Technical Report Documentation Page

1. Report No. ABC-UTC-2013-C2-ISU02-Final	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle **An Integrated Project to Enterprise-Level Decision-Making Framework for Prioritization of Accelerated Bridge Construction**	**5. Report Date** September 2018 6. **Performing Organization Code**
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9. Performing Organization Name and Address Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTRT13-G-UTC41
12. Sponsoring Organization Name and Address Accelerated Bridge Construction University Transportation Center Florida International University 10555 W. Flagler Street, EC 3680 Miami, FL 33174 U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology and Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report (January 2016 - September 2018) **14. Sponsoring Agency Code**

15. Supplementary Notes

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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.

17. Key Words accelerated bridge construction—bridge maintenance—mixed-integer programming—optimization	**18. Distribution Statement** No restrictions.

19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 39	**22. Price** NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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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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Sponsored by
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ACKNOWLEDGMENTS

This project was supported by the Accelerated Bridge Construction University Transportation Center (ABC-UTC at https://abc-utc.fiu.edu/) at Florida International University (FIU), as the lead institution, with Iowa State University, the University of Nevada-Reno, the University of Oklahoma, and the University of Washington as partner institutions. The authors would like to acknowledge the ABC-UTC support.

The research team would like to extend special appreciation to the ABC-UTC and the U.S. Department of Transportation (DOT) Office of the Assistant Secretary for Research and Technology for funding this project. They would also like to thank the Research Advisory Panel members: Ahmad Abu-Hawash and Matthew Haubrich with the Iowa DOT.

This report contains material submitted for journal publication as follows:

Zhang N, Alipour A. (2019) *A two-level mixed-integer programming model for bridge replacement prioritization*. Computer Aided Civil Infrastructure Engineering 2019;1–18.https://doi.org/10.1111/mice.12482

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 and based on investment, outcomes are estimated for the enhanced serviceability of bridges, efficient ABC techniques for different bridges, an optimal bridge replacement strategy, and minimized total cost during the entire process. These outcomes could provide decision makers and stakeholders with a complete understanding of the prioritization process at both the network and project levels.

This project is the first phase of a multi-year and multi-phase effort to develop this two-level framework as a computational backend of an optimization tool that could be utilized by the state DOTs in selecting the critical bridges based on a host of different factors while choosing the most appropriate ABC techniques. It is expected that a working tool will be available to states, after completion of all phases.

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 (Douglas et al. 2017), and increasing traffic loads. More than 600,000 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 exacerbate 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 (Alipour 2016).

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). ABC 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 (Alipour et al. 2010, Alipour et al. 2013, Alipour and Shafei 2016a, Almeida et al. 2017, Kim et al. 2016, Liu and Frangopol 2005, Shafei and Alipour 2015, Shafei et al. 2013). 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 chapters consist of the following:

- Review of ABC techniques, including the comparison of cost estimates between recently completed ABC and conventional techniques
- Methodology description for the proposed mixed-integer programming framework
- Computational study and discussion of results
- Comparison of the developed model with existing AHP tool
- 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.

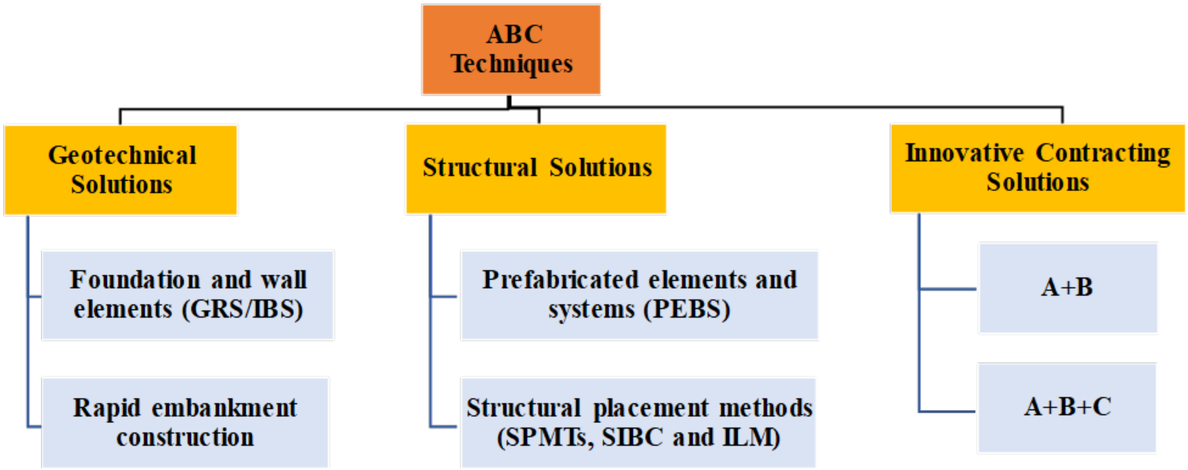


Figure 1. Commonly applied ABC techniques in the US

Table 1 displays the unique definitions, benefits, and limits of these ABC techniques for bridge replacements.

Table 1. The definition of ABC techniques

Technique	Definition	Benefit	Limitation
GRS/IBS Geosynthetic reinforced soil-integrated bridge system	• This method of foundation installation combines the foundation, abutment, and approach embankment into one composite system.	• Simple construction • Low initial cost • A safe, cost-effective, long-lasting structure	• Local roads only • Bridge span less than 140 ft • Currently applied only for single span bridges

Technique	Definition	Benefit	Limitation
		• Construction time in weeks not in months	• Expensive when construction over water
EPS Expanded Polystyrene Geofoam	•The lightweight, rigid foam plastic EPS blocks can be placed behind a conventional abutment or around the piles of an integral abutment.	• Fast construction • Cost saving • Extremely lightweight • Eliminates or reduces pre-load settlement times	• A layer of subbase is required • Restricted by the site water table
PBES Prefabricated Bridge Elements and Systems	• 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.	• High-performance and long-term structure • Reduce on-site construction time • Construction under controlled environmental conditions	• High prefabrication and construction costs • Geometric constraints
SPMTs Self-Propelled Modular Transporters	• 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.	• Construction time within few hours • Significantly reduce traffic disruption • Improve work zone safety and improve quality and constructability • Increase contractor and owner options	• Significantly high construction cost • Limited by the length and geometry of the travel path • Restricted by the supporting soil
SIBC slide-in bridge construction	• 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.	• Enhance safety • Shorten on-site construction time • Reduce mobility impacts • Potentially reduce project costs • Improve quality and constructability	• Limited right-of-way (ROW) for staging • Geometric constraints • Lack of SIBC experience • Profile changes • Utility impacts

Technique	Definition	Benefit	Limitation
ILM Incremental launching method	• 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.	• 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	• 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	• 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.	• Control and stimulate the project progress	• Extra rewards may be paid

Sources: 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

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.). 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).

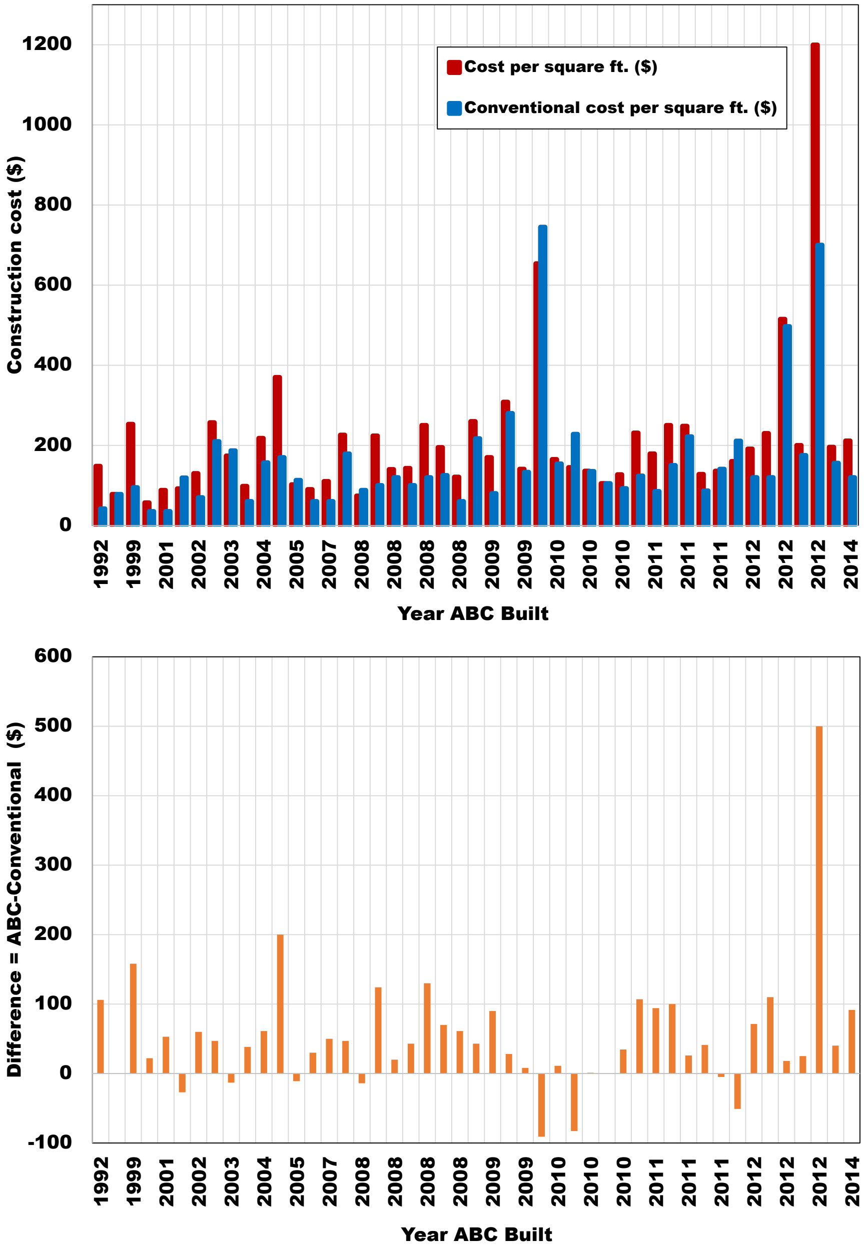


Figure 2. Comparisons (top) and gaps (bottom) of the construction cost per square foot between ABC techniques and conventional techniques for 48 bridges from ABC-UTC project database

Figure 2 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.

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. 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.

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.

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.

The objective function is given in Equation 1.

$$O(r,x):\ \min_{r,x}\ C_{r\&t}r+\sum_{h=1}^{H}C_{unit}\sum_{a,h}\int_{0}^{v_{a,h}}t_{a,h}(x)dx \tag{1}$$

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 1, the direct construction cost is formulated as the matrix multiplication of all bridge replacement costs and the strategy on replacement and technique.

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 required input data and the expected output data are listed in Figure 3.

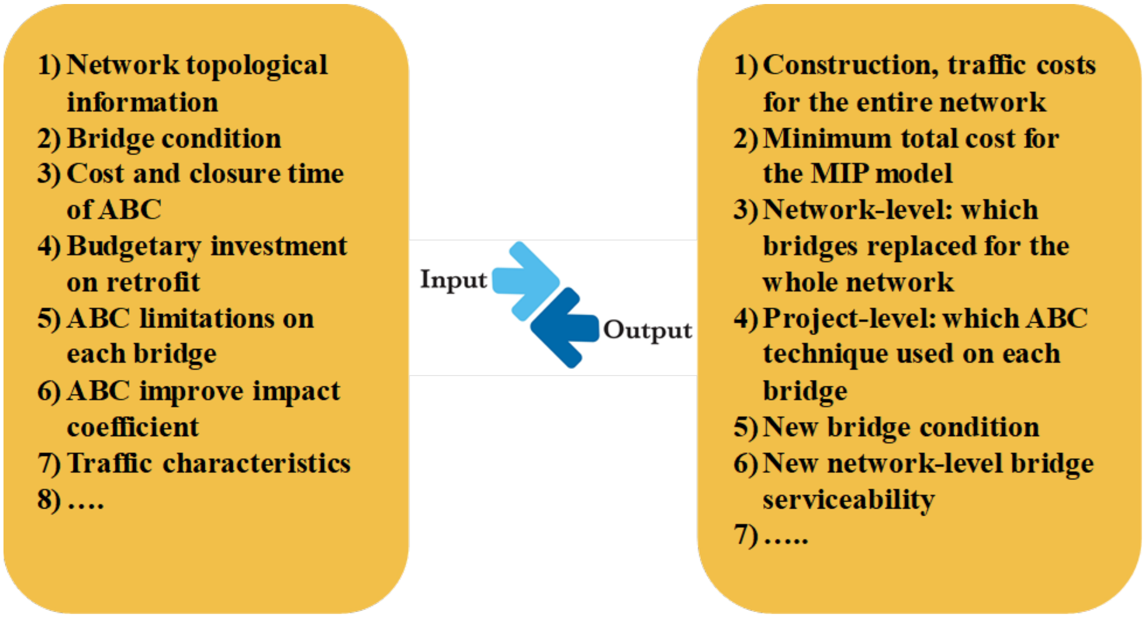


Figure 3. The input and output data in the current MIP model

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. For this purpose, 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. For instance, every candidate strategy bounded to a specified investment budget, the technique limitations for each bridge are identified, and 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. 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.

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 ten times the bridge cost (Alipour and Shafei 2016b, Furtado and Alipour 2014, Testa et al. 2015). 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, FWHA 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 2 shows the calculation of the overall SR for a bridge:

$$SR = \sum_{i'} S_1^{i'} \sum_{j'} S_1^{j'} + \sum_{k'} S_1^{k'} - \sum_{l'} S_1^{l'} \tag{2}$$

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 (FHWA 1995, Adams and Myungook 2009). The relationship between SR and the replacement decision is outlined in Table 2.

Table 2. Relationship between SR value and bridge replacement

Percentage	Bridge condition	Replace requirement
SR≥80	Good serviceability	No action
50% ≤SR<80	Light deficiency	Replacement/rehabilitation
SR<50	Severe deficiency	Replacement

Based on the requirements shown in Table 2, a number of constraints are set for SR values. For instance, the SR value after replacement, SR_{post}, is a function of the replacement strategy. If the bridge is replaced with any ABC technique, then its SR_{post} is set to be 100, with excellent serviceability, but if a bridge is not replaced, then SR_{post} is set as the original bridge serviceability. The average value of SRs of the network after replacement is calculated and required 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. Furthermore, an initial SR value for a bridge larger than 80, implies that the bridge does not require the replacement action (see Table 2) and the replacement decision of bridge should be set equal to zero. Otherwise, no constraint on bridge should be applied. This constraint also has an economic contribution on controlling the expenses. The replacement of bridge is a mandatory action, when the SR_{pre} 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.

It should be noted that the mentioned thresholds are only preliminary assumptions for the current study and are used as a basis to conduct the analyses presented in this report. It is expected that a multitude of bridge rating metrics would be introduced to the final tool and DOTs would have the opportunity to set their pre-defined thresholds for those metrics.

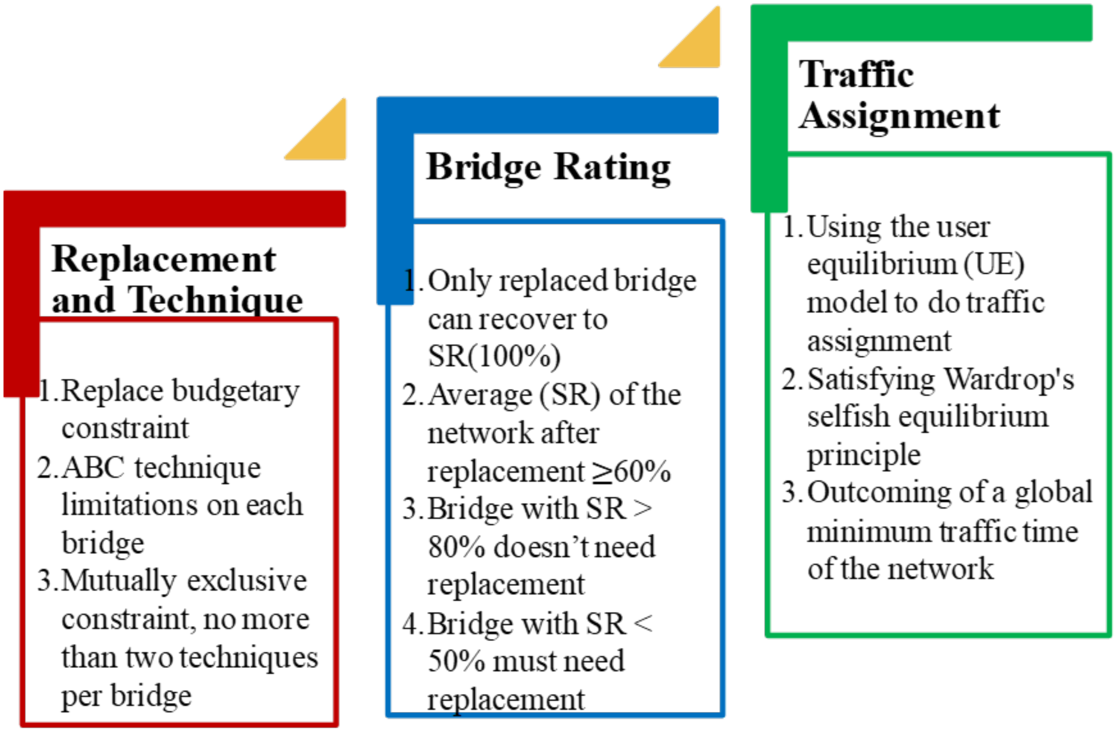
Dynamic Traffic Assignment

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). 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 3 is a component of the current MIP model as stated in Equation 1.

$$\min_{r,x} \sum_{a,h} \int_0^{v_{a,h}} t_{a,h}(x)dx \tag{3}$$

Equation 3 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. 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). The link capacity during the replacement process 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. A dynamic assignment of traffic flows during network restoration is considered.

To sum up, Figure 4 lists the main constraints and goals that the decision makers desire in the network-level bridge replacement actions.



Replacement and Technique

1. Replace budgetary constraint
2. ABC technique limitations on each bridge
3. Mutually exclusive constraint, no more than two techniques per bridge

Bridge Rating

1. Only replaced bridge can recover to SR(100%)
2. Average (SR) of the network after replacement ≥60%
3. Bridge with SR > 80% doesn't need replacement
4. Bridge with SR < 50% must need replacement

Traffic Assignment

1. Using the user equilibrium (UE) model to do traffic assignment
2. Satisfying Wardrop's selfish equilibrium principle
3. Outcoming of a global minimum traffic time of the network

Figure 4. Limitations and constraints of the MIP model

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.

Branch and Cut Solution Algorithm

The branch and cut (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). 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 are branched from their parent problem, and the same process will be repeated for all parent problems. Before branching, the cutting constraint is added, which is iteratively increasing the selection of bridges in M_b. The continuous expansion of the bridge selection is stored. 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 is calculated. 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 form root to the desired node needs to be followed. Based on the above explanation, the solution algorithm is outlined in the following Figure 5.

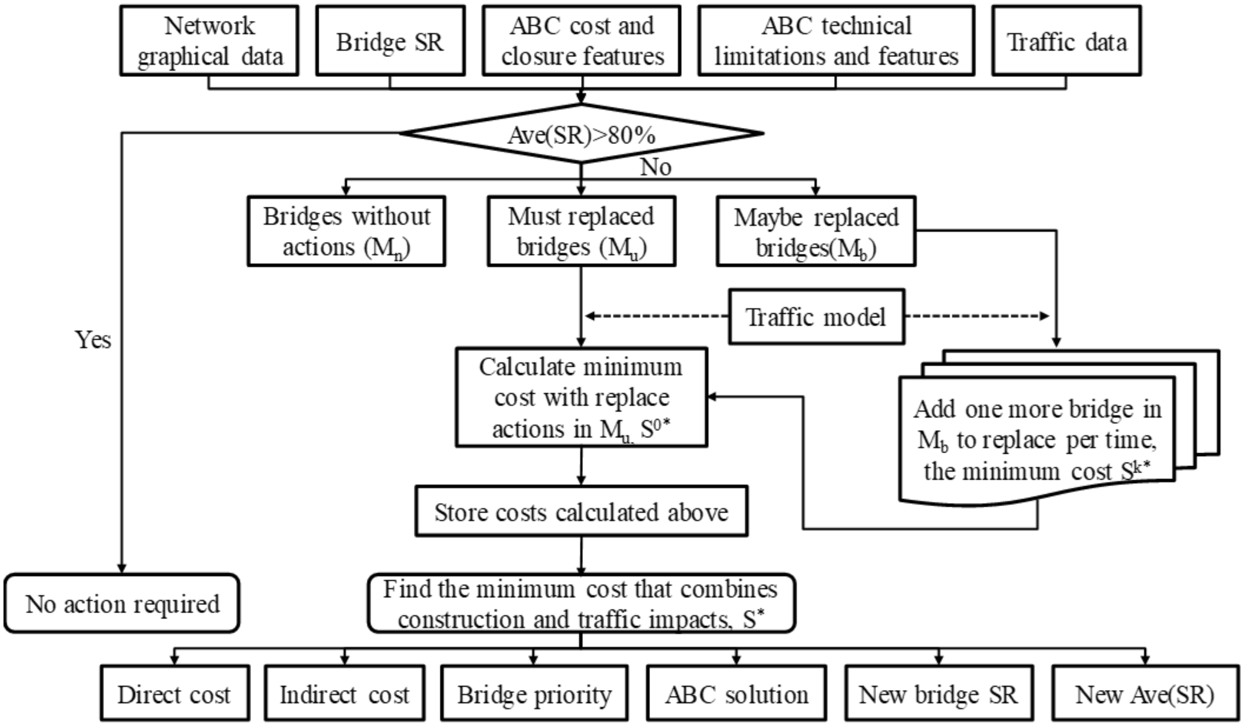


Figure 5. BC solution algorithm outline for project-level to network-level MIP model

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, South Dakota 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.

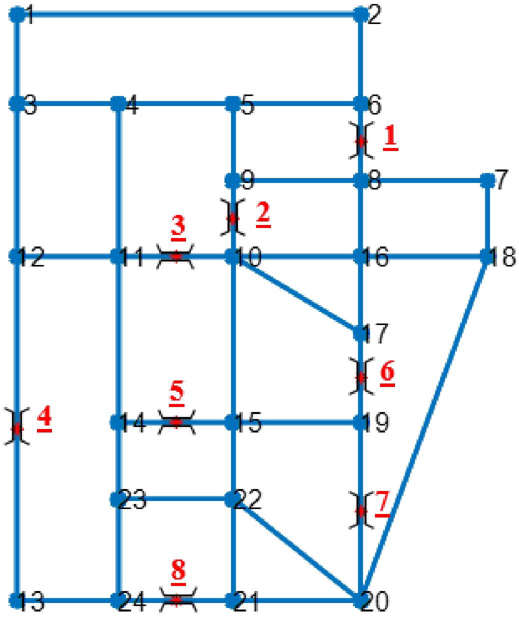


Figure 6. The node, link, and bridge locations for the case study network (Note that bridge numbers are in bold and underlined)

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 55 and it doesn't require an imperative replacement but could be considered as the potential candidate given the availability of construction resources.

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	82	25	9	55	15	6	85	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.

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.

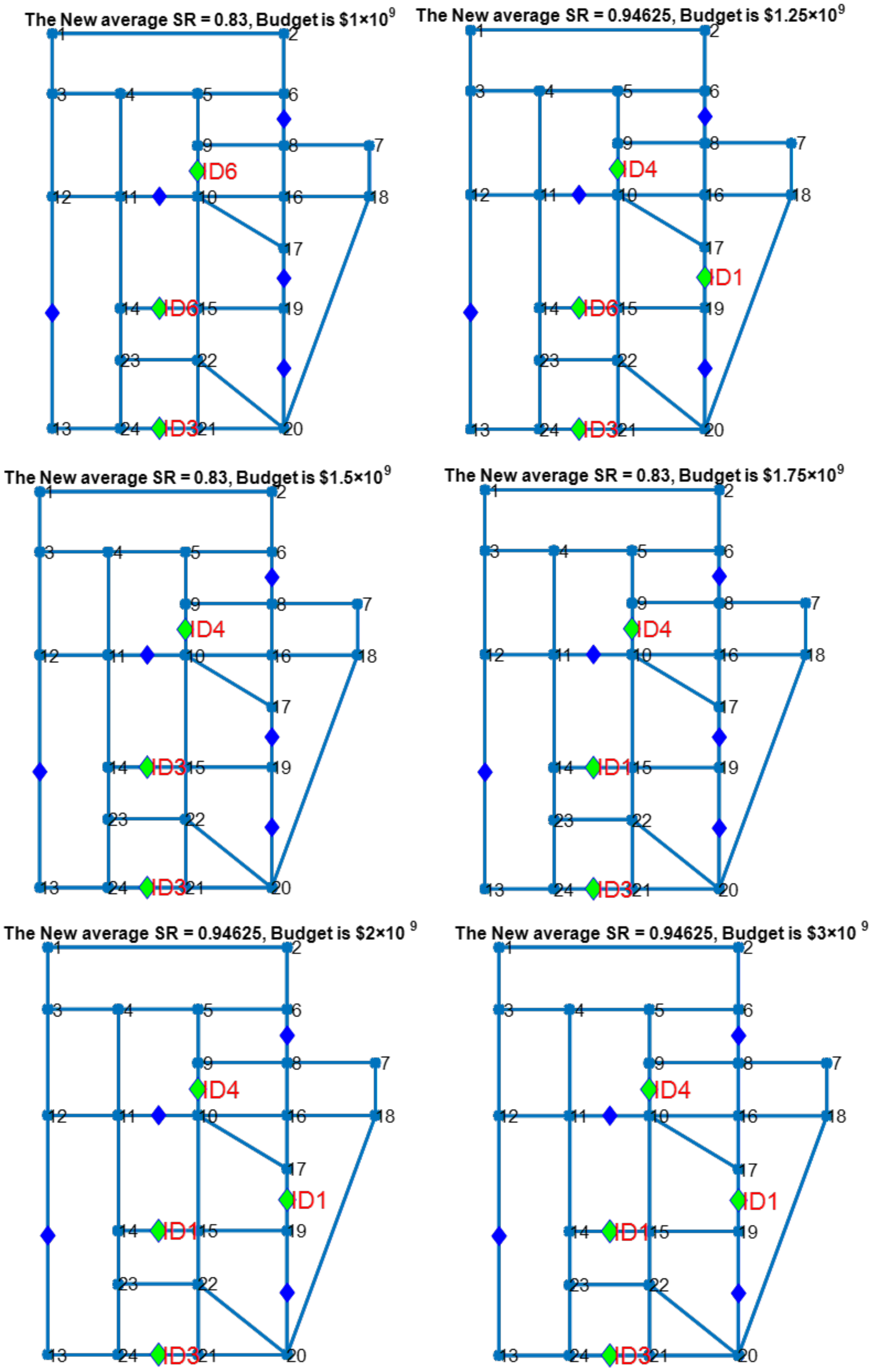
The replacement cost of the bridge (in Table 4) represents the cost required through conventional methods (not ABC techniques) to replace the bridge. It's a function of the bridge size, material, structural type, and location. The direct cost of each ABC technique is the multiplication of the conventional 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: $t_{ID1}<t_{ID2}<t_{ID3}<t_{ID4}<t_{ID5}<t_{ID6}$.

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; bridges 2, 5, and 8 are in set M_u; and bridges 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. 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. 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) Location: [(6,8), (9,10), (10,11), (12,13), (14,15), (17,19), (19,20), (21,24)]	Network traffic time 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}



Note that SR values are reported as percentages

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

Figure 8, which is shown and discussed further on the next page, shows the relative accuracies of total cost estimation with budgeted replacement during the entire network restoration process.

Reviewing the direct costs associated with bridges in set Mu, 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 Mu 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.

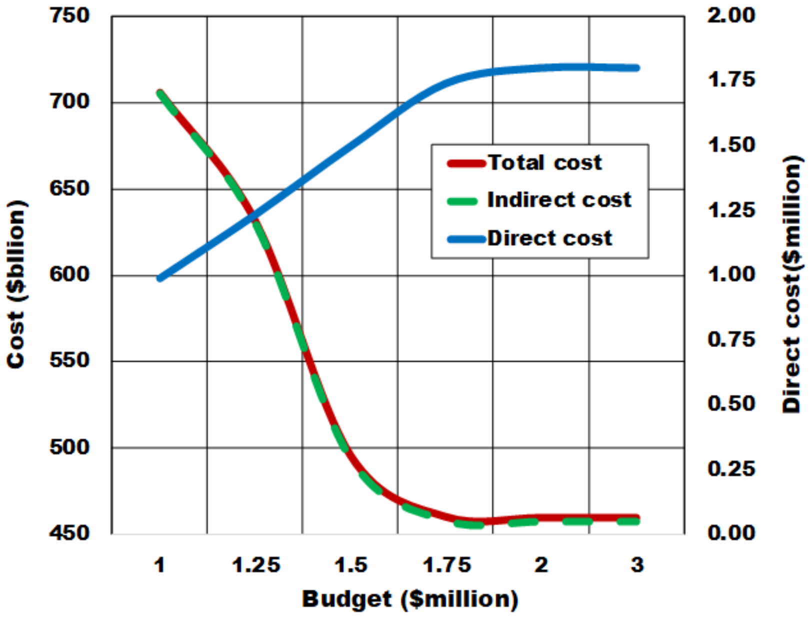


Figure 8. Comparison of direct, indirect, and total costs for the different strategies considered

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.

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 9.

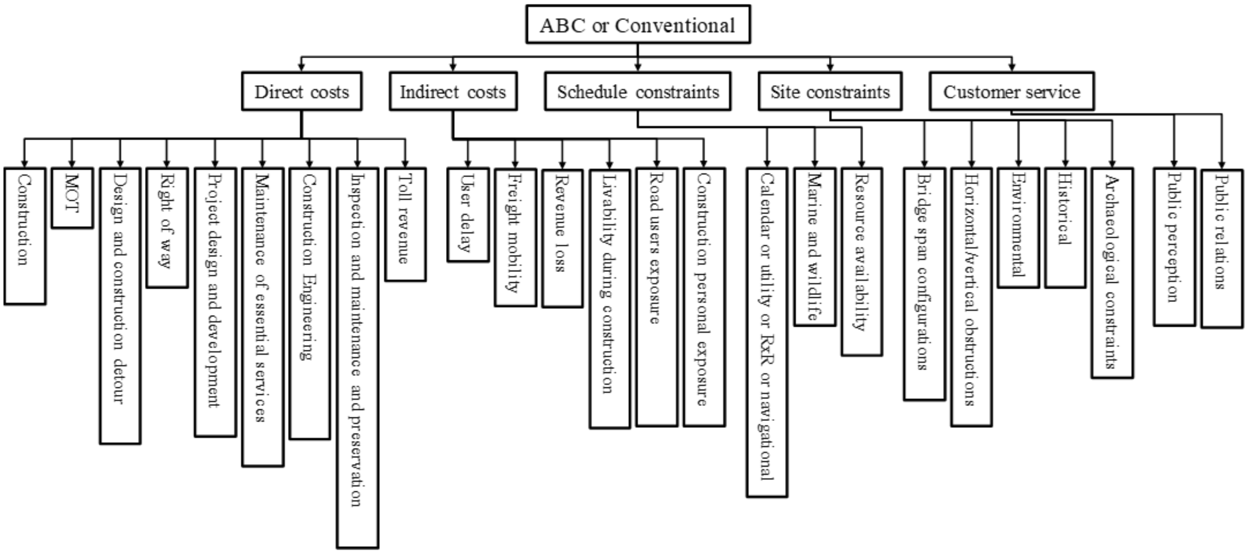


Figure 9. Frame of the traditional ABC-AHP tool

In Figure 9, 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 10 provides 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).

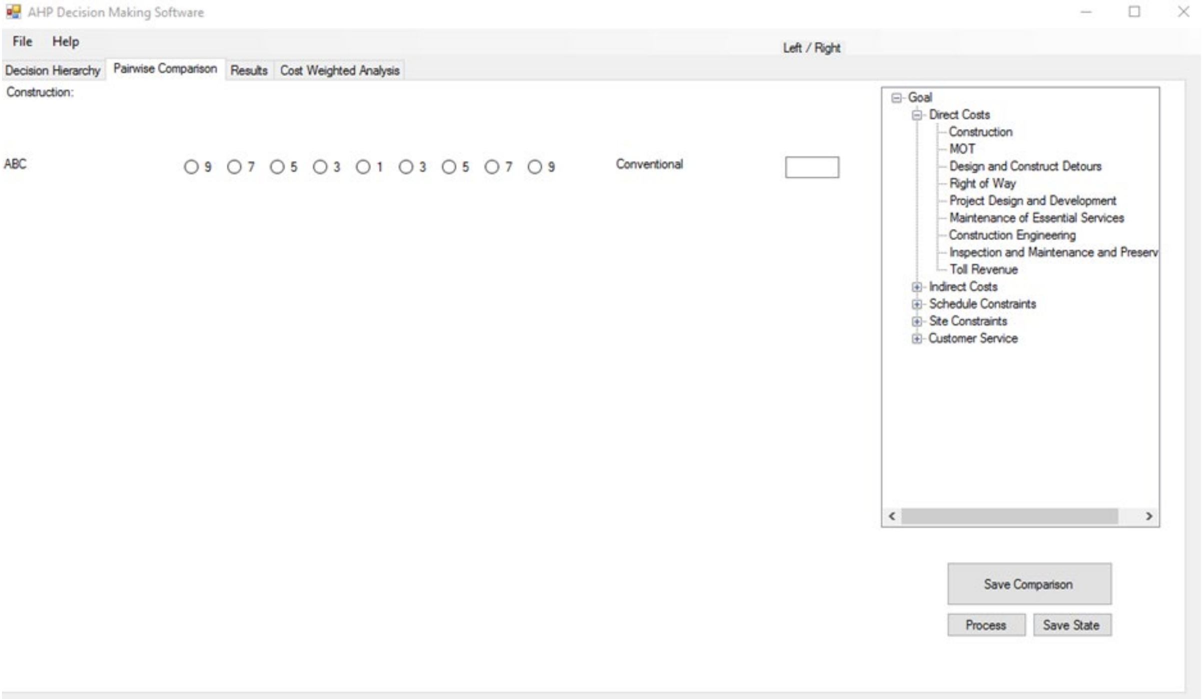


Figure 10. Rating pairwise comparison value for each element

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 10.

Comparison and Improvement

This section introduced the mechanism of the ABC-AHP tool. It also implies many differences from the developed MIP model in this project. 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, expert elicitation is significantly important. The MIP model is used for a macroscopic network planning and analysis that allows for consideration of the criticality and importance of a suite of bridges in the network. 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 and indirect costs. 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 prioritize the bridges across the states while recommending a suitable ABC technique for its replacement. The uniqueness of approach is that it accounts for the fact that selection of different ABC techniques, impacts indirect costs (i.e, user costs) and factors it in bridge prioritization scheme as well.

- 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.

CONCLUSIONS AND FUTURE WORK

The purpose of this project was 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 were developed as a modified uncapacitated fixed-charge location problem that uses mixed-integer programming as a solution mechanism. 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. The conclusions of the study 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.

- The capabilities of the developed algorithm could be improved by using a heuristic-solving algorithm of a limited discrepancy search using a greedy algorithm. This will allow for the future application of the MIP model on larger, real-life networks.

- This project is the first phase of a multi-year and multi-phase effort to develop this two-level framework as a computational backend of an optimization tool that could be utilized by the state DOTs in selecting the critical bridges based on a host of different factors while choosing the most appropriate ABC techniques. It is expected that a working tool will be available to states, after completion of all phases.

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