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16. Abstract Accelerated bridge construction (ABC) techniques are rapidly gaining acceptance as an alternative to conventional construction to reduce construction duration and minimize the impact of closures at the network level. There are different types of ABC and each technique has its limitations and speed of completion. The choice of using a specific ABC depends on a host of different factors including its applicability to specific bridge site, criticality of the bridge to the network, and availability of capital funds for its implementation. Some of these factors tend to have contradicting affects, as a faster ABC technique often entails higher investment levels; on the other hand, a faster technique for a bridge with high criticality to the network may result in large savings in user costs. This report details the development of a mixed-integer programming model that provides a balanced portfolio of construction techniques on bridge sites over a prioritization process for bridges at the network level. For this purpose, while a network-level scheme is used to select the bridges for rapid replacement based on their criticalities to the network, a project-level scheme accordingly is conducted to optimize the choice of accelerated construction techniques. To account for the effects of different accelerated construction techniques, the costs associated with each replacement technique is calculated including direct costs from the actual replacement of bridges and indirect costs experienced by network users due to the bridge closure during the maintenance period. Using the mixed-integer programming model, based on the investment budget, the new service performances of bridges, and the optimal accelerated construction techniques for different bridges, the bridge replacement strategy and the costs during the entire process are estimated, which could provide the decision-makers and stakeholders a detailed understanding of the prioritization process at both the network and project level.			
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AN INTEGRATED PROJECT TO ENTERPRISE- LEVEL DECISION-MAKING FRAMEWORK FOR PRIORITIZATION OF ACCELERATED BRIDGE CONSTRUCTION

**Final Report
September 2018**

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	vii
EXECUTIVE SUMMARY	ix
INTRODUCTION	1
REVIEW OF ACCELERATED BRIDGE CONSTRUCTION TECHNIQUES	3
MATHEMATICAL MODEL	7
Model Overview	7
Bridge Replacement Limitations	11
Bridge Rating	12
Dynamic Traffic Assignment	14
BC Solution Algorithm	16
COMPUTATIONAL STUDY AND DISCUSSION	19
VALIDATION ANALYSIS	25
SCALABILITY OF THE DEVELOPED MODEL TO LARGER NETWORKS	28
COMBINATION WITH TRADITIONAL AHP DECISION TOOL	31
Traditional ABC-AHP Tool	31
Comparison and Improvement	32
CONCLUSION	34
REFERENCES	35

LIST OF FIGURES

Figure 1. Common applied ABC solutions in the US.....	3
Figure 2. Comparisons (top) and gaps (bottom) of the construction cost per square foot between ABC techniques and conventional techniques for 48 bridges from ABC-UTC project database	6
Figure 3. The input and output data in the current MIP model.....	11
Figure 4. Limitations and constraints of the MIP model	16
Figure 5. BC solution algorithm outline for project-level to network-level MIP model	18
Figure 6. The node, link, and bridge locations for the case study network (Note that bridge numbers are in bold and underlined).....	19
Figure 7. Six different investment strategies and the optimal bridge prioritization and ABC technique selection	22
Figure 8. Comparison of direct, indirect, and total costs for the different strategies considered	24
Figure 9. All feasible solutions and the optimal solution under various budgets	26
Figure 10. Application of LDS algorithm for bridge selection.....	28
Figure 11. Sample solution with the exact one discrepancy of ABC technique selection for each of bridges 4 and 6.....	29
Figure 12. LDS solution algorithm outline for project-level to network-level MIP model.....	30
Figure 13. Frame of the traditional ABC-AHP tool	31
Figure 14. Rating pairwise comparison value for each element.....	32

LIST OF TABLES

Table 1. The definition of ABC techniques	4
Table 2. Relationship between SR value and bridge replacement.....	13
Table 3. SR value, replacement action, and ABC technique limitation of bridges	20
Table 4. Bridge replacement closure time, basic direct cost, and the technique IC values	20
Table 5. Bridge replacement closure time, basic direct cost, and the technique IC values	21
Table 6. Validation and improvement on MIP model and BC algorithm.....	27

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EXECUTIVE SUMMARY

Accelerated bridge construction (ABC) techniques are rapidly gaining acceptance as an alternative to conventional construction to reduce construction duration and minimize the impact of closures at the network level. There are different types of ABC and each technique has its limitations and speed of completion. The choice of using a specific ABC depends on a host of different factors including its applicability to specific bridge site, criticality of the bridge to the network, and availability of capital funds for its implementation. Some of these factors tend to have contradicting affects, as a faster ABC technique often entails higher investment levels; on the other hand, a faster technique for a bridge with high criticality to the network may result in large savings in user costs.

This report details the development of a mixed-integer programming model that provides a balanced portfolio of construction techniques on bridge sites over a prioritization process for bridges at the network level. For this purpose, while a network-level scheme is used to select the bridges for rapid replacement based on their criticalities to the network, a project-level scheme accordingly is conducted to optimize the choice of accelerated construction techniques. To account for the effects of different accelerated construction techniques, the costs associated with each replacement technique is calculated including direct costs from the actual replacement of bridges and indirect costs experienced by network users due to the bridge closure during the maintenance period.

Using the mixed-integer programming model, based on the investment budget, the new service performances of bridges, and the optimal accelerated construction techniques for different bridges, the bridge replacement strategy and the costs during the entire process are estimated, which could provide the decision-makers and stakeholders a detailed understanding of the prioritization process at both the network and project level.

INTRODUCTION

Transportation infrastructure forms the backbone of the economy and typically requires annual investments in the order of several billions of dollars. These investments are mainly for maintenance, rehabilitation, and replacement of the assets of the transportation infrastructure. The overall expenditures are expected to increase due to infrastructure aging, increased frequency and intensity of severe weather, and increasing traffic loads. More than 685,000 bridges in the United States are no exception to these conditions. One of the main challenges facing transportation asset managers is the need to cost-effectively prioritize the repair and replacement of the large inventory of deteriorating bridges considering the ever-increasing budgetary constraints. The indirect costs (such as traffic delay) associated with the closure times during these activities exacerbates the decision-making processes. The vitality of the bridge network to the transportation network and to economic development, the large investments in their repair and replacement, and the impact of their closures on the socio-economic prosperity of the society, inspires the implementation of new construction techniques, planning approaches, and policies for their management.

To address the growing infrastructure management investment needs, transportation agencies constantly aim to find solutions in four major areas: technological innovations to develop more durable materials and design of bridges, innovative construction techniques that lead to better quality and project delivery in a faster time, advanced monitoring and condition assessment techniques, and novel decision-making processes. Accelerated bridge construction (ABC) has received significant recognition and popularity as a method to construct and rehabilitate bridges in recent years (Ralls 2007). Accelerated bridge construction uses both new technology and innovative project management techniques to mitigate the effects of bridge construction on the public, reduce construction costs, promote traffic and worker safety, and improve the bridge durability due to standardized and controlled construction conditions (Saeedi et al. 2013). The perceived higher initial costs associated with ABC are often cited as a reason for less inclination toward its adaptation for repair and replacement projects (Barutha et al. 2017).

Another major factor contributing to this hesitancy is the unavailability of decision support systems (DSS) that would help with the selection of appropriate techniques. Multiple research projects in the field of infrastructure management have addressed DSS for bridges. These research projects have been majorly focused on either the detailed assessment of the total life-cycle analysis of the bridges under deterioration mechanisms or the selection of maintenance actions for individual bridges. As for the availability of DSS, there are three tools that are available. The first one developed by the Federal Highway Administration (FHWA) is based on a framework for prefabricated bridge elements and systems decision-making, where a flowchart and matrix incorporating a set of decision criteria are used to help decision makers choose between conventional and accelerated bridge construction alternatives (Tang 2006, Salem and Miller 2006). The second approach is a method to evaluate the construction plans based on factors such as safety, accessibility, schedule performance, and budget performance where a scoring system based on expert opinion is used to prioritize the construction plans (El-Diraby and O'Connor 2001). The third method is based on analytic hierarchy processes (AHP) (Escobar and Moreno-Jiménez 2002, Saaty 1980) that uses pairwise comparisons to evaluate the importance of defined factors relative to other factors using either a numerical or verbal scale

(Doolen et al. 2011). The AHP consists of three components: the overall goal of the decision, a hierarchy of criteria by which the alternatives will be evaluated, and the available alternatives (Iowa DOT 2017). The common trait between the aforementioned tools are: (1) lack of a holistic prioritization approach that accounts for criticality of the bridge to the network, (2) the capability to consider the uniqueness of each bridge condition and site , and (3) a systematic and justifiable method on criteria weighting, which are easily affected by different subjective factors (Durán and Aguilo 2008).

This highlights the need for a holistic decision-making model that integrates the project-level decision process that involves the choice of optimized construction techniques together with the network-level process that implements regional prioritization schemes considering indirect costs, such as drivers' delay and socio-economic impact, in addition to the direct costs associated with implementation of the ABC techniques (Zhang et al. 2018). In the current report, a mixed-integer programming model is established to address these gaps. This model is based on engineers' wide technical knowledge of bridge structures, construction processes, and cost control, which can provide this model the most professional input data. Via the evaluation process, all possible solutions (available ABC technique for each bridge and the potential bridges judged as poor serviceability) are tested and their direct and indirect costs are calculated. From those, the optimal solution is defined as the one that could use the smallest integrated cost to replace bridges at a network level and guarantee the serviceability of each bridge and the entire network. As a result, several main objectives are assessed as outcomes: the bridge performance after replacement, the optimal construction technique at the project level, their relative closure time, their construction cost under the limited resources, the replacement strategy of bridges, and the cost at the network level. These details are the highlighted features of this mixed-integer model that will provide decision makers the macroscopic view of bridges' serviceability and traffic conditions in a specific network and microscopically allow the decision makers to prioritize, select, and apply ABC techniques in a more effective manner.

The next sections consist of the following:

- A review of ABC techniques, including the comparison of cost estimates between recently completed ABC and conventional techniques
- A methodology description for the proposed mixed-integer programming framework
- A computational study and discussion of results
- A validation analysis of the methodology
- A look at options to compare the model with traditional AHP tools
- Conclusions and future work

REVIEW OF ACCELERATED BRIDGE CONSTRUCTION TECHNIQUES

ABC techniques are the bridge construction techniques where innovative contracting, planning, design, environmental process, materials, and construction methods are used during projects (Culmo 2011). Reduction of road closure times, traffic disruption, and user costs, in addition to improvements in construction quality utilizing prefabricated elements are attractive qualities of the implementation of ABC techniques. ABC techniques, initially reserved for routes with large average daily traffic (ADT) and critical thoroughfares, have significantly improved and increased in popularity. For example, the successful applications of ABC techniques helped nine transportation agencies to reduce bridge construction time and save over \$30 million (FHWA 2006). Additionally, improvements of ABC techniques at different bridge elements and systems have enhanced the durability of bridge structures (Phares and Cronin 2015, Hosteng et al. 2016).

Due to the specific features pertaining to bridge site conditions, weather, and terrain at the bridge locations, not all ABC techniques can be implemented on a specific site. This is an important factor that needs to be accounted for in any DSS developed for this purpose. Figure 1 provides the wide application of ABC solutions.

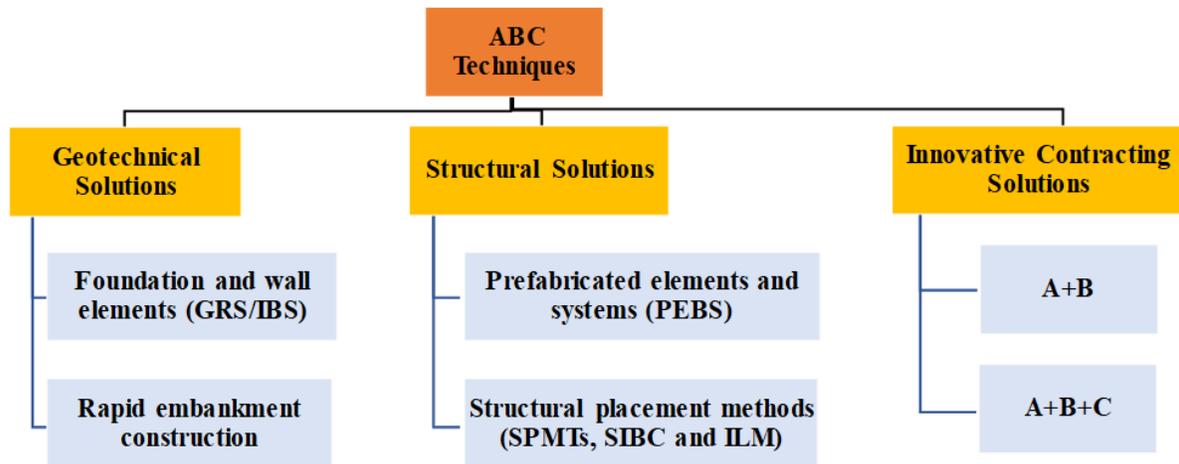


Figure 1. Common applied ABC solutions in the US

Table 1 displays the unique definitions, benefits, and limits of these ABC techniques for bridge replacements. It is obvious that ABC techniques can significantly reduce the project duration and provide a better construction environment for workers while resulting in more durable structures. One of the most extensive databases for the completed ABC projects was reviewed to collect information on the construction costs of ABC projects (ABC-UTC n.d.).

Table 1. The definition of ABC techniques

Technique	Definition	Benefit	Limitation
GRS/IBS Geosynthetic reinforced soil- integrated bridge system	<ul style="list-style-type: none"> • This method of foundation installation combines the foundation, abutment, and approach embankment into one composite system. 	<ul style="list-style-type: none"> • Simple construction • Low initial cost • A safe, cost-effective, long-lasting structure • Construction time in weeks not in months 	<ul style="list-style-type: none"> • Local roads only • Bridge span less than 140 ft • Currently applied only for single span bridges • Expensive when construction over water
EPS Expanded Polystyrene Geofoam	<ul style="list-style-type: none"> • The lightweight, rigid foam plastic EPS blocks can be placed behind a conventional abutment or around the piles of an integral abutment. 	<ul style="list-style-type: none"> • Fast construction • Cost saving • Extremely lightweight • Eliminates or reduces pre-load settlement times 	<ul style="list-style-type: none"> • A layer of subbase is required • Restricted by the site water table
PBES Prefabricated Bridge Elements and Systems	<ul style="list-style-type: none"> • PBES are structural components of a bridge that are built offsite, under or near site of a bridge and include features that reduce the onsite construction time and the mobility impact time that occurs when building new bridges or rehabilitating or replacing existing bridges relative to conventional construction methods. 	<ul style="list-style-type: none"> • High-performance and long-term structure • Reduce on-site construction time • Construction under controlled environmental conditions 	<ul style="list-style-type: none"> • High prefabrication and construction costs • Geometric constraints
SPMTs Self-Propelled Modular Transporters	<ul style="list-style-type: none"> • SPMT is a combination of multi-axle platforms operated through a state-of-the-art computer-controlled system that is capable of pivoting 360 degrees as needed to lift, carry, and set very large and heavy loads of many types. 	<ul style="list-style-type: none"> • Construction time within few hours • Significantly reduce traffic disruption • Improve work zone safety and improve quality and constructability • Increase contractor and owner options 	<ul style="list-style-type: none"> • Significantly high construction cost • Limited by the length and geometry of the travel path • Restricted by the supporting soil

Technique	Definition	Benefit	Limitation
SIBC slide-in bridge construction	<ul style="list-style-type: none"> • This method requires that the new bridge be built in parallel to the proposed finished location. The structure is normally built on a temporary support frame that is equipped with rails. The bridge can be moved transversely using cables or hydraulic systems. 	<ul style="list-style-type: none"> • Enhance safety • Shorten on-site construction time • Reduce mobility impacts • Potentially reduce project costs • Improve quality and constructability 	<ul style="list-style-type: none"> • Limited right-of-way (ROW) for staging • Geometric constraints • Lack of SIBC experience • Profile changes • Utility impacts
ILM Incremental launching method	<ul style="list-style-type: none"> • Bridges are mostly of the box girder design and work with straight or constant curve shapes, with a constant radius. 15 to 30 meter box girder sections of the bridge deck are fabricated at one end of the bridge in factory conditions. Each section is manufactured in approximate one week. 	<ul style="list-style-type: none"> • Minimal disturbance to surroundings including environmentally sensitive areas • Smaller, but more concentrated area required for superstructure assembly • Most reasonable way for a bridge over an environmentally protected obstacle 	<ul style="list-style-type: none"> • Deep water crossings steep slopes or poor soil conditions making equipment access difficult • Requiring environmentally protected species or cultural resources beneath the bridge
A+B or A+B+C	<ul style="list-style-type: none"> • The ‘A’ component is the dollar bid for the contract work items. • The ‘B’ component is the time to complete the project. • The ‘C’ component that is tied to the completion of a phase of construction. 	<ul style="list-style-type: none"> • Control and stimulate the project progress 	<ul style="list-style-type: none"> • Extra rewards may be paid

Source: Synthesized from Culmo 2011, Stark et al. 2004, Joint ACI-ASCE Committee 550, Culmo 2009, FHWA 2007, Utah DOT and Michael Baker Corporation 2013, LaViolette et al. 2007, Culmo et al. 2017

Figure 2 is the data of the construction cost per square foot of bridges published by the Accelerated Bridge Construction University Transportation Center (ABC-UTC). It shows the results where 83% of ABC projects have higher costs compared to equivalent convention construction costs (Figure 2, top). On average, ABC techniques need a 48.9% additional investment per square foot compared to the conventional method (Figure 2, bottom), which agrees with the general consensus on ABC techniques being more costly. Consequently, there is a necessity to integrate the project-level and network-level studies to find the suitable ABC

technique for every bridge and use their saving effects on bridge closure time and the transportation system to offset their high construction costs.

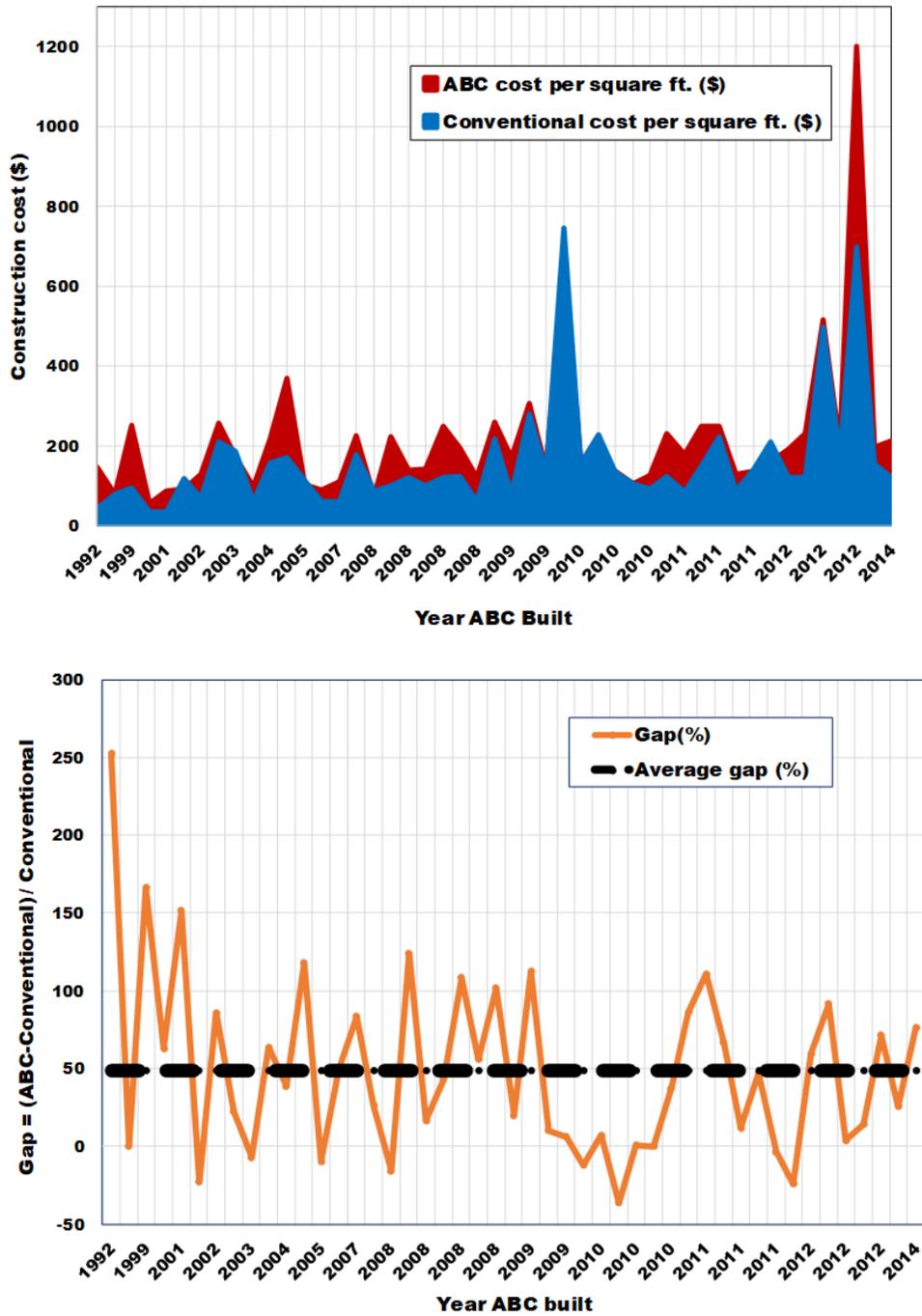


Figure 2. Comparisons (top) and gaps (bottom) of the construction cost per square foot between ABC techniques and conventional techniques for 48 bridges from ABC-UTC project database

MATHEMATICAL MODEL

Model Overview

The transportation network is defined as a graph with nodes and links. Each link may have no bridge, one bridge, or more bridges. The replacement of bridges will result in partial or full closure of that portion of the network and could result in indirect costs associated with users if closures persist. There are six different ABC techniques that could be used, that are categorized based on their speed of construction and the cost to complete. The faster a construction technique the higher cost for using it. With a faster construction cost, comes a shorter closure duration and a lower cost associated with users (i.e., indirect costs). With including more bridges in the replacement plan, the bridge serviceability, the road capacity, and the network connectivity are promoted. There is a total budget constraint for the investment that could not be exceeded and there is a requirement for the bridges to reach a certain level of serviceability defined by a target performance measure. Considering the ever-decreasing budgetary resources that agencies are facing, the decision makers need to explore the optimal replacement strategies that would result in lowest direct costs and indirect costs on the users (note that the two are contradicting as a lower direct investment results in higher user indirect costs due to extended closure times) and highest levels of serviceability.

This solution to the problem fits in to the fundamental uncapacitated facility location (UFL) problems that have been studied for decades on many topics of similar nature. In the fundamental UFL, the goal is where to open facilities and how to allocate costumers to them so that the sum of the set up and the cost of transportation is limited. Different applications of the UFL could be an emergency response facility allocation (Fiedrich 2000), subnetwork design (Chu 2018), and uncapacitated fixed-charge location problem (UFLP) (Álvarez-Miranda et al. 2015). UFLP optimizes the uncapacitated resources to the desired locations to minimize the costs induced by fixed charge on constructions and their transportation costs (Snyder and Daskin 2005). However, such a standard optimizing problem outputs a single scheme of facility locations (Melkote and Daskin 2001). It ignores the long-term continuous impact on the network and the detailed objectives at each location, which could make the computed optimal solution trend to be only feasible or even infeasible.

These are specific requirements that need to be considered when making the decision on the bridges that need to be replaced and the type of ABC techniques that needs to be employed. For this purpose, the report is based on the idea of UFLP and extends the application to remedy the mentioned gaps. To date, it is common to use the mixed-integer programming (MIP) model to formulate UFLP as the resources and locations are normally integers. The extensive research on the MIP model of UFLP in this section were mostly expanded on the formulation provided by Balinski (1965), where a binary decision variable was set to select a facility location (Balinski 1965), which is one of the first computationally successful practices in the formulation and analysis of UFLP. A MIP formulation of the UFLP can be given as follows:

$$\min_{x,y} \sum_j f_j x_j + \mu \sum_i \sum_j n_i d_{ij} y_{ij} \quad (1)$$

$$\text{s. t. } \sum_j y_{ij} = 1, \forall i, j \in I, J \quad (2)$$

$$x_j - y_{ij} \geq 0, \forall i, j \in I, J \quad (3)$$

$$x_j, y_{ij} \in \{0,1\}, \forall i, j \in I, J \quad (4)$$

The objection function minimizes the result of the fixed-facility cost at their locations and the transportation cost from the locations to the demand sites. The definition of x_j is the facility locating decision at site j . y_{ij} is the assignment of the facility at site j serving the demand node i . f_j, μ, n_i are the fixed cost at site j , unit transportation cost, and facility demand at i , respectively. The constraints 2 and 3 limit that each demand node is provided one facility and the demand at node i cannot exceed the support number at site j . The constraint 4 requires the integer property of variables. This MIP formulation determines the optimal facilities assignment depending on the demands.

Based on the basic MIP formulation of UFLP, in the case of bridge prioritization and ABC construction technique selection, a more complex MIP model is developed. Besides the constraints on resources themselves, more constraints on investment, bridge structure, network serviceability, and transportation performance are added to make the model worthwhile for decision makers at transportation agencies. Notation in the mathematical model is introduced here, and includes related definitions.

The contributions of this work can be summarized as the following: i) Due to the nature of the bridge prioritization and construction technique selection, and its impact on the indirect costs at the network level, the bridge and network performances are improved, the available ABC construction techniques are made the best use by decision makers at a network level, and the losses of traffic users are decreased. ii) Considering the changeable property of the network capacity during the bridge replacement, the dynamic network traffic assignment is analyzed all the time in the MIP model to timely respond to the indirect cost of the entire network. iii) The computational expenses are reduced by using the branch and cut method that establishes a rigorous logical searching structure and helps quickly find the global solution (the best solution that could be found). iv) The heuristic solution algorithm of least discrepancy search is discussed for the application of this model on the large network, which could cut a large part of the computing time in the MIP model and generate a local optimal solution (the pretty good but not the best solution that could be found to improve the bridge and network serviceability under the limitation of the budget). The reason is that the searching of the global optimal solution in a large network for most programming models is extremely computing expensive and commonly couldn't be solved in polynomial time, which implies the infinite running of models. The local search is widely proved as an efficient way to obtain a solution for a large-scale dataset.

Notation

Sets

- N : Set of topological network nodes.
- L : Set of topological network links.
- D : Set of O-D pairs, indexed by i and j . $D \subseteq N$.
- B : Set of bridges, indexed by k .
- S : Set of ABC techniques, indexed by l .
- R : Set of ABC techniques that cannot be used on bridges, indexed by k and l .
- $C_{r\&t}$: Set of bridge replacement costs of all ABC techniques.
- SR_{pre} : Set of pre-replacement sufficiency rating values of bridges in network, indexed by k .
- SR_{post} : Set of post-replacement sufficiency rating values of bridges in network, indexed by k .

Parameters

- $O(r, x)$: Minimum total cost of the traffic network after bridge replacement.
- C_{unit} : Standard unit mileage rating for each business mile driven, 53.5 cent/mile, announced by the Internal Revenue Service for 2017 (2016).
- C_{time} : Matrix of bridge closure time for different bridges with various construction techniques.
- c_a^E : Excellent link capacity of link a , $a \in L$.
- c_a^0 : Initial link capacity of link a , $a \in L$.
- $c'_{a,h}$: Residual link capacity of link a at interval h of bridge closure time, indexed by k , $a \in L$.
- $t_{0,a}$: Free flow traffic time of link a .
- $t_{a,h}(x_{ij,h}^p)$: Traffic time of link a through route p from node i to node j under interval h of bridge closure time.
- Ite : Bridge closure time interval that a bridge condition will keep the same in this replacement interval and be improved to a new condition in the next interval.
- $v_{a,h}$: Total traffic flow on link a under interval h of bridge closure time.
- $T_{ij,h}$: Traffic demand from node i to node j under interval h of bridge closure time.
- I : Available investment budget for all bridge replacements.
- H : Max interval number of bridge closure time, associated with the variable r .
- $S_1^{i'}$: The i^{th} factor of structural adequacy and safety items in National Bridge Inventory (NBI), $\max i'=4$.
- $S_2^{j'}$: The j^{th} factor of serviceability and functional obsolescence items in NBI, $\max j'=13$.
- $S_3^{k'}$: The k^{th} factor of essentiality for public use items in NBI, $\max k'=3$.
- $S_4^{l'}$: The l^{th} factor of special reductions items in NBI, $\max l'=3$.
- ε : A sufficiently small positive constant associated with the artificial variable r .
- M : A large positive penalty constant associated with the artificial variable r .
- $\sum_{h=1}^H T_{closure}$: Sum of the closure time for each bridge of all intervals.
- $\sum_h^H T_{closure}$: Sum of closure time for each bridge from interval h of bridge closure to the end.

- n : Number of bridges of the transportation network.
- m : Number of ABC techniques for the transportation network.

Decision Variables

- r : Integral bridge replacement variable including candidate bridges and the assigned ABC techniques, indexed by k and l .
- $\delta_{ij,h}^{a,p}$: Binary variable. $\delta_{ij,h}^{a,p} = 1$, when link a is involved in route p from node i to node j under interval h of bridge closure time, and 0 otherwise.
- $x_{ij,h}^p$: Continuous variable of traffic flow on route p from node i to node j under interval h of bridge closure time.

The objective function $O(r, x_{ij,h}^p)$ is given in Equation 5. The outputs of this model are: i) the optimal bridge replacement locations, ii) the most socio-economic ABC technique for the replaced bridges, and iii) the average bridge network serviceability rating that requires the condition of bridges after replacement to meet the target condition as a minimum. The objective goal is to minimize the sum of the direct and indirect costs to meet the budgetary constraints (imposed by the decision maker) and reduce the traffic time of the entire network (i.e., indirect costs). In Equation 5, the direct construction cost is formulated as the matrix multiplication of all bridge replacement costs and the strategy on replacement and technique.

$$O(r, x_{ij,h}^p): \min_{r,x} C_{r\&t}r + \sum_{h=1}^H C_{unit} \sum_{a,h} \int_0^{v_{a,h}} t_{a,h}(x_{ij,h}^p)dx \quad (5)$$

The indirect cost associated with the traffic network is converted from traffic time of users into cost by using C_{unit} during the closure time of all candidate replacement activities. Notable is, as the transport cost of construction equipment has been considered in the direct construction cost, it won't be counted again in this objective function. The extensions and constraints of the MIP model are interpreted with Equations 2–21 in the following sections. The required input data and the expected output data are listed in Figure 3.

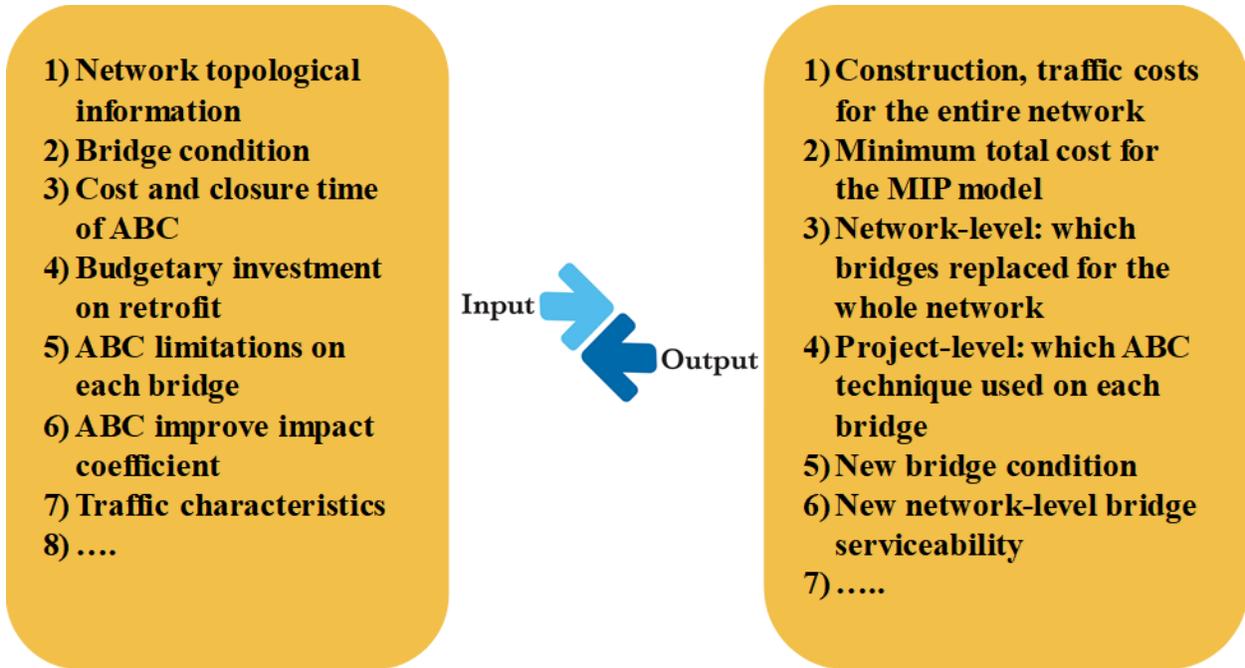


Figure 3. The input and output data in the current MIP model

Bridge Replacement Limitations

Due to the specific features pertaining to bridge site conditions, weather, and terrain at the bridge locations, not all ABC techniques can be implemented on a specific site. This is an important factor that needs to be accounted for in any DSS developed for this purpose. Equations 6–10 are constraints on the strategies of bridge replacement prioritization and ABC technique selection that ensure the engineering practicalities of all strategies are accounted for in the model. Equation 6 restricts every candidate strategy bounded to a specified investment budget, I , in Equation 10. Equation 7 highlights the technique limitations for each bridge. If the l th ABC technique can't be adopted on bridge k , the $r(k,l)$ in any potential strategy is set to zero, which implies that the bridge k will never be replaced with the l th ABC technique. The subset R represents the unavailable ABC techniques for all bridges. The mutually exclusive constraint of Equation 8 reflects the contingency of techniques that no more than one ABC technique can be used on a specific bridge, because any ABC technique is a series of improved construction activities that could be used for specific replacement projects. Equation 9 reflects the assignment of ABC techniques at their respective bridge locations, where $r(k,l)$ is an integer variable deploying technique l at bridge k . Additionally, there are some other constraints on bridge replacement, which will be discussed later when the constraints of bridge rating are incorporated into the MIP model.

$$C_{r\&t}r \leq I \quad (6)$$

$$r(k,l) = 0, \forall k, l \in R \quad (7)$$

$$\sum_l r(k, l) \leq 1, \forall k \in B, l \in S \quad (8)$$

$$r(k, l) \in \{0, 1\}, \forall k \in B, l \in S \quad (9)$$

$$I, \text{ constant} \quad (10)$$

Bridge replacement activity will result in partial or full closure at the bridge location. Commonly, at first the bridge will be completely closed to finish the basic construction of bridge structures and after that, a low traffic flow is allowed over the bridge. Equations 11 and 12 represent the constraint functions for closure time under a specific replacement strategy and the associated closure intervals that result in estimation of the indirect losses due to traffic delay. The value of H is closely related to the fixed replacement interval time, I_{te} . A smaller I_{te} implies a bigger H and a more accurate estimation on the total traffic cost from Equation 5, as a result of the tiny intervals. In this report, I_{te} is denoted as three weeks of bridge closure for the control of the computational expense.

$$H = \left\lceil \frac{1}{I_{te}} \max(rC_{time}) \right\rceil \quad (11)$$

$$\sum_{h=1}^H T_{closure} = rC_{time} \quad (12)$$

Bridge Rating

The closure of a bridge due to failing to meet the serviceability or strength requirements results in partial or full closure of the bridge, which adversely impacts the network connectivity and may result in long detours for the network users. Recent studies have shown that the closure of bridges results in indirect costs associated with travelers' delay that can be more than 10 times the bridge cost. The higher indirect costs require the stakeholders to invest in strategies that would result in expedited replacement of the bridges while maintaining the bridge network to an acceptable level. For this purpose, a bridge performance measure needs to be considered that facilitates the selection and prioritization of the bridges based on a pre-set criteria [MAP-21].

There are two commonly used guide manuals within the bridge community that could be used as a basis for this selection: the American Association of State Highway and Transportation Officials (AASHTO) condition rating index ranging from 1 (sound condition) to 4 (beyond the established structural limits) and the National Bridge Inventory (NBI) condition rating index ranging from 0 (failed condition) to 9 (excellent condition) (AASHTO 2010, FHWA 1995). While the manuals provide an assessment on each component of a bridge, such as deck, pier, and abutment, they fail to supply an overall estimation on the service condition of the bridge. This specificity complicates the problem at the network level when bridges with various ages, types, materials, structure types, and geometries exist. To address this issue, many global bridge rating indices have been developed over the years. For example, FHWA defined the structurally deficient (SD) category to classify bridges requiring federal aid (FHWA 1992). The SD metric consists of the structural and appraisal ratings using the values from NBI. Shepard and Johnson

proposed the bridge health index (BHI) that is identified as the percentage number of the current element inspection data to their initial ones (Shepard and Johnson 2001), which was widely used by federal agencies and state departments of transportation (DOTs) (Jiang and Rens 2010, FHWA 2014). The vulnerability rating index (VR) ranging from 1 (requiring safety priority action) to 5 (requiring no action) was put forward by New York state DOT to detect the bridge failure probability when facing the hydraulic, collision, and overload events (NYSDOT 1996, Valenzuela et al. 2010). All above indices have been adopted as the performance measure on large-scale studies. A survey of all bridge rating indices showed that the sufficiency rating index (SR) (Adams and Myungook 2009) is the most commonly used indicator used for bridge replacement prioritization. The reason is that SR accounts for the funding allocation and structural performance of the bridge network (Patidar et al. 2007). Equation 13 shows the calculation of the overall SR for a bridge:

$$SR = \sum_{i'} S_1^{i'} \sum_{j'} S_2^{j'} + \sum_{k'} S_3^{k'} - \sum_{l'} S_4^{l'} \quad (13)$$

SR ranges from 0% (failed condition) to 100% (best condition). The four parameters in the SR function are structural adequacy and safety, functionality and serviceability, essentiality to public use, and special reductions related to traffic impacts, represented as S_1, S_2, S_3, S_4 . From Adams and Myungook (2009), the maximums of $\sum_{i'} S_1^{i'}$, $\sum_{j'} S_2^{j'}$, $\sum_{k'} S_3^{k'}$, and $\sum_{l'} S_4^{l'}$ are 55%, 30%, 15%, and 13%, respectively. More details of the parameters can be found in the Notations section and (FHWA 1995, Adams and Myungook 2009). The relationship between SR and replacement decision is outlined in Table 2.

Table 2. Relationship between SR value and bridge replacement

Percentage	Bridge condition	Replace requirement
$SR \geq 80\%$	Good serviceability	No action
$50\% \leq SR < 80\%$	Light deficiency	Replacement/rehabilitation
$SR < 50\%$	Severe deficiency	Replacement

Based on the requirements shown in Table 2, the following constraints are set for SR values Equations 14–17. Equation 14 states that the SR value after replacement is a function of the replacement strategy. For $\varepsilon \geq 0$ sufficiently small and $M \geq 0$ sufficiently big, the value of $SR_{post}(k)$ has the same trend as $\sum_l r(k, l)$. If the bridge k is replaced with any ABC technique, $\sum_l r(k, l) = 1$, then its $SR_{post}(k)$ is set to be 100%, with excellent serviceability, but if a bridge is not replaced, $\sum_l r(k, l) = 0$, then $SR_{post}(k) = SR_{pre}(k)$, as the original bridge serviceability. Equation 15 calculates the average value of SRs of the network after replacement and requires the value to be equal to the pre-set target performance measure of 60%. This value is shown to represent a satisfactory performance condition that indicates bridges only show some minor deteriorations and could continue to service in the network satisfactorily (FHWA 1995).

$$\sum_l r(k, l) \varepsilon \leq SR_{post}(k) - SR_{pre}(k) \leq \sum_l r(k, l) M, \forall k \in B, l \in S \quad (14)$$

$$\frac{1}{n} \sum_{i=1}^n SR_{post}(k) \geq 0.6, \forall k \in B \quad (15)$$

$$SR_{post}(k) \in \{SR_{pre}(k), 100\%\}, \forall k \in B \quad (16)$$

$$\varepsilon, M, \text{ constant} \quad (17)$$

Equations 18 and 19 are the additional constraints on the bridge replacement decision process. Equation 18 states that an initial SR value for bridge k larger than 80%, implies that the bridge does not require the replacement action (see Table 2) and the replacement decision of bridge k should be set equal to zero, $\sum_l r(k, l) = 0$. Otherwise, no constraint on bridge k should be applied. This constraint also has an economic contribution on controlling the expenses. Equation 19 ensures that the replacement of bridge k is a mandatory action, $\sum_l r(k, l) = 1$, when the $SR_{pre}(k)$ is lower than 50%, as the bridge does not meet the service requirements. Merging these two constraints, the replacement strategies can only be chosen from the following: Bridges with a SR value lower than 50% must be replaced; bridges with a SR value larger than 80% will not be replaced; and bridges with a SR value in the range of 50% to 80% may be selected to be replaced.

$$(SR_{pre}(k) - 0.8) \sum_l r(k, l) \leq 0, \forall k \in B, l \in S \quad (18)$$

$$(SR_{pre}(k) - 0.5)(1 - \sum_l r(k, l)) \geq 0, \forall k \in B, l \in S \quad (19)$$

Dynamic Traffic Assignment

To assess the indirect costs associated with the closures during bridge replacement in the MIP model, a network-level dynamic analysis on traffic flow and travel time is necessary. For this purpose, the four step transportation forecasting model (FSM) is applied to generate the origin-destination (OD) trip table and assign the OD trips to the network. The traffic assignment model of FSM in this report is the user equilibrium (UE) model satisfying Wardrop's selfish equilibrium principle that states the traffic time on the unused routes must be larger than or equal to the traffic time along the used routes (Ortúzar and Willumsen 1994). The UE model has been proven to be a convex problem, which implies the outcome of a global minimum traffic time of the network (Beckmann et al. 1955). The sub-problem can be written as objective function of Equation 20 with constraints mentioned in Equations 21–27. As the network capacity is continuously increasing in the process of bridge replacement, the traffic assignment is run repeatedly until the end of the entire network replacement. The objective minimized network traffic time of Equation 20 is a component of the current MIP model as stated in Equation 5.

$$\min_{r,x} \sum_{a,h} \int_0^{v_{a,h}} t_{a,h}(x_{ij,h}^p) dx \quad (20)$$

$$t_{a,h}(x_{ij,h}^p) = t_{0,a} (1 + 0.15 (\frac{v_{a,h}}{c_{a,h}})^4), \forall i, j \in D, a \in L \quad (21)$$

$$c'_{a,h}(k)(\sum_h^H T_{closure} - \frac{2}{3}\sum_{h=1}^H T_{closure}) \leq 0, \forall a \in L, k \in B \quad (22)$$

$$v_{a,h} = \sum_i \sum_j \sum_p \delta_{ij,h}^{a,p} x_{ij,h}^p, \forall a \in L, i, j \in D \quad (23)$$

$$\sum_p x_{ij,h}^p = T_{ij,h}, \forall i, j \in D \quad (24)$$

$$c'_{a,h}(k) \in \left\{ c_a^E(k) \frac{\sum_h^H T_{closure}}{\frac{2}{3}\sum_{h=1}^H T_{closure}}, c_a^0(k), 0 \right\}, \forall a \in L, k \in B \quad (25)$$

$$x_{ij,h}^p \geq 0, \forall i, j \in D \quad (26)$$

$$\delta_{ij,h}^{a,p} \in \{0,1\}, \forall a \in L, i, j \in D \quad (27)$$

Equation 20 returns the sum of traveling time throughout the network during the closure interval, h . The minimizing process can realize the convergence to the Wardrop's selfish equilibrium. Equation 21 is the Bureau of Public Roads (BPR) function to calculate the link traffic time resulting from the assigned flows on a specific route for each OD pair (Cambridge Systematics, Inc. 2010). Equation 22 redefines the link capacity during the replacement process that can have three potential values. If there is no bridge located on a link, the capacity of this link is assumed to be a constant. If the sum of closure time of a bridge from the start to the interval h is less than $\frac{1}{3}$ of the entire closure time, the link capacity that the bridge located is set zero at interval h . Otherwise, for the last 2/3 of closure time duration, the link capacity is defined as the multiplication of the full capacity of the link and the fraction of the residual time by the entire closure time (Equation 25). The purpose of Equations 22 and 25 is to realize the dynamic assignment of traffic flows during network restoration. Equations 23 and 24 state the equilibrium states of a link and the traffic demand of an OD pair at each interval h , respectively. The non-negative trips constraint of Equation 26 is important, which ensures the assignment decision is reasonable and practical. Equation 27 states the selection of routes. If path p of OD pair (i,j) is used at interval h , $\delta_{ij,h}^{a,p} = 1$, and $\delta_{ij,h}^{a,p} = 0$, otherwise.

To sum up, Figure 4 lists the main constraints and goals that the decision makers desire in the network-level bridge replacement actions. All constraints in Figure 4 are changeable and could be re-defined based on each specific network dataset and the expert experiments. For example, the average SR value in the group of bridge rating could be increased up to 80% to satisfy the good serviceability of a network.

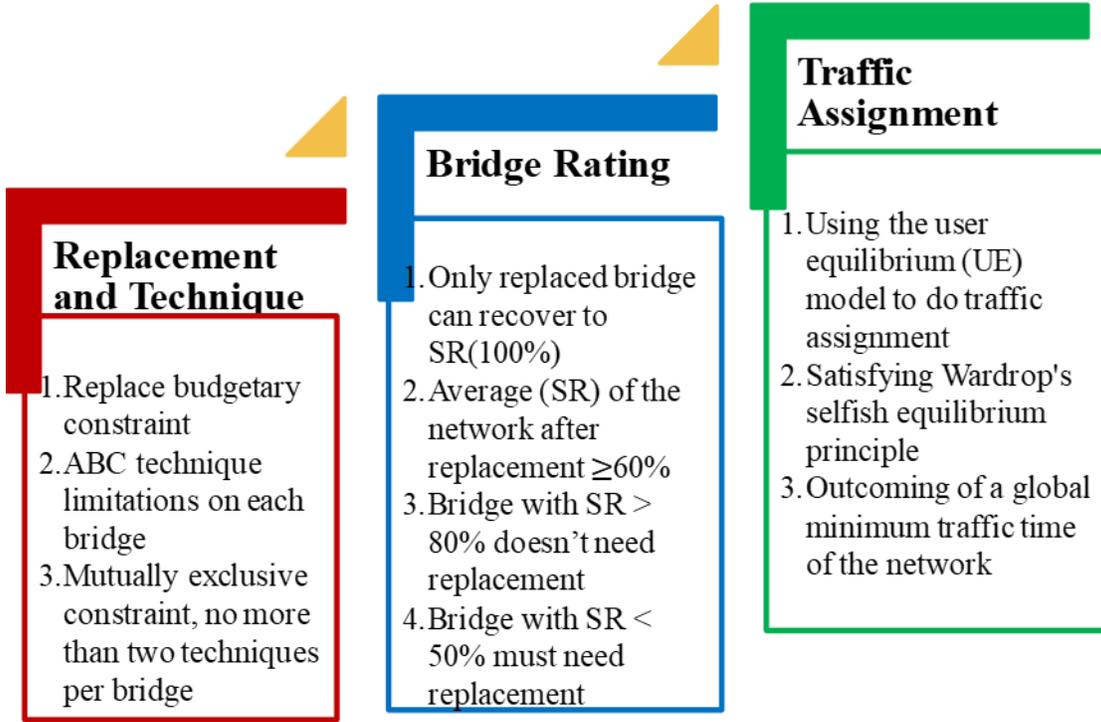


Figure 4. Limitations and constraints of the MIP model

BC Solution Algorithm

There are many solution algorithms for solving the MIP problem such as the branch and bound (BB) method, cutting plane (CP) method, and their combination method of branch and cut (BC) (Balinski 1965). Using the BB approach, the objective problem can be partitioned into smaller sub-problems according to the optimal solution of its integer-relaxed problem (Clausen 1999). Through evaluating the sub-problems, the sets of feasible solutions, unbounded solutions, and infeasible solutions are separated. Comparing the sub-optimal values in each feasible set, the MIP optimal solution is found (Clausen 1999, Kumar and Kanal 1983). CP is an optimization method that iteratively adds cutting constraints to the initial relaxed problem to reshape the feasible set until the integer optimal solution appears. The more efficient algorithm is BC. The superiority of BC algorithm is applying the CP step before the branching step of BB to accelerate the searching speed (Mitchell 2000). The BC algorithm for this current MIP is developed such that the specific cutting constraints are used to bound the selected bridge number for each sub-problem, which directly restricts parts of the r variable integral (Danczyk and Liu 2011), see Equations 28–34.

$$P: \{(r, x) \in \{1\}^{n_{Mu} \times m} \times \mathbf{Z}_+^{n_{Mb} \times m} \times \{0\}^{n_{Mn} \times m} \times \mathbf{R}_+^p : s. t. Eqs. (2) - (21)\} \quad (28)$$

$$P_0: \{(r, x) \in \{1\}^{n_{Mu} \times m} \times \mathbf{R}_+^{n_{Mb} \times m} \times \{0\}^{n_{Mn} \times m} \times \mathbf{R}_+^p : s. t. Eqs. (2) - (21)\} \quad (29)$$

$$C_{i-1_1}: \sum_l r(k, l) = 1, \forall k \in H_T, l \in R \quad (30)$$

$$C_{i-1_2}: \sum_l r(k, l) = 0, \forall k \in \{H_T - H_{T'}\}, l \in R \quad (31)$$

$$P_{i-1_{1,2}}: \left\{ \begin{array}{l} (r, x) \in \{1\}^{n_{Mu} \times m} \times \mathbf{Z}_+^{n_{H_{T'}} \times m} \times \mathbf{R}_+^{n_{Mb-H_{T'}} \times m} \times \{0\}^{n_{Mn} \times m} \times \mathbf{R}_+^p : \\ \text{s. t. Eqs. (2) - (21)} \\ H_{T'} \subseteq C_{i-2} \end{array} \right\} \quad (32)$$

$$P_{i_{1,2}}: C_{i-1_1} \cap P_{i-1_1}, P_{i_2}: C_{i-1_2} \cap P_{i-1_2} \quad (33)$$

$$H_{T'} \subseteq H_T \quad (34)$$

The natural MIP is set as P , in Equation 28. Its relaxation problem is P_0 (Equation 29), and the solutions of P and P_0 are S^* and S_0 , respectively. According to Table 2, the bridges can be divided into three classes: Bridges that must be replaced are denoted as set M_u ; bridges with good conditions denoted as set M_n ; and bridges having no imperative replacing demands denoted as set M_b . In BC, the sub-problems P_{i_1} and P_{i_2} are branched from their parent problem P_{i-1_1} , and the same process will be repeated for all parent problems at the same height of $i-1$. Before branching, the cutting constraint C_{i-1_1} is added, which is iteratively increasing the selection of bridges in M_b . The continuous expansion of the bridge selection set in C_{i-1} is stored in H_T , whose size is simultaneously the same as the height of P_{i-1} in BC tree. Since only the variable r related to M_b can be used to realize the process of branch and cutting, the maximum possible height of BC tree is the size of M_b . To start the BC process, a heuristic feasible solution, S_0 , is calculated for P_0 . At first, let $S^* = S_0$. Then, in sub-problem P_i , the feasible solution S_i is calculated. If $S_i < S^*$, let $S^* = S_i$. Repeating the comparison at all feasible sub-problems, the S^* will reach to an optimal value. To sum up, the specific BC searching structure refers to the binary searching tree (BST) stating that to search for a node in BST, the unique path from root to the desired node needs to be followed. Based on the above explanation, the solution algorithm is outlined in the following Figure 5.

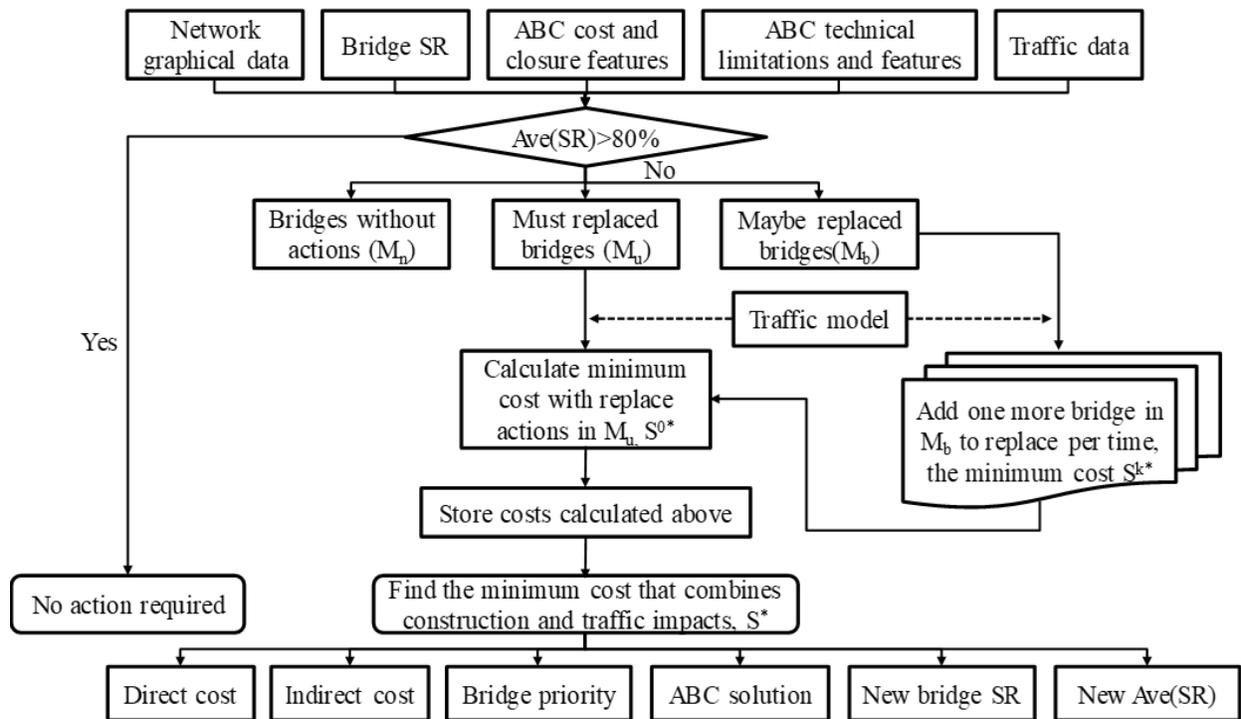


Figure 5. BC solution algorithm outline for project-level to network-level MIP model

For this purpose, the Frank-Wolfe algorithm (convex combination algorithm) (Ortúzar and Willumsen 1994) is used to find the approximate solution of the minimum traffic time of the transportation network at the traffic assignment segment of MIP for each bridge closure interval.

COMPUTATIONAL STUDY AND DISCUSSION

To assess the performance of the proposed MIP model, a case study on the bi-directional transportation network of Sioux Falls, SD is conducted. All network data are from LeBlanc et al. (1975). As shown in Figure 6, there are 24 zones and 76 directed links in the network. In addition to network topology, the OD matrix, link capacity, and the free flow traffic time (in hours) are input to the model. The total traffic demand in OD matrix is 360,600. The basic assumptions for the computational case study are organized and defined as follows:

- Eight bridges are located on the transportation network. The details of bridge location, SR value, replacement action, and ABC technique limitation are assumed in Table 3 and Figure 6. For instance, bridge 4 is located between node 12 and 13 on the left corner of network. Its SR value is 0.55 (55%) and it doesn't require an imperative replacement but could be considered as the potential candidate given the availability of construction resources.

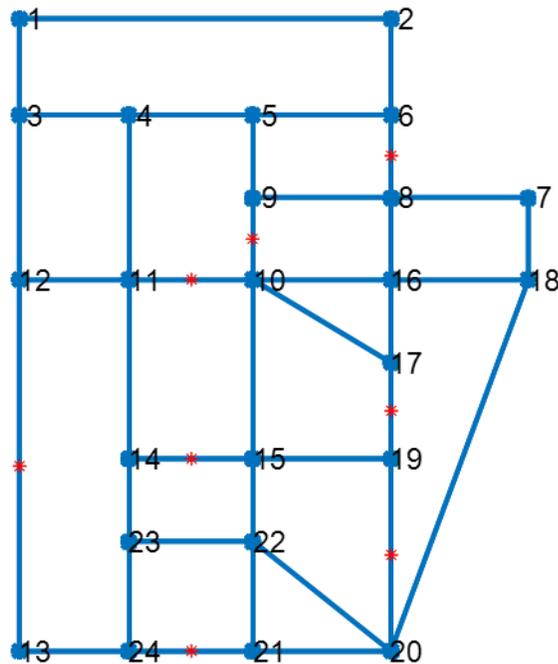


Figure 6. The node, link, and bridge locations for the case study network (Note that bridge numbers are in bold and underlined)

Table 3. SR value, replacement action, and ABC technique limitation of bridges

Bridge ID	1	2	3	4	5	6	7	8
Location	(6, 8)	(9, 10)	(10, 11)	(12, 13)	(14, 15)	(17, 19)	(19, 20)	(21, 24)
SR	0.82	0.25	0.9	0.55	0.15	0.6	0.85	0.4
Action	None	Replace	None	Potential replace	Replace	Potential replace	None	Replace
Unavailable technique ID	1, 5	1, 2, 3	3	2, 5	4, 5	2, 5, 6	None	1, 2, 4, 6

- One ABC technique is adopted in a bridge construction project. In practice, most ABC techniques listed in Table 1 are normally combined with the prefabricated technique (PBES). Thus, PBES is taken as an assistant technique that is applied to all bridges. The remaining six techniques (ID1–6) are separately used in each bridge site, considering the bridge site and local construction constraints. For instance, the ABC technique ID2 and 5 are assumed not to be implemented to bridge 4 considering the site condition.
- Each bridge is assigned a specific closure time and direct cost depending on the size and location representing the real conditions. Because of the efficiency of ABC techniques, the closure time can be reduced and the direct cost will increase. The assumed values for bridge closure time, basic direct cost and impact coefficient (IC) value of ABC techniques are listed in Table 4. The replacement cost of the bridge (in Table 4) represents the cost required through conventional methods (not ABC techniques) to replace the bridge. It's a function of the bridge size, material, structural type, and location. The direct cost of each ABC technique is the multiplication of the conventional direct cost and the IC value. A larger impact coefficient (IC) value signifies a more rapid ABC technique and also implies a higher construction cost. Thus, the final direct cost depends on the IC values of the optimal strategy. The construction techniques have been sorted and named based on their IC showing the closure time relations as follows: $t_{ID1} < t_{ID2} < t_{ID3} < t_{ID4} < t_{ID5} < t_{ID6}$.

Table 4. Bridge replacement closure time, basic direct cost, and the technique IC values

ABC ID	ID1	ID2	ID3	ID4	ID5	ID6	Replacement cost
Bridge1	80	115	140	170	210	250	71.3
Bridge2	72	103.5	126	153	189	225	308.1
Bridge3	80	115	140	170	210	250	53.46
Bridge4	40	57.5	70	85	105	125	60.61
Bridge5	80	115	140	170	210	250	403.1
Bridge6	32	46	56	68	84	100	23.9
Bridge7	52	74.75	91	110.5	136.5	162.5	16.79
Bridge8	72	103.5	126	153	189	225	109.4
IC	2.5	2.1	1.9	1.7	1.4	1.1	-

Note: The unit of the closure time is day; the unit of the replacement cost is in millions of dollars.

The applicability of the proposed MIP model and BC solution algorithm is tested considering different levels of available budget. In this case, bridges 1, 3, and 7 belong to set M_n ; bridged 2, 5, and 8 are in set M_u ; and bridged 4 and 6 belong to set M_b . The bridge closure interval time, Ite , is used to calculate the total number of the replacement closure intervals for the entire network, H , in Equation 11. The technique ID6 has the lowest effect on accelerating construction and technique ID1 has the highest effect. At the start of solution process, the heuristic feasible solution of S_0 is set as the best solution that only replaces bridges in M_u with the most economically effective ABC techniques, which satisfy the existing constraints on bridge and network SR ratings in Equations 14–19. Then, the cuts that control the selection of bridges in M_b are added, which speed up the branching process. For example, the cut that bridge 6 should be replaced is added before the first branching. Then the sub-problems can be divided into two that either bridges 2, 5, 6, 8 should be replaced or keep the solution in the parent step. If the replacement of bridge 2, 5, 6, 8 is more cost-saving, the sub-sub-problems can be described that whether bridge 4 should be replaced or not and which ABC technique should be used when bridges 2, 5, 6, and 8 are determined to replace. Step by step, the search for optimal solution, S^* , is conducted for different investment cases and results are displayed in Table 5 and Figure 7.

Table 5. Bridge replacement closure time, basic direct cost, and the technique IC values

Investment (\$ billion)	Optimal total direct cost (\$ billion)	Bridge optimal closure time (days)	Network traffic time
		Location: [(6,8), (9,10), (10,11), (12,13), (14,15), (17,19), (19,20), (21,24)]	after all replacements (hours)
1.00	0.9355	[0, 225, 0, 0, 250, 0, 0, 126]	2.9376×10^{10}
1.25	1.2348	[0, 153, 0, 0, 250, 32, 0, 126]	2.6264×10^{10}
1.50	1.4976	[0, 153, 0, 0, 140, 0, 0, 126]	2.0590×10^{10}
1.75	1.7394	[0, 153, 0, 0, 80, 0, 0, 126]	1.9096×10^{10}
2.00	1.7991	[0, 153, 0, 0, 80, 32, 0, 126]	1.9071×10^{10}
3.00	1.7991	[0, 153, 0, 0, 80, 32, 0, 126]	1.9071×10^{10}

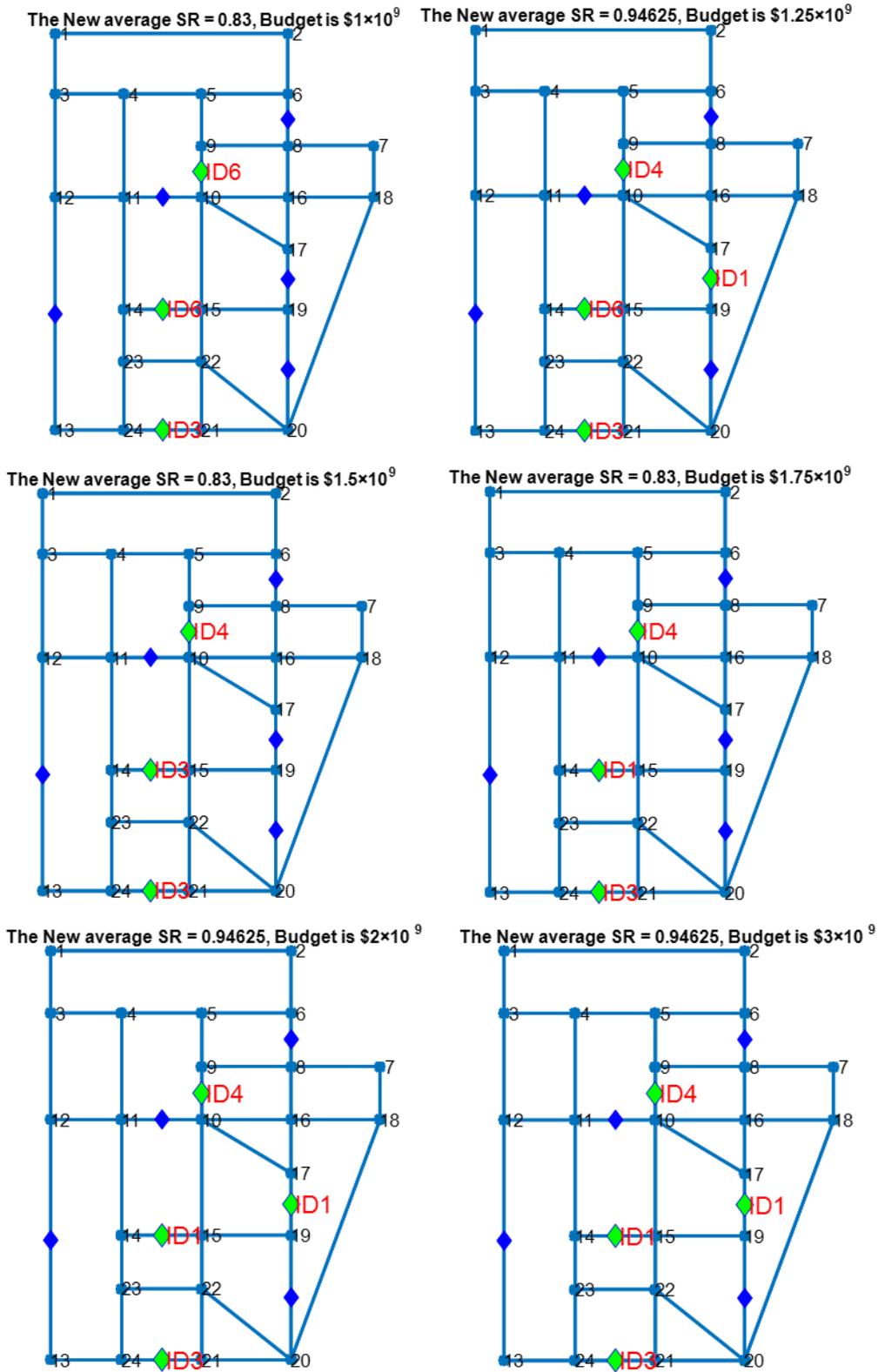


Figure 7. Six different investment strategies and the optimal bridge prioritization and ABC technique selection

Reviewing the direct costs associated with bridges in set M_u , investments under \$1 billion are far insufficient for the replacement optimization even with the slowest ABC techniques. Additionally, investments over \$2 billion cannot provide a better optimal solution than the solution with \$2 billion investment. That is because the investment of \$2 billion has covered all direct costs of bridges in set M_u and M_b . The budgetary constraint in Equation 6 doesn't play a role for investments over \$2 billion. There is little room to improve when bridges are replaced with their fastest techniques in the case of the \$2 billion investment. All the optimal strategies shown in Table 5 and Figure 7 have resulted in an improvement in average network SR value. In the range of \$1 billion and \$2 billion, a variety of optimal strategies are provided that affect the SR, total cost, or both. With the lower budgetary constraint of \$1 billion, only bridges in set M_u are replaced and the slower ABC techniques are selected. This results in long closure durations and a long time to restore the bridges. The network traffic time after replacement of all selected bridges is also the largest. Increasing the investment by 25% results in selection of bridge 2, 5, 6, and 8 for replacement with ABC techniques ID4, ID6, ID1, and ID3, respectively.

The adoption of expedited construction techniques contributes to the saving on traffic time and achieves a shorter closure at bridge sites, while replacement of bridges contributes to higher SR values at the network level. Increasing the investment to \$1.5 billion, only bridges 2, 5, and 8 are replaced. But it should be noticed that a more expedited construction technique (i.e., ID3) is selected to replace bridge 5 in this situation, which could reduce the closure time of bridge 5 by 44%, resulting in much lower traffic delay compared to the previous case (\$1.25 billion investment). Here, although SR values dropped compared to the previous case, it is still above the target value of 60%. The traffic cost saved on closure time offsets the cost associated with the disregarding bridge 6 for replacement, which is easy to see in Table 5. In the fourth investment scenario (\$1.75 billion), the construction technique changes from ID3 to ID1 (the more expedient and more expensive technique) for bridge 5, which results in another 24% reduction of its original closure time and the network traffic time as presented in Table 5. With the higher investment (=\$2 billion), all previously selected bridges and construction techniques remain the same and now bridge 6 is also selected for replacement with the most expedited construction technique. However, increasing the available budget doesn't result in selection of more bridges for replacement. For instance, while bridge 4 between node 12 and 13 could be potentially replaced (barring availability of funds), the location of the bridge and less strategic role it plays in savings on traffic time and closure time, results in disregarding it for replacement even when funds are available (=\$3 billion case). This is because, the MIP is designed to find the most optimal case considering the following targets: minimum network-level total cost (which is associated with construction and traffic time), ensuring average bridge network SR over 60% to support a satisfactory bridge network service functionality, and SR value for each bridge larger than 50% to ensure a fair bridge condition (defined as a bridge with sound structural elements but with minor deterioration).

Therefore, the optimal solution for the transportation network of Sioux Falls is to replace bridges 2, 5, 6, and 8 (not all bridges in set M_u and M_b) with their fastest techniques (the technique that is available and not limited in Table 4) of ID4, ID1, ID1, and ID3, which is a balanced portfolio of the construction techniques that result in optimum closure time and construction cost.

In Figure 8, the direct and indirect costs for each defined scenario are compared. It displays the relative accuracies of total cost estimation with budgeted replacement during the entire network restoration process.

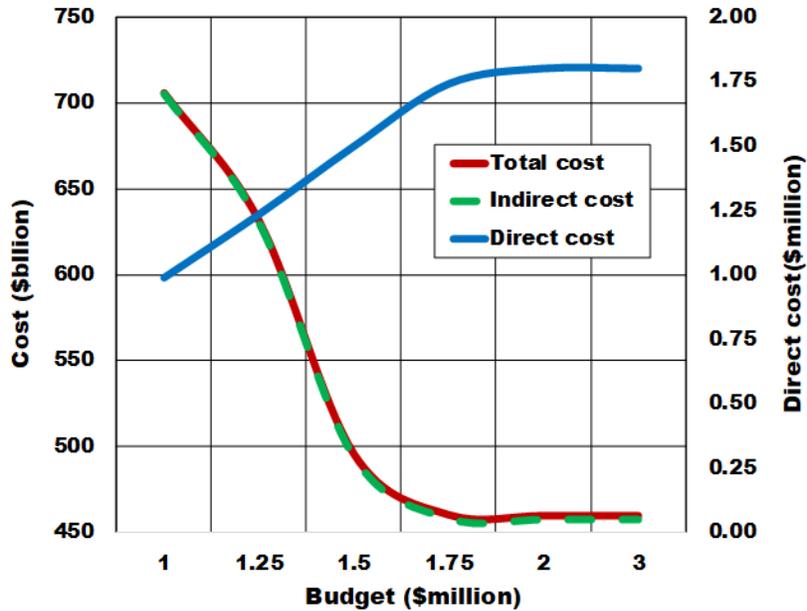


Figure 8. Comparison of direct, indirect, and total costs for the different strategies considered

The values in this figure are the optimal outcomes from the various investments mentioned before (summarized in Table 5). Increasing the investment on bridge construction decreases the network total cost. It is obvious that for the long term the indirect cost from transportation plays a conclusive role in the total network cost. It implies that increasing investment to reduce bridge closure time during replacement is very important. For instance, the network direct cost increases on a unit of \$250 million may promote approximately a \$50 billion decrease on the indirect and total cost. Moreover, focusing on the gap of the network optimal direct costs of the six cases, an additional \$810 million investment on the basic of \$1 billion redounds to an extraneous earning of \$247 billion on the entire network cost whose socio-economic return rate reaches up to 305%. All the results imply the remarkable success of the MIP model on the project- to network-level prioritization of bridge replacement.

VALIDATION ANALYSIS

The BC algorithm for MIP model is a solution method to search all feasible solutions and find the optimal one. In other words, there are a series of feasible values generated during the BC process in the MIP model. And the results in Table 5 and Figure 7 are only the optimal solutions and values that are picked out from the feasible set under different budget constraints. To prove the fitness and meaningfulness of the MIP model and BC solution algorithm, and the accuracy of the results in the computational study part of the report, the data validation analysis is implemented in this chapter to ensure their qualities.

In Figure 9, all feasible values are shown under the six budget constraints that could be matched with the budgets in the computational study.

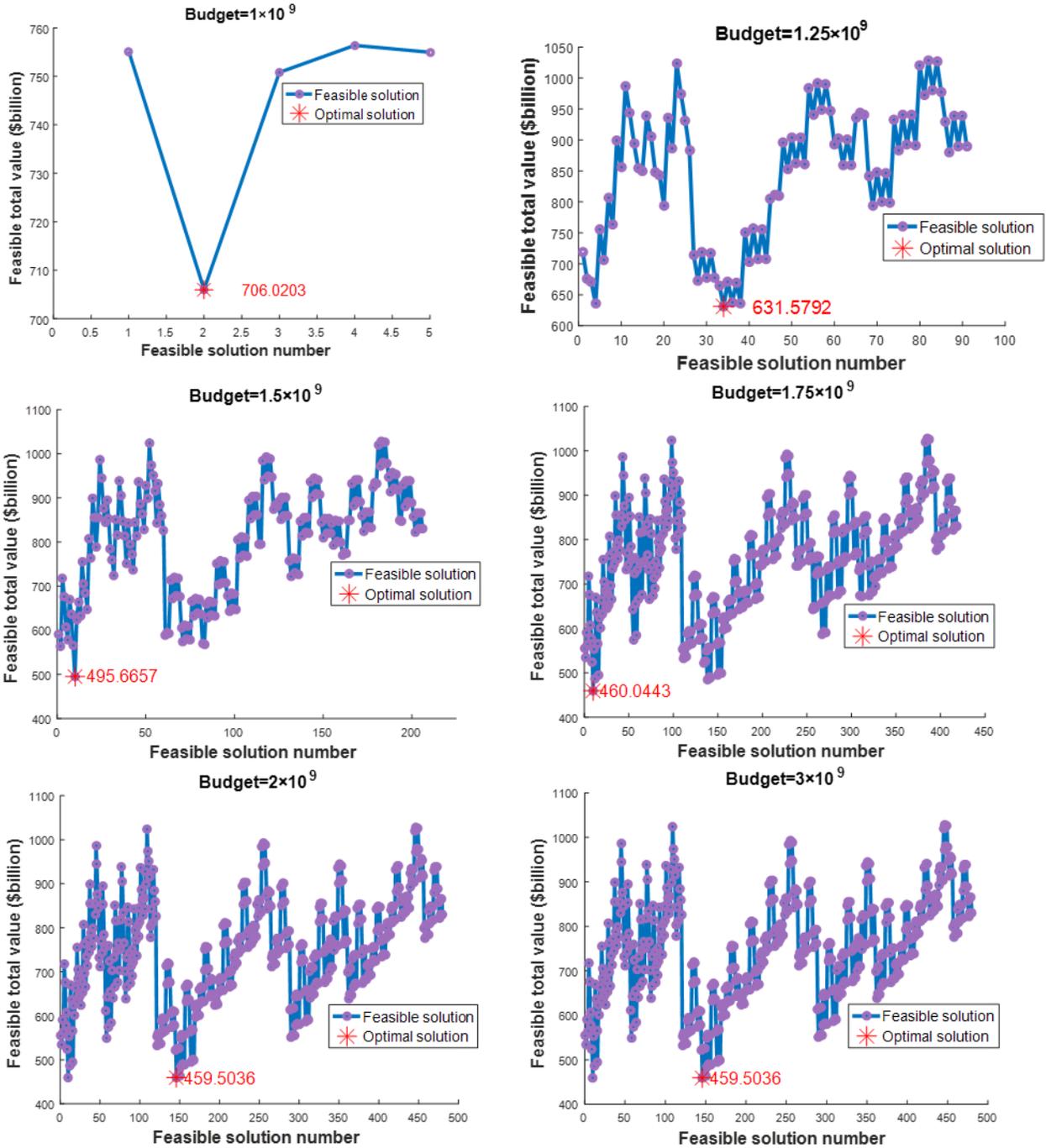


Figure 9. All feasible solutions and the optimal solution under various budgets

Table 6 represents the data characteristics and solution improvements related to Figure 9. At the same time, the optimal direct cost of each budget scenario is given, which is used to create the connection with all results that have been described in the computational study.

Table 6. Validation and improvement on MIP model and BC algorithm

Budget ($\\$ \times 10^9$)	1	1.25	1.5	1.75	2	3
Feasible solution number	5	91	206	418	480	480
Minimum bridge SR in feasible solution set	0.52	0.52	0.52	0.52	0.52	0.52
Minimum ave (SR) in feasible solution set	0.83	0.83	0.83	0.83	0.83	0.83
Optimal direct cost (\$ billion)	0.9355	1.2348	1.4976	1.7394	1.7991	1.7991
Optimal cost (\$ billion)	706.0203	631.5792	495.6657	460.0443	459.5036	459.5036
Cost improvement (%)	0%	11%	30%	35%	35%	35%

It is clear to see that with the growing of budget value, the number of feasible solutions (the number of the purple nodes in each image of Figure 9 and the feasible solution number in Table 6) increases significantly. It adequately satisfies the common evidence that the high investment provides a high possibility to replace more questionable bridges comparing to the low investment. When focusing on the optimal value of each image in Figure 9 (the red star mark), it can be affirmatively concluded that the current MIP model could always return the minimum total cost (the best desired value for decision makers) no matter how many feasible solutions the MIP model obtains, and furthermore, all the other feasible solutions could not lead to a total cost that is equal or less than the optimal one.

In the MIP model, it is required that bridges whose SR value under 0.5 (poor condition) must be replaced and the average bridge SR value at the network level should not be lower than 0.8 in order to guarantee a good network serviceability. In Table 6, the bridge SR value is checked no less than 0.52 and the average bridge SR value is no less than 0.83. It implies that all solutions obtained by the MIP model can achieve the goals on bridge SR values. On the model performance, due to the enhancement on construction investment, the incremental improvement percentage reaches up to 35% that consequently brings an outstanding cost-saving benefit around \$247 billion after all processes of bridge replacements in the network in the long term.

The validation analyses on MIP model and the searching results with BC algorithm are assessed as aforementioned in this chapter. The evaluations implemented in Figure 9 and Table 6 well prove the correctness and usefulness of these two methods. In summary, the results calculated by the MIP model and BC algorithm could satisfy their requirements and constraints and return the best solution to decision makers.

In the first interval, the zero discrepancy strategy is explored that bridge 4 and 6 in M_b are both replaced (the leftmost bold path in the first tree of Figure 10). If the solution is infeasible or the feasible solution is not the most desired, more intervals should be searched. In the second interval that allows the one discrepancy, two paths are searched: one is to not replace bridge 4 but replace bridge 6; another is to replace bridge 4 but not replace bridge 6. In the paths of the one discrepancy strategy (middle two trees in Figure 10), one wrong turn (right turn) is enabled. If the local solution satisfies requirements, then stop. If the solution set is infeasible, then go to the next interval. Finally, the strategy of two discrepancies with two wrong turns is considered that none of the bridges in M_b is replaced (the rightmost bold path in the right tree of Figure 10). The searching order of this LDS is based on the greedy algorithm with the objective of replacing as many bridges as possible.

Figure 11 shows the application of LDS on selection of appropriate ABC technique, which is embedded in each LDS interval of bridge selection problem and the network indirect cost is calculated in this process.

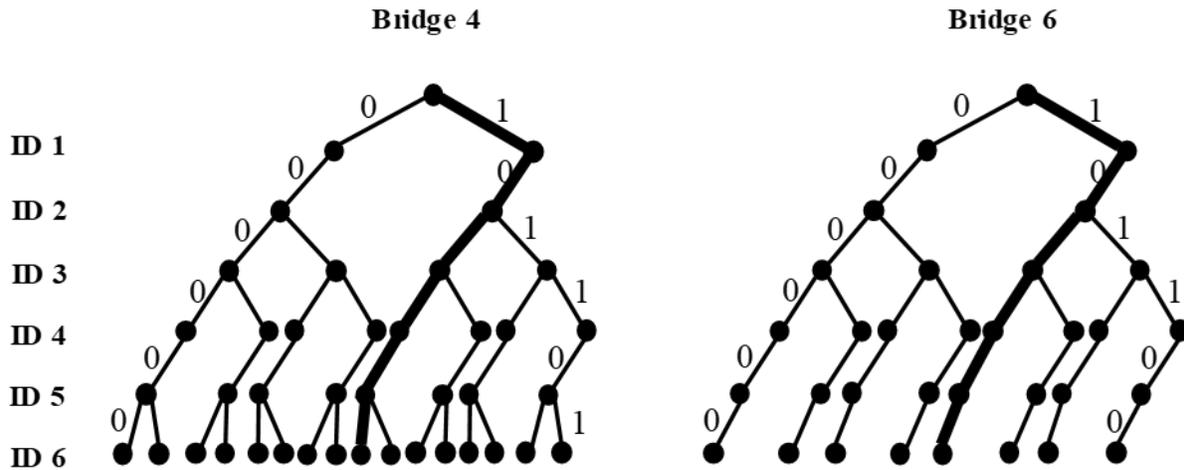


Figure 11. Sample solution with the exact one discrepancy of ABC technique selection for each of bridges 4 and 6

As one bridge can adopt one ABC technique on the basis of PBES, to promote the computing efficiency, the leftmost path is defined that no ABC technique is selected for a bridge. The discrepancy here means the number of techniques used for a bridge. Then, in this part, only paths with zero or one discrepancy are tested. At the same time, the tree in Figure 11 is a pruning tree having the same technique limitations of Table 3. For instance, technique 4 and 1 could not be used on bridge 4. The branching order for each tree coordinates with the accelerated impact coefficient (IC) of ABC techniques to ensure that the faster technique will be checked earlier. Figure 11 shows a sample of the fastest feasible solution that the exact one wrong turn happens at the fastest ABC technique node, the wrong turn from the root. For this paper, to achieve the network-level bridge selection and project-level ABC technique selection in one MIP model, the structure of the entire network LDS process is that the outer LDS interval is for the bridge selection

and the inner LDS interval is for the ABC technique selection for each bridge depending on the outer LDS condition.

The frame is shown in Figure 12 of this section. In the network- and project-level LDS processes, limitations can be embedded based on the specific demands from decision makers. For instance, the upper bound of discrepancy for bridge selection is one that means the strategy of bridges without replacements will not be searched, or the height of the ABC technique selection tree is three that represents the last three relatively slow ABC techniques will not be selected. Thus, the heuristic learning and solution searching can be implemented.

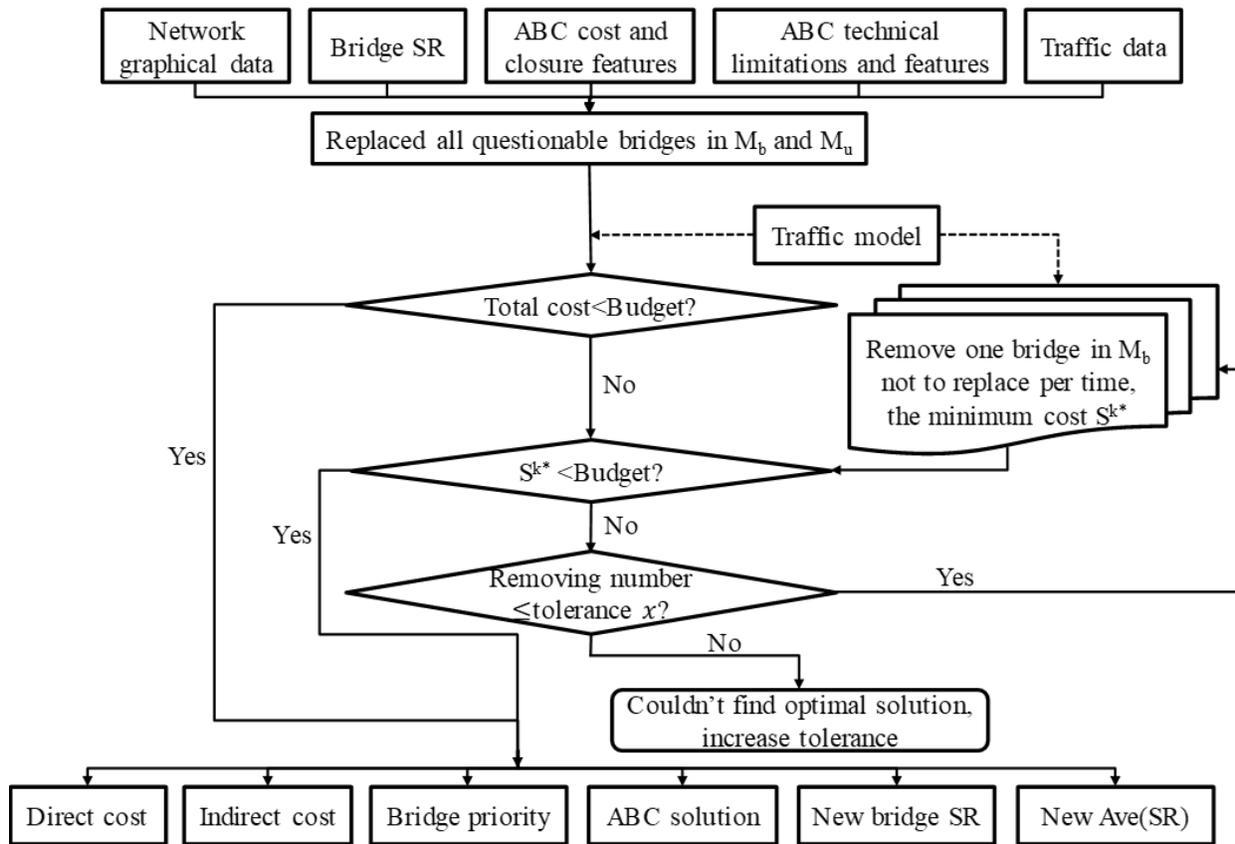


Figure 12. LDS solution algorithm outline for project-level to network-level MIP model

COMBINATION WITH TRADITIONAL AHP DECISION TOOL

The MIP model is a decision-making model that provides decisions not only on a specific bridge project but also on a strategy of the network. In fact, as mentioned in the introduction chapter, there already exists several ABC decision tools to help decision makers to judge the benefits between ABC construction method and the conventional construction method. Among these methods, the most widely used approach or the base of other redeveloped decision tools is the ABC-AHP decision tool developed by FHWA (2012). In order to clarify the necessity to create the MIP model, this chapter takes the traditional ABC-AHP tool as a comparison to show the difference and advantage of the MIP model.

Traditional ABC-AHP Tool

Analytical Hierarchy Process (AHP) is a decision-making methodology that is designed to deal with the group decision making in many areas. The process of this method is to construct multi-level hierarchies that include all relative criteria related to the objective decision-making problem; after a hierarchy tree is established to display the relationship of all criteria, a series of judgments based on pairwise comparisons of the elements are conducted at each level. Then, by synthesizing all judgments from the bottom level to the top root, a set of overall priorities for the hierarchy are yielded. Comprehensively, the final decision could be made via checking the consistency of the judgements. To extend to the AHP method on ABC projects according to the manual of the ABC-AHP decision tool (FHWA 2012), the AHP hierarchy structure and elements of each level are detailed in Figure 13.

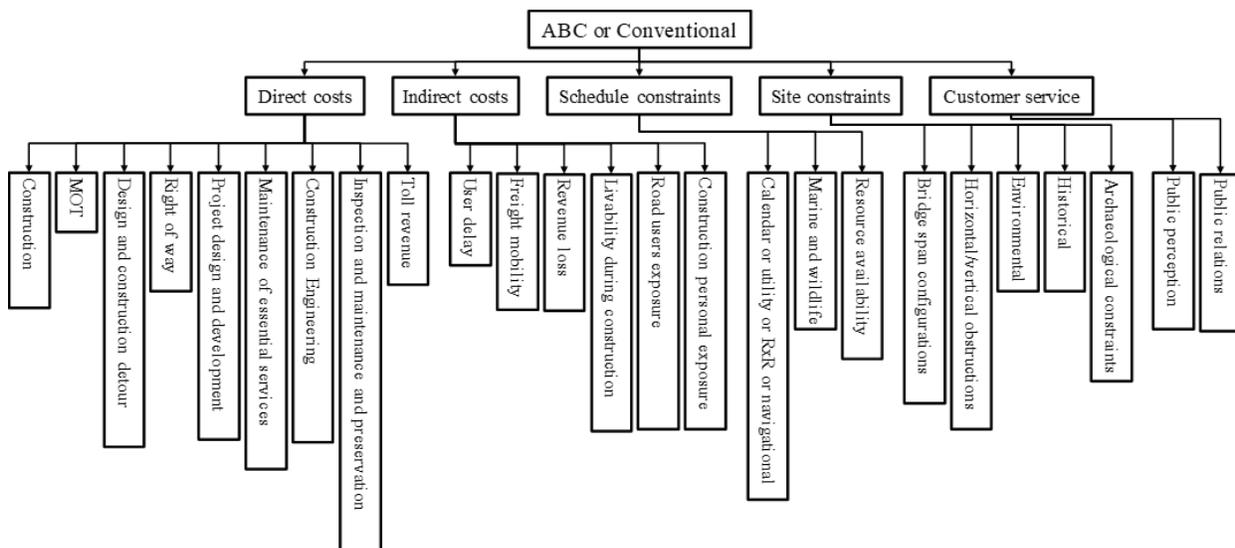


Figure 13. Frame of the traditional ABC-AHP tool

In Figure 13, there are three levels for the ABC-AHP tool, the goal or the root is to decide the selection of construction method, ABC or conventional. The second level is the main elements that a bridge construction project could relate to, which are direct costs, indirect costs, schedule constraints, site constraints, and customer service. The third level is the elements that impact the

elements in the second level. In this ABC-AHP tool, the elements in the same level are assumed to be independent.

Figure 14 gives the simple rating method for the pairwise comparison value for each element that each element has two implementations-ABC or conventional. And they can be rated from 1(equal importance) to 9 (absolute importance). For each element, if the intensity of ABC is absolute importance than that of conventional, the number of 9 on the left near ABC should be selected; otherwise, the number on the right near the conventional method should be selected. Or, the exact fraction value of left/right (ABC/conventional) can be added in the blank box in Figure 14.

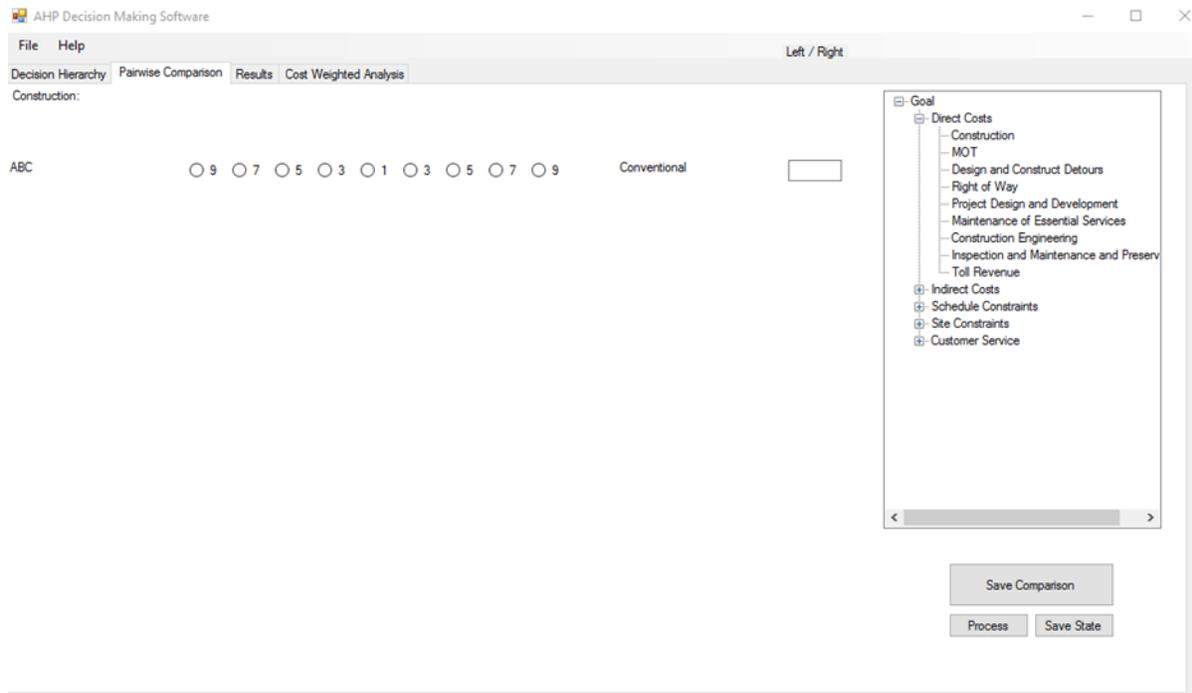


Figure 14. Rating pairwise comparison value for each element

Comparison and Improvement

This section introduced the mechanism of the ABC-AHP tool. It also implies many differences from the current MIP model. The following lists the major differences and the improvements that the MIP model achieves when compared with traditional decision tools.

- It is clear that the ABC-AHP tool is used for a specific bridge project. It requires a deep understanding on every aspect related to the bridge. As a result, some experienced experts are significantly important. While, the MIP model is used for a macroscopic scheme when more than one bridges are required to be maintained. This model is on the root of basic data input. The human factors impact less for the MIP model.
- The indirect cost is one-fifth of the entire ABC-AHP tool. According to the tool manual, the weight of indirect cost is 0.192, which is unchangeable and doesn't reflect the expected

importance of transportation. At the same time, for many cases, the indirect cost has an interactive relationship with other factors such as customer service. The tool lacks the consideration of factor dependence or else it may risk overlapping scoring. MIP calculates the indirect cost via the cost of the standard business mileage rates for the use of a car per mile and reflects a real and visible indirect cost on traffic and business in the scale of the entire network. It can also show the importance prioritization of bridges and promote the decision makers to maintain the important bridges in a timely manner.

- The hierarchies of the ABC-AHP tool can be edited to add or remove parts of it. However, the pairwise comparison values can only be in the range of 1 to 9 and no real data can be inputted in this tool. This makes the tool inflexible. The MIP model in this report develops a general formulation that includes the direct cost and indirect cost parts. The parameters of the MIP model don't rely on decision makers to provide much empirical data but the technical data related to the bridge or traffic, which leads to the rationality of this model. Furthermore, the formulation is flexible so that more types of direct or indirect costs can be added via creating their functions and constraints.
- The objective goal of the ABC-AHP tool is to help make a decision on the choice of ABC or conventional construction. The objective goal of MIP model is to provide important bridges to maintain and their recommended ABC techniques.
- Generally, if a fast and project-specific decision of a bridge is required to be made, the ABC-AHP tool could satisfy the demand. If a network-level decision is required and the decision focuses on the large-scale impact of bridge maintenance, the MIP model is good to use.

CONCLUSION

The purpose of this paper is to develop a holistic decision-making framework for use in the network-level replacement of bridges, in addition to the project-level selection of the cost-efficient ABC technique for each bridge. The problem to determine the optimal replacement scheme on both levels under a set investment are developed as a modified uncapacitated fixed-charge location problem that uses mixed-integer programming as a solution mechanism. The key point of this MIP is to find a formulation to analyze the two level problems in one process and could output all desirable results at the end. To solve it, the objective function of the special MIP model is defined to search the minimum cost of the entire network not only on construction (direct cost) but also on traffic time (indirect cost). Meanwhile, constraints from decision makers, bridges themselves, and traffic planning are added to make the MIP realistic. The branch-and-cut algorithm is applied to speed up the solution process of this MIP model. And a heuristic solving algorithm of a limited discrepancy search using a greedy algorithm is discussed for the future application of the MIP model on larger networks. Through the studied case, the correction of the MIP model is proved, and several conclusions can be summarized as follows:

- The available resources influence the performance and result of the MIP model; these include the availability of limited budgetary resources and the perceived limitations in use of construction techniques considering aspects such as bridge site, type, and availability of resources.
- Increasing the investment on construction results in two potential solution trends for the network recovery and bridge replacement problem. One is to increase the number of replaced bridges to improve the sufficiency rating of each individual bridge and the entire network. The other is to use more efficient ABC techniques to replace bridges to reduce the impact on traffic due to the bridge closures. Either of them can achieve the improvement of the network serviceability and bridge operation conditions.
- The infinite investment doesn't represent the infinite optimization on the results of the objective problem. The upper bound of the effects from investment can be found, at which all requirements on the project can be realized and any other strategy or increase on the investment will lead to the rise of the total cost at the network level.
- In the long-run, the mixed-integer decision tool could provide the optimal resource allocation solution either with any possible construction techniques related to the traffic network or with any infrastructure network having the requirement of service enhancement. If focusing on the innovative constructional techniques, the network condition can also be extended from daily operation to the combination of the operational condition and the emergent condition. If paying more attention on the indirect cost, the opportunity cost from transportation, the economic loss because of the reduction of traffic flows, can be added in the MIP objective function. All aforementioned movements can contribute to the practical improvement of the MIP model.

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