100 represents the structure of a newly built bridge and vice versa. This index is categorized into five groups of: 0–19, 20–39, 40–59, 60–79 and 80–100 labeled as dangerous, slightly dangerous, moderate, fairly safe and safe, respectively. Dangerous state specifies that the bridge should be demolished and replaced with a new structure; slightly dangerous is a condition where the bridge structure must be rehabilitated urgently. In this study, a system level reliability based deterioration model is developed through a similar biquadratic pattern, displayed Equation (3), where, β_0 is the reliability index for a newly constructed bridge superstructure. The SCI and β are interrelated as both are used to define the condition of a bridge superstructure (Grussing et al. 2006). Thus, the reliability-based deterioration model can be normalized to entail the index of 100 for the newly constructed bridge.

[1] $SCI_t = 100 - b_L t^4$

[2] $\beta_t = \beta_0 - bt^4$

The Reliability-based deterioration is adopted as a tool to predict the probability of maintaining or exceeding the performance across the bridge service life. The deterioration curve could be regularly updated based on the visual inspections over time. In this study, the reliability indices are calculated for a bridge superstructure designed based on the code of Canada (CHBDC-S6). The superstructure cross section and the related specifications of this bridge superstructure was supported by 17 m span. According to the simulations made by Ghodoosi et al. (2015), the biquadratic deterioration pattern accurately presents the degradation process of the bridge.

2.2.2 Asphalt surface degradation model

Given the spatial interdependency between the bridge superstructure and the asphalt deck, the detrimental impact of the climate change in increasing the number of freeze and thaw cycles, this study considered the asphalt surface degradation in the decision-making process. Thus, the International Roughness Index (IRI) was used as a measure for the asphalt level of service. It represents the asphalt surface roughness, which is a global indicator for measuring the level of service from a customer perspective. Several scholars derived a mathematical relation between the pavement condition index (PCI), which represents the surface condition based on the distresses, and IRI due to the costly IRI inspection process. The computations of the IRI and PCI could be displayed in the equations below (Mohammed et al. 2017):

[3] $\log(\mathrm{PCI}) = 2 - 0.436 \log(\mathrm{IRI})$

[4] $\mathrm{PCI}_n = 0.033n^2 - 2.688n + \mathrm{PCI}_i$

Where; PCI_n is the anticipated PCI after n years; and PCI_i is the initial PCI (0-100) at year i.

It is worth noting that the model is flexible to adopt either deterministic (i.e. regression) or probabilistic (i.e. markov, semi-markov, Weibull) to represent the degradation of the bridge asphalt deck.

2.2.2 Bridge superstructure condition index model

The SCI and IRI were integrated together into a bridge superstructure condition index (BSCI). This indicator represents the overall structural and asphalt deck condition. It is helpful to support decision-makers in taking informed intervention decisions on the long-term. Weighted sum mean method was used to compute the BSCI as displayed in the equation below. The weights of importance between the SCI and IRI could vary according to the decision-makers preferences, as long as the structural capacity and safety are not compromised. For that reason, an unacceptable threshold for the SCI was designed to alert decision-makers once the bridge structural capacity is at risk.

[5] $BSCI_t = \left[(\mathrm{W_i} * SCI) + (\mathrm{W_v} * \frac{\mathrm{IRI}}{IRI_{max}})\right]$

2.2.4 Life-cycle costing model

Given the tight operating budgets government and the bridges' long service life that is associated with lots of uncertainties, proper management of the expenditures is necessary. Thus, a life-cycle costing model was built to compute the costs of the intervention actions that could be undertaken across the service life along with their corresponding user costs. Table 2 summarizes those costs. Furthermore, given the existence of several intervention scenarios and the necessity of comparing different alternatives with different cash flows, time value has been used. Equivalent uniform annual cost (EUAC) was used to represent the equivalent annual costs of different scenarios. Furthermore, it assists decision-makers in comparing the alternatives with different expected life-cycles. The initial capital costs for all the alternatives are assumed to be the same and thus excluded from the calculations. The EUAC could be calculated as shown in the equation below:

[6] $EUAC = \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \times \frac{i(1+i)^n}{(1+i)^n - 1}$

where, C_t is the expenditure at time t; n is the system service life; and i is the interest rate.

Type of Cost	Without minor intervention ($/$m^2$)	With minor intervention ($/$m^2$)
Minor intervention	$0	$132
Major intervention	$968	$379
User cost for minor intervention	$0	$177
User cost for major intervention	$3,061	$576

Table 2: Unit intervention costs for bridges super-structure (Ghodoosi et al. 2018)

2.3 Optimization model

Due to the complex and combinatory nature of this problem (dynamic and lengthy planning horizon in addition to the huge search space), an evolutionary optimization algorithm should be applied to efficiently solve the optimization problem. Furthermore, different combinations of major and minor activities (i.e. schedule) entails different service lives for the bridge structures. Therefore, genetic algorithms (GAs) was used to select a near-optimal solution for this combinatorial of nature problem in a reasonable running time. The GA optimization model was built to minimize the deviations from the BSCI and EUAC. Several hard constraints were placed to ensure that the bridge is structurally safe and meets the service life indicated in the code. The optimization formulation could be displayed in the equations below:

[7] $\mathbf{Min}(\mathbf{Z}) = \sum_{\mathrm{t}=1}^{T}[\mathrm{W_i} * \mathrm{W_v} * (\mathrm{d}_k^- + \mathrm{d}_m^+)]$

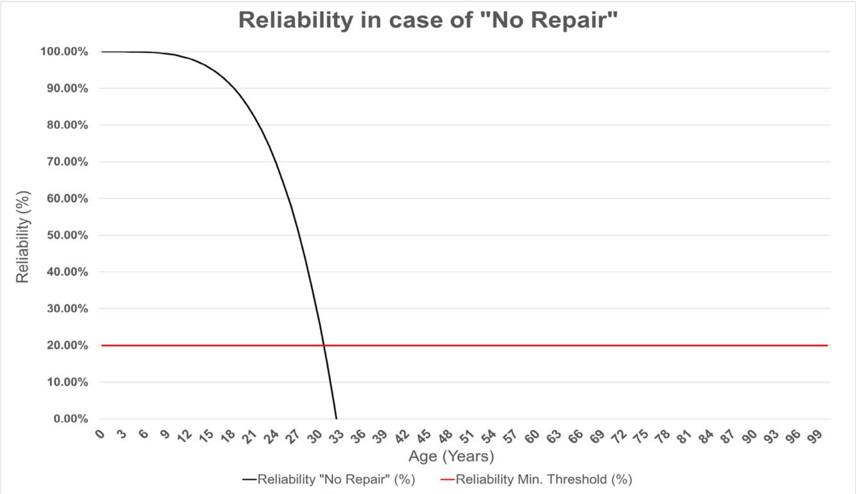
Subject to the following constraints:

[8] $t \geq 75\ years$
[9] $I_t = 0\ ; for\ t \geq 75\ years$
[10] $\beta_t \geq 20$
[11] IRI$\leq 171\ in/mi$
[12] $d^-_{k\,t} = \sum_{i=1}^{n_s} \sum_{h=1}^{H} \frac{BSCI_t - BSCI_{Th}}{BSCI_{Th}}$
[13] $d^+_{m\,t} = \sum_{i=1}^{n_s} \sum_{l=1}^{L} \frac{EUAC - BUD}{BUD}$
[14] $\textbf{Decision variables} = [I_t \quad ... \quad ... \quad I_T]$
For I_{t_o} = 0, 1, 2, .. n
t = 1, 2, … T

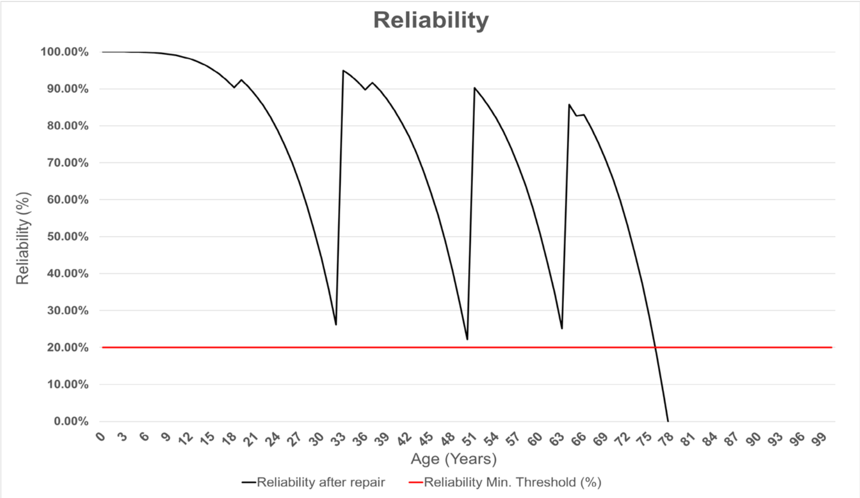
3 RESULTS AND ANALYSIS

To demonstrate the functionality of the system, it was applied to a 17 m span (center-to-center of bearings) simply supported reinforced concrete bridge superstructure designed according to the simplified method of CHBDC-S6. The structural system consists of four simply supported reinforced concrete beams supporting the 0.2-m-thick slab. The T-section supporting concrete beams are 2.3 m apart. The nominal concrete cover is 60 mm, meeting the CHBDC-S6 requirements. Four concrete diaphragms are designed at two ends and quarters of the 17 m span for each side in transverse direction. The total area is 514.5 m^2, which contains de-icing material. The repair costs were presented in Table 2. For each repair method, the corresponding estimated cost (C_t) and improvement to the structural or asphalt deck IRI are applied to the performance models. Bridge user cost considers the delay, detour and accidents. For instance, the user costs in the case of a minor repair activity will be normally less that the major repair ones given that it will require partial traffic closure. The biquadratic degradation curve illustrates the deterioration pattern for the designed reinforced concrete bridge superstructure located in a cold region with harsh corrosive environment as highlighted previously in sub-section 2.2.1. As displayed in Figure 2(a), in case no action is taken, the superstructure deteriorates fast and becomes unsafe in a short period of time (33 years). Several trade-off scenarios were studied by the optimization engine to find the minimum deviations from the budget and performance thresholds. The model aims at selecting a near optimal solution that would last for a longer period, at least for the designed service life of the bridge.

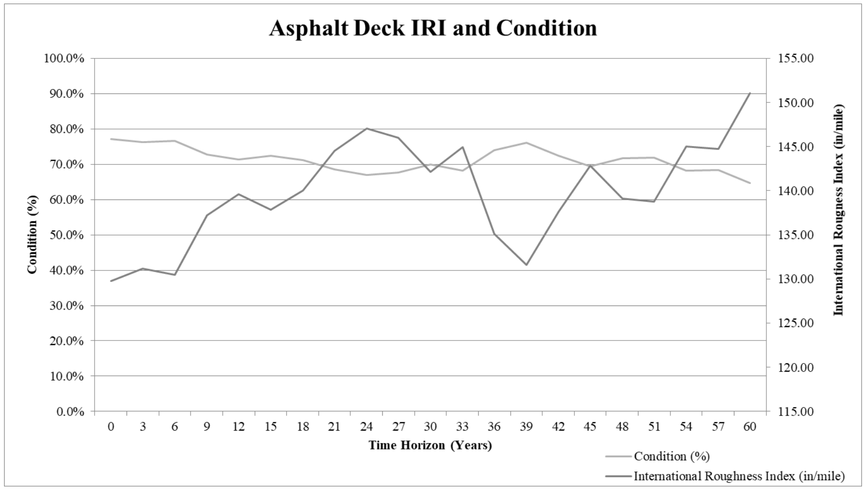
The model was developed using spreadsheets and Evolver software was used as the optimization genetic algorithms engine. The population selected to run this problem was 200 and 80% vs 20% were selected for the crossover and mutation ratios. After running the optimization engine, the results of the SCI, IRI and LCC were obtained as displayed in Figure 2 (b), (c), and (d). The average SCI was 73% across the bridge service life. The bridge life was 45 years more than the scenario with no repair and 3 years more than the expected code service life. In order to maintain the SCI, the system required 3 major rehabilitations and 3 minor repairs for the bridge structure. The comparison between the reliability with no repair and the optimized reliability after repair could be displayed in Figure 2 (a) and (b). Similarly, the IRI and condition of the asphalt deck were modelled, and the results displayed an average IRI of 140 in/mi, which corresponds to a surface condition of 71%. The degradation and improvement of the IRI and surface condition could be displayed in Figure 2 (c). Finally, the life-cycle costs were modeled taking the time value of money into account. A 2% interest rate was assumed in this study. The EUAC of the structural actions was $18,175. However, the EUAC of the asphalt deck IRI enhancement actions was $7,765, which is 40% of the structural actions. The overall EUAC of the combined superstructure was $25,940. Figure 2 (d) summarized the LCC across the planning horizon. However, Figure 3 displays the distribution of the structural actions as opposed to the surface actions. The structural actions are less frequent but much costly as opposed to the more frequent actions but less costly asphalt surface actions.



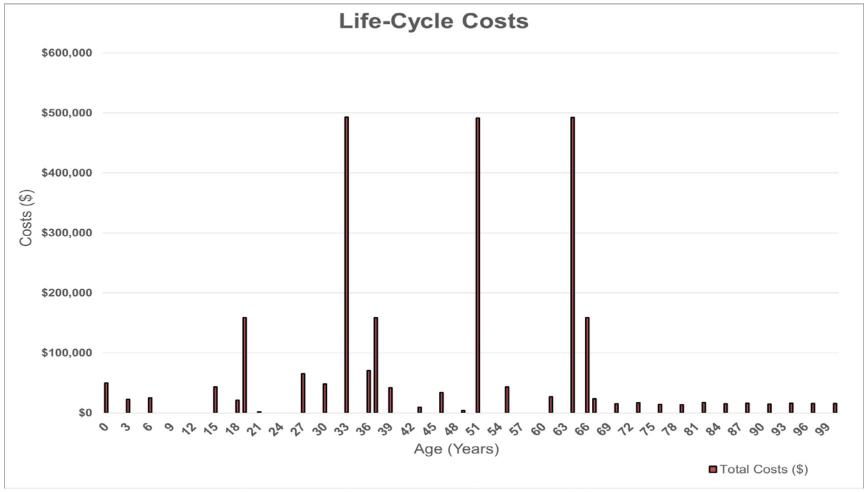
(a) Reliability without repair



(b) Structural reliability with repair



(c) Asphalt deck IRI and condition degradation after repair



(d) Life-cycle costs for structural and asphalt deck repair

Figure 2: Optimization results

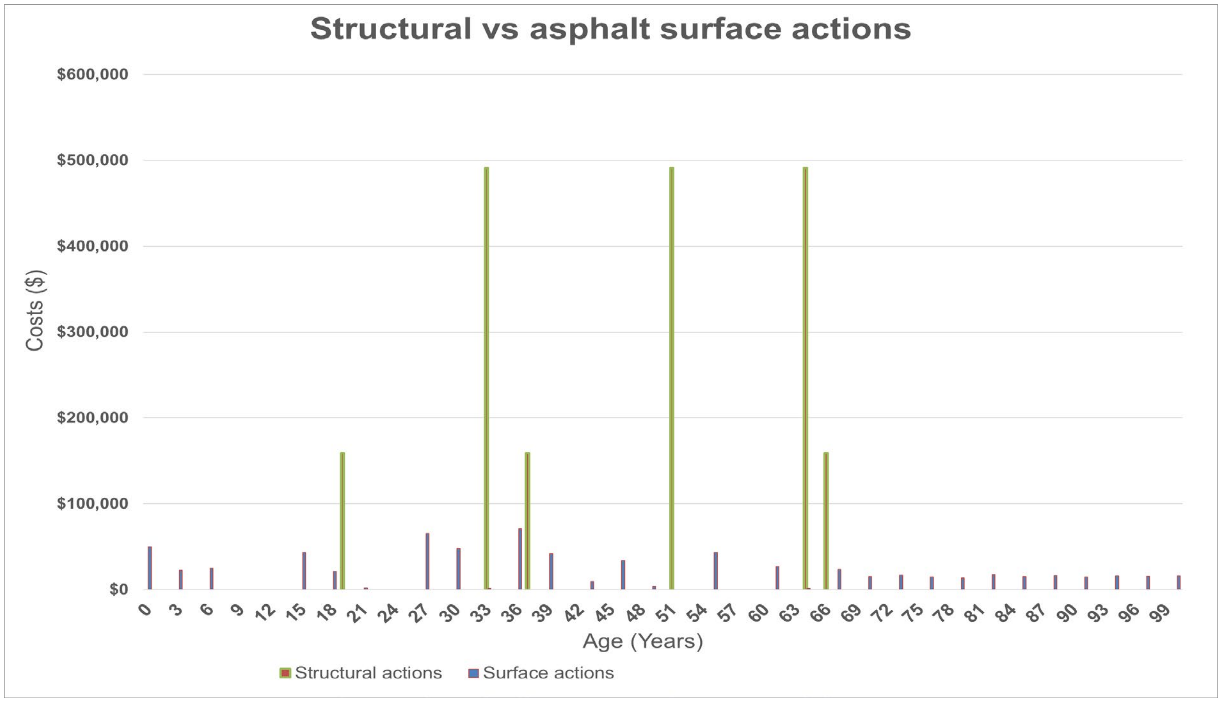


Figure 3: Cost distribution among structural and asphalt surface repair actions

4 CONCLUSIONS

Canada's aging municipal infrastructure is placing tremendous pressure on the government through steeply growing deficits to repair/replace the failing assets. This paper developed a coordination and optimization decision-support tool for the bridges' superstructure and asphalt deck. The decision-support tool aids decision-makers in scheduling the coordinated repair of the concrete structure as well as the asphalt deck. The framework went through three phases: (1) asset inventory, (2) performance models, and (3) optimization model. The asset inventory contained all the information that are needed to take informed decisions. The performance models included structural deterioration model; asphalt degradation model; and life-cycle costing model. The structural deterioration model computes the deterioration of the bridge structure with respect to aging, steel reinforcement corrosion, etc. The asphalt degradation model computes the asphalt surface deterioration across time. The impact of undertaking an intervention is reflected as an improvement in the asphalt surface as well as the structural condition of the bridge. The life-cycle costing models computes the direct and indirect repair costs. The optimization model used genetic algorithms to trade-off the different scheduling alternatives for the repair activities.

The framework was applied to a 17 m span (center-to-center of bearings) simply supported reinforced concrete bridge superstructure designed according to the simplified method of CHBDC-S6. The results resulted in an extension of 45 years in the service life as opposed to the no repair scenario. The bridge superstructure experienced three major rehabilitation and three minor repairs for the concrete superstructure. The age of the bridge superstructure was 78 years, which is 3 years more than the expected design life according to the code. Furthermore, it resulted in an average IRI of 140 in/mi. For the costs, the EUAC of the structural actions was $18,175. However, the EUAC of the asphalt deck IRI enhancement actions was $7,765, which is 40% of the structural actions. The overall EUAC of the combined superstructure was $25,940. Despite the capabilities and flexibility of the system, the future work is underway to address some of the limitations including but not limited to: (1) considering the application of FRP laminates for strengthening the reinforced-concrete deck, which might increase the cost and extend the bridge service life; and (2) applying probabilistic-based deterioration to account for the uncertainties that might arise during the bridge service life.

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