Iowa State University

Civil, Construction and Environmental Engineering

ACCELERATED BRIDGE CONSTRUCTION UNIVERSITY TRANSPORTATION CENTER

An Integrated Project- to Enterprise-level Decision Making Framework for Prioritization of Accelerated Bridge Construction

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Presentation Outline

- Introduction (current state, challenges, and solutions)
- Accelerated bridge construction (ABC) techniques
- Review of ABC projects databases
- Motivation of study
- Mathematical Model and solution algorithm
- Application to case study
- Conclusions and future work

What to expect in this presentation?

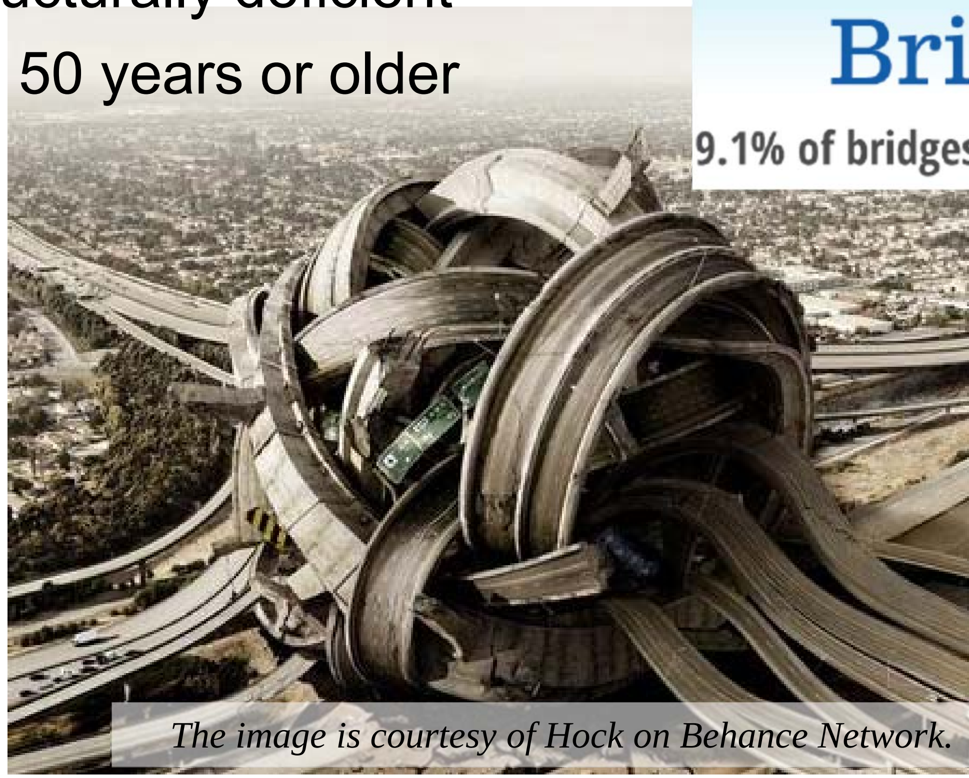
- A project aimed at engineers, planners, and decision makers that are involved in prioritizing bridges for ABC, and selecting specific ABC techniques for a project site
- The outcome is the algorithmic developments that will be implemented in a user friendly environment for bridge owners to use

What to not expect?

- Discussion on how different specific ABC techniques are implemented at bridge site
- Discussions on contracting methods
- Design outcomes that would change the current practice of ABC implementation

Overview of Current State

- **9.1%** structurally deficient
- **40%** are 50 years or older



The image is courtesy of Hock on Behance Network.

- **Required rehabilitation cost:**
  $123 billion dollars

[Ref: ASCE 2017 Report Card]

Challenges

- The need to cost-effectively prioritize the repair and replacement of a 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 process.

Solutions

- 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
- Novel decision making processes

Accelerated Bridge Construction

ABC uses both new technology and innovative project management techniques to:

- Mitigate the effects of bridge construction on the public
- Promote traffic and worker safety
- Improve the bridge durability due to standardized and controlled construction conditions.

Accelerated Bridge Construction

Reasons to avoid ABC:

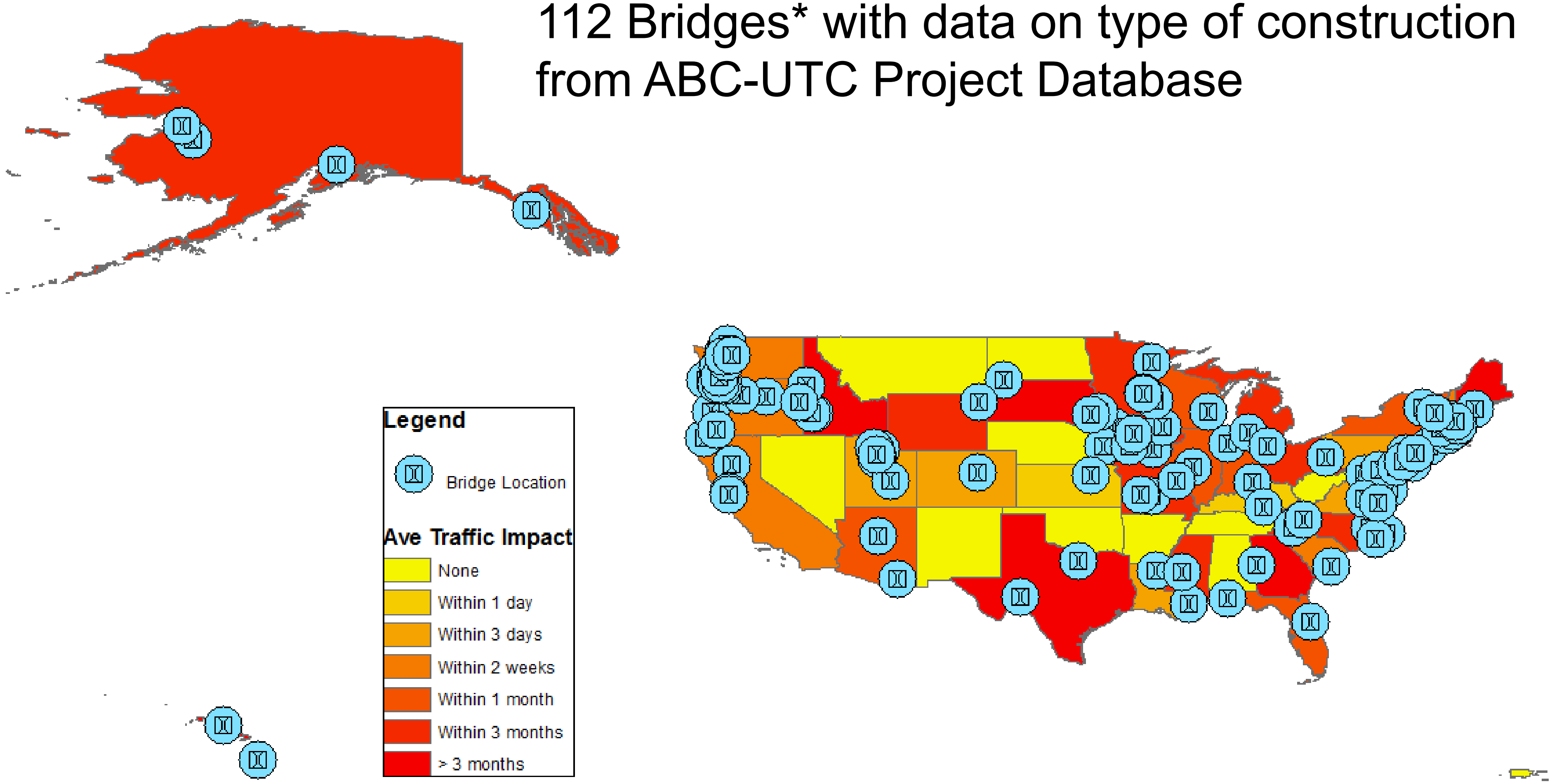
- Perceived risks
- Perceived higher costs (tax dollars spent)

However:

- Time saved due to shorter construction-closure duration
- Lower cost and higher quality of the standardized design approaches implemented in bundled designs

Sample ABC Projects

112 Bridges* with data on type of construction from ABC-UTC Project Database

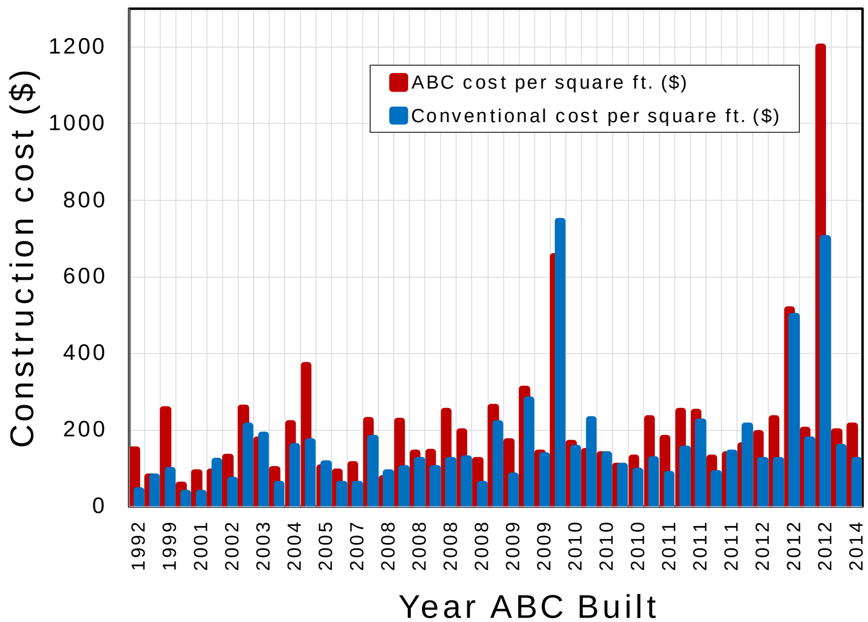


*at the time of this project

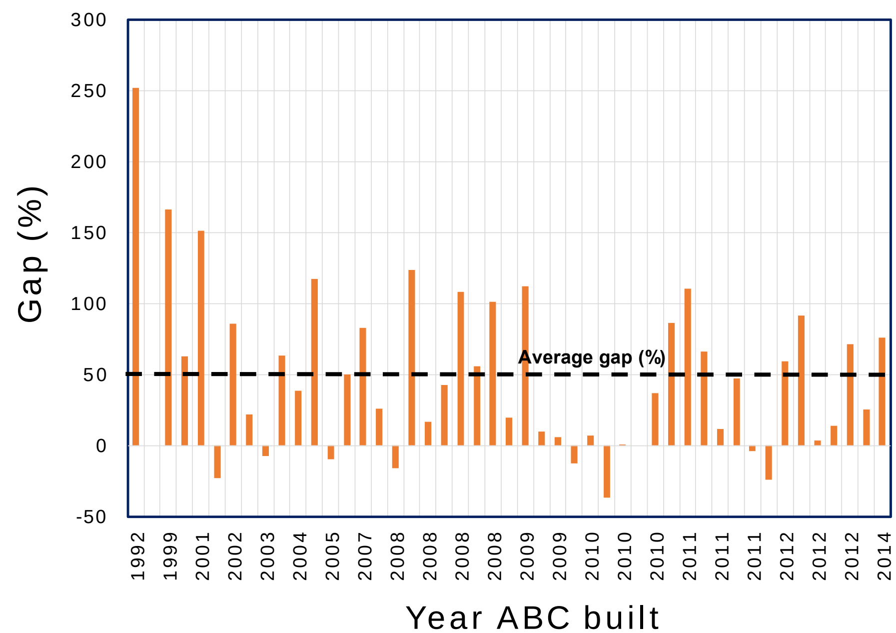
Source: https://abc-utc.fiu.edu/resources/project-research-databases

Synthesis of Sample ABC Projects

- In the 112 instances of bridge construction data, 48 of them have the **information related to construction costs**.
- The data implies the **initial cost** of ABC is **higher** than conventional construction.

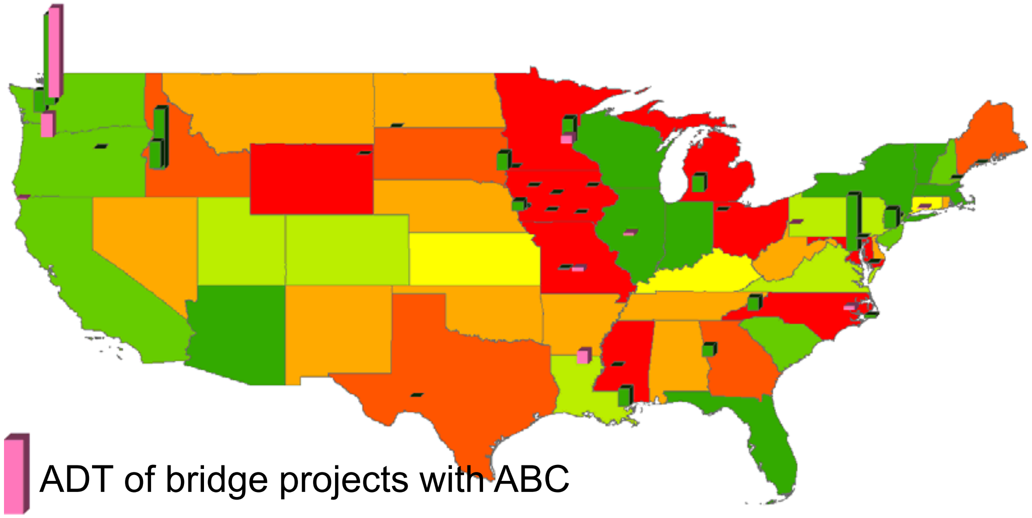


Comparison between the cost per square ft. of ABC and the conventional construction



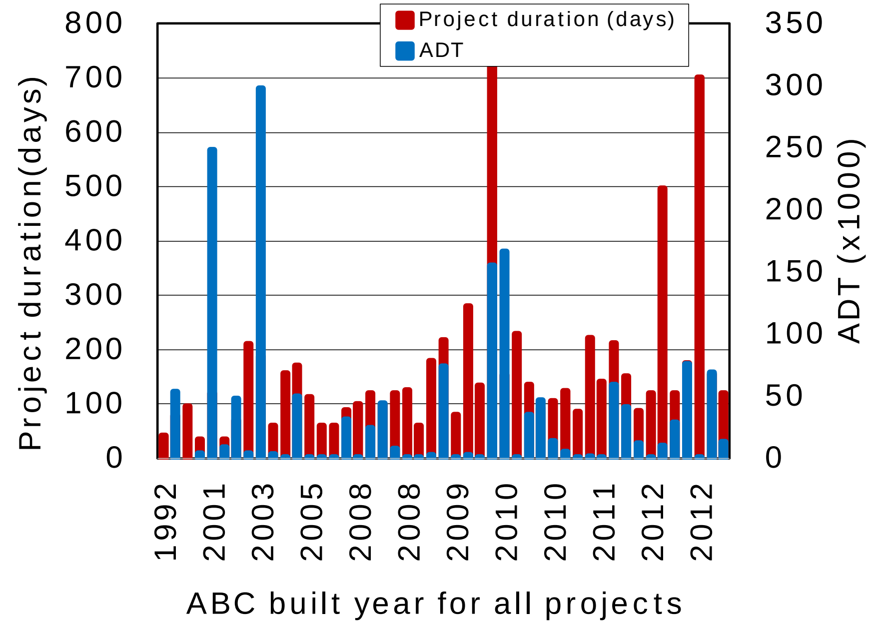
Cost gap between ABC and the conventional construction methods
Gap=(ABC-conventional)/conventional

Synthesis of Sample ABC Projects



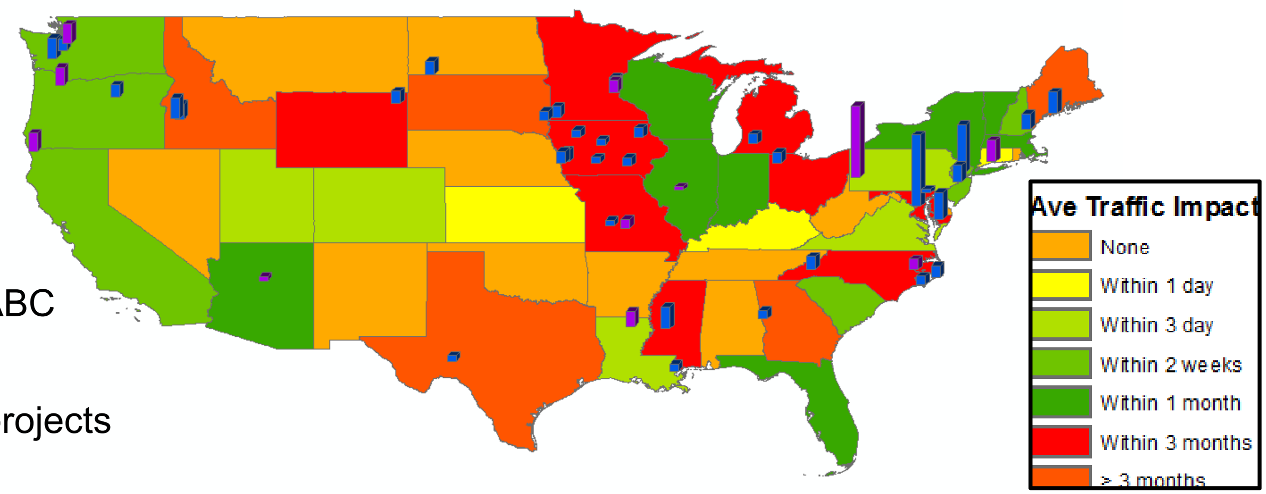
ADT of bridge projects with ABC

ADT of conventional bridge projects



Duration of bridge projects with ABC

Duration of conventional bridge projects



Motivation

Available decision support systems:

- The tool developed by FHWA to choose between conventional and ABC
- Analytic hierarchy processes (AHP) evaluating importance of defined factors relative to other factors
- State Ad-hoc processes
- Based on ADT and experiences of decision makers

Motivation

Common traits among available tools/processes:

Lack of a prioritization approach that accounts for criticality of the bridge to the network- accounting specifically for the level of redundancy available

Lack of the capability to consider uniqueness of each bridge site and emphasize on the overall functionality of bridge network.

Lack of a systematic and consistent method on criteria weighting capable of prioritizing bridges and selecting suitable techniques

Requiring a more holistic DSS:

Project level: involves the choice of optimized construction techniques considering site-specific limitations.

Network level: implements regional prioritization schemes considering indirect costs such as drivers' delay and social-economic impact in addition to the direct costs associated with implementation of the ABC techniques.

Mathematical Model

Model Overview

- Network performance and total project cost during replacement is dependent on the ABC technique selection for two reasons:

  1) Direct costs of ABC implementation
  2) Indirect costs due to impact on the network (due to closures)

- Exploring the optimal resource allocations under budgetary constraints (for initial construction+ impact on the users), and target bridge network functionality.

Mathematical Model

Objective Function :

$$O\left(r, x_{ij,h}^{p}\right):\ \min_{r,x} \sum_{k\in B, l\in S} C_{r\&t}(k,l)r(k,l) + \sum_{h=1}^{H} C_{unit}\left[\min_{x}\sum_{a,h}\int_{0}^{v_{a,h}} t_{a,h}(x_{ij,h}^{p})dx\right]$$

Construction cost Traffic cost of the entire network

Total network- level cost

Required Input Exchange

1) Network topological information
2) Bridge condition
3) Cost and closure time of each ABC technique
4) Budgetary investment on retrofit
5) ABC limitations on each bridge
6) ABC impact coefficient
7) Traffic characteristics
8) …

1) Construction and traffic-related costs for the entire network
2) Minimum total cost for the model
3) Network-level: Bridge prioritization
4) Project-level: ABC technique selection for each bridge
5) New bridge condition
6) New network-level bridge serviceability
7) ...

Bridge Condition State

How to define bridge condition state?

Two commonly used guide manuals:

1. AASHTO condition rating index ranging from 1 (sound condition) to 4 (beyond the established structural limits)
2. National Bridge Inventory (NBI) condition rating index ranging from 0 (failed condition) to 9 (excellent condition).

- Both provide an assessment on <u>each component</u> of a bridge, such as deck, pier, and abutment.
- Both lack an overall estimation on the service condition of the bridge.

Sufficiency Rating Index

The four parameters are (1) structural adequacy and safety, (2) functionality and serviceability, (3) essentiality for public use, and (4) special reductions related to traffic impacts.

$$\mathrm{SR} = \sum_{i'} S_1^{i'} + \sum_{j'} S_2^{j'} + \sum_{k'} S_3^{k'} - \sum_{l'} S_4^{l'}$$

Max: 55 30 15 15

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

*It should be noted that the developed model is capable of replacing any indicator, other than SR, to represent the condition state in the model based on the preferences of the agency using the model.

Model Constraints

Replacement and Technique

1. Replacement budgetary constraint
2. ABC technique limitations on each bridge site
3. Mutually exclusive constraints (no more than one 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 are eligible for replacement

Traffic Assignment

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

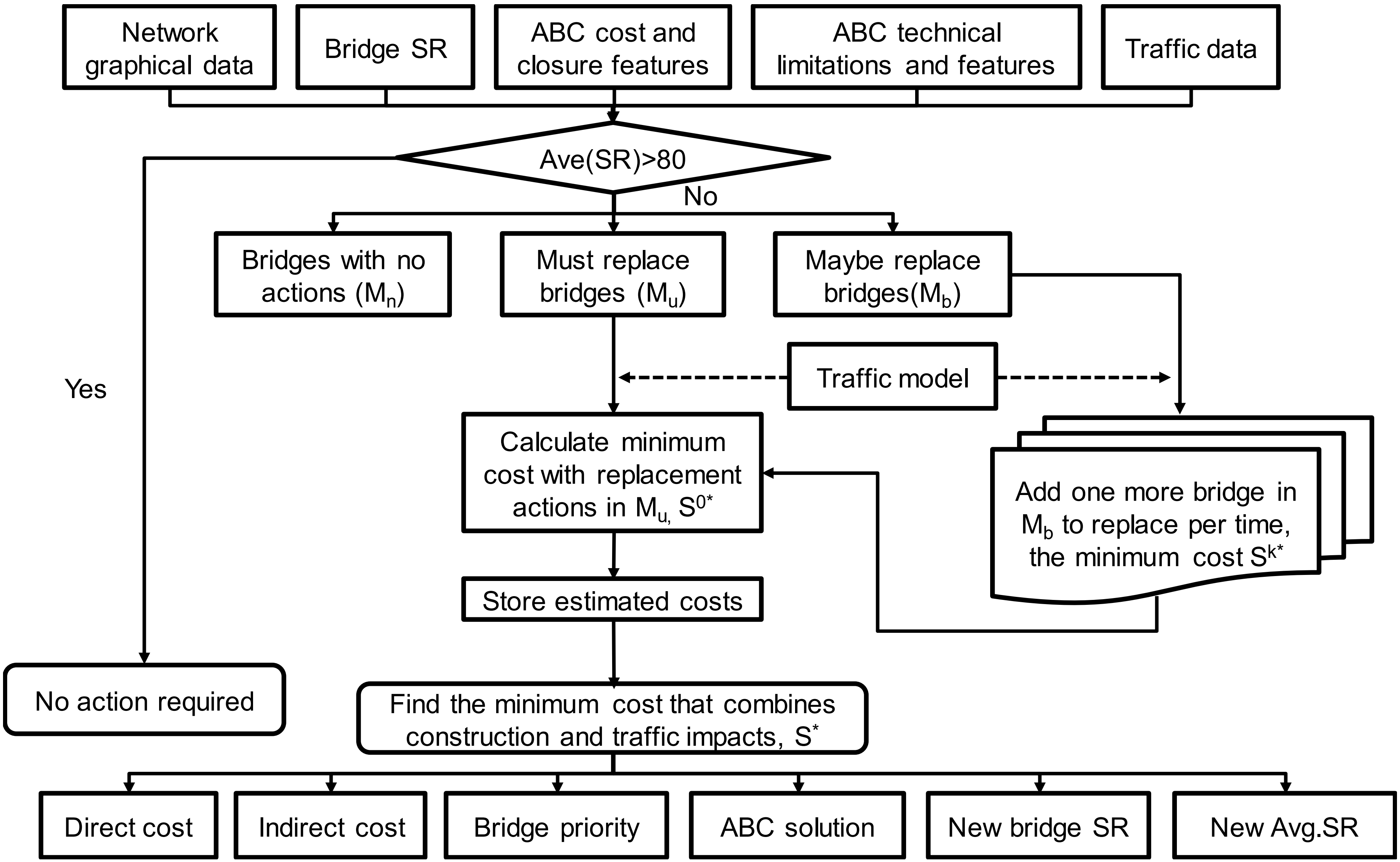
*Items with red number are specific to example problem in this study and could be updated based on preferred project constraints

Multi-Step Traffic Assignment

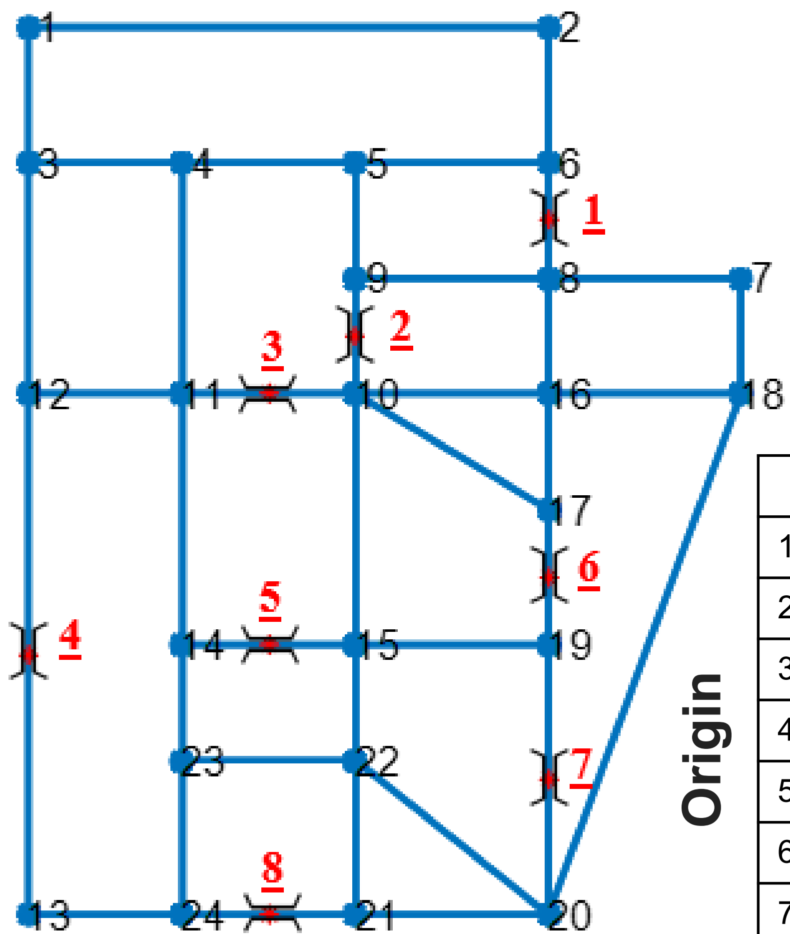
- The network capacity is continuously improving as bridge replacements are completed
- To represent the change of capacity, the construction time is divided into small time steps
- At each time step, the traffic assignment model is ran based on the updated bridge conditions and link capacities
- This is the reflection of the multistep analysis on the network traffic operation

$$c'_{a,h} = c_a^E \frac{\sum_h^H T_{closure}(k)}{\frac{2}{3}\sum_{h=1}^H T_{closure}(k)}, \text{ if replaced}$$

Solution Algorithm



Case Study Assumptions

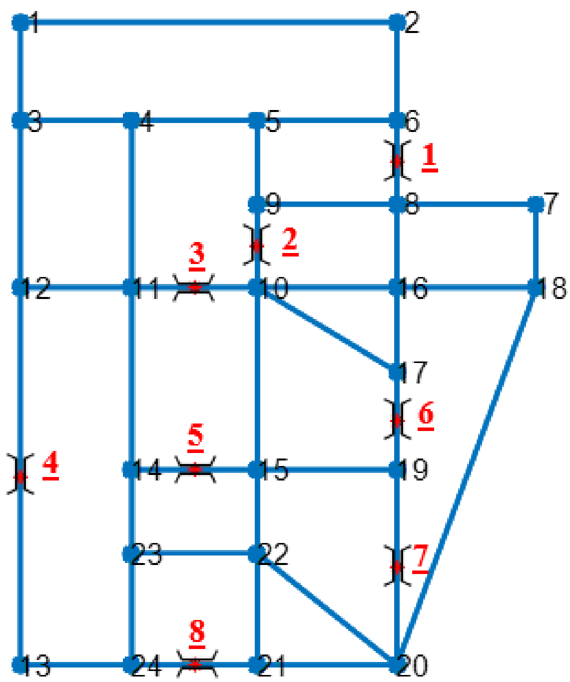


- A preliminary bi-directional network consisting of 24 nodes, 76 directed links, and 8 bridges
- With the O-D matrix below, the total traffic time of network with no closures is 4.4×10^{10} hrs

Destination (columns); **Origin** (rows)

	1	2	3	4	5	6	7	8	…
1	0	232	0	65	435	0	223	45	…
2	265	0	123	456	89	341	0	212	…
3	0	123	0	54	98	143	234	0	…
4	65	456	54	0	321	324	412	156	…
5	435	89	98	321	0	232	342	67	…
6	0	342	143	324	232	0	127	458	…
7	223	0	234	412	342	127	0	76	…
8	45	212	0	156	67	458	76	0	…
…	…	…	…	…	…	…	…	…	0

Case Study Assumptions



Bridge ID	Location	SR	Action	Technique limitation
1	(6, 8)	82	None	1, 2
2	(9, 10)	25	Replace	2, 4, 6
3	(10, 11)	90	None	6
4	(12, 13)	55	Potential replace	1, 4
5	(14, 15)	15	Replace	1, 3
6	(17, 19)	60	Potential replace	1, 4, 5
7	(19, 20)	85	None	None
8	(21, 24)	40	Replace	2, 3, 4, 5

- SR values are given for each bridge
- Each bridge site has different limitations in terms of techniques that could be applied.

Case Study Assumptions

- Six different construction techniques are considered
- The techniques have varying rates of completion:

$$t_{ID1} < t_{ID2} < t_{ID3} < t_{ID4} < t_{ID5} < t_{ID6}$$

- The techniques have varying initial costs of implementation.

$$Cost_{ID1} > Cost_{ID2} > Cost_{ID3} > Cost_{ID4} > Cost_{ID5} > Cost_{ID6}$$

- The techniques have different initial costs at different bridge locations.

ABC ID	ID1	ID2	ID3	ID4	ID5	ID6	Conventional cost (M$)
Bridge1	80	115	140	170	210	250	71.3
Bridge2	72	104	126	153	189	225	308.1

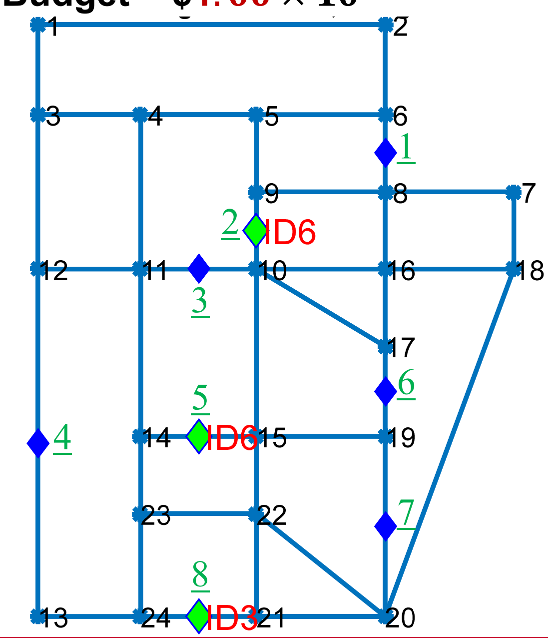
Case Study Results

Objective: 1) Minimum network cost
2) Average network SR > 60
3) Individual bridge SR ≥ 50

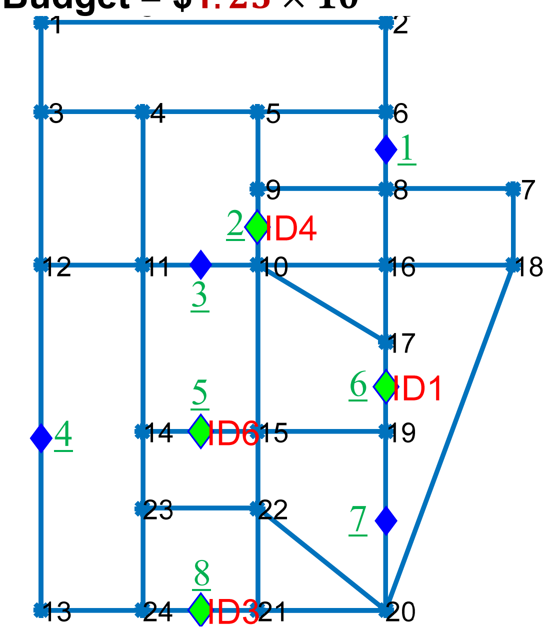
Constraints: $t_{ID1}<t_{ID2}<t_{ID3}<t_{ID4}< t_{ID5}< t_{ID6}$
M_n: bridge 1,3,7 M_u: bridge 2,5,8 M_b: bridge 4,6

Bridge	1	2	3	4	5	6	7	8
Unavailable ABC ID	1, 2	2, 4, 6	6	1, 4	1, 3	1, 4, 5	None	2, 3, 4, 5

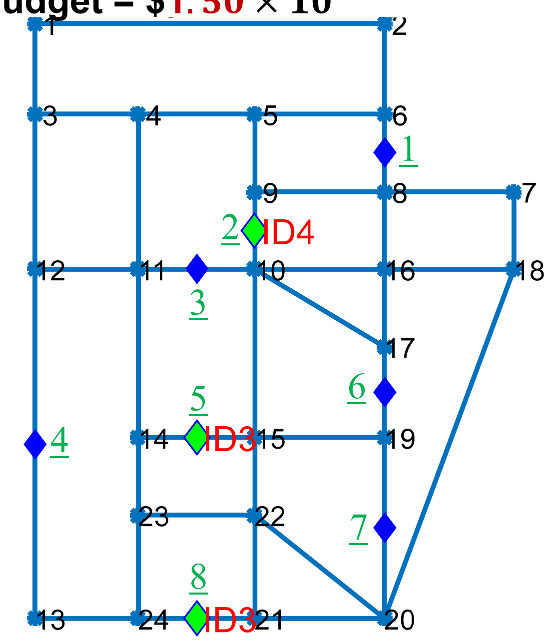
Avg. SR after replacement = 83
Budget = $\$1.00 \times 10^9$



Avg. SR after replacement = 95
Budget = $\$1.25 \times 10^9$



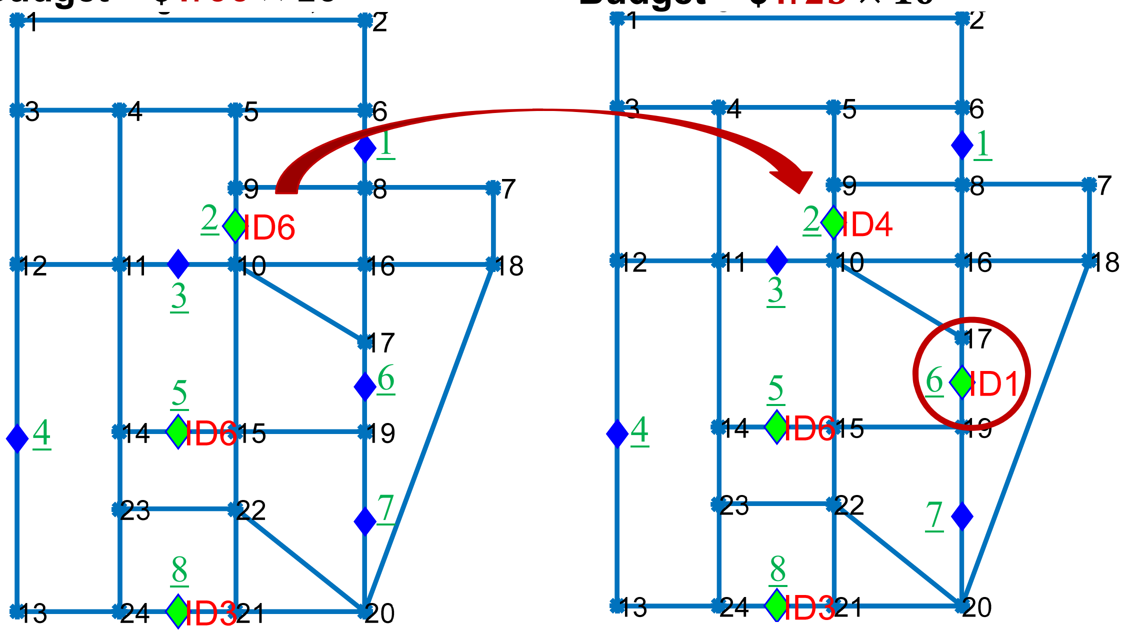
Avg. SR after replacement = 83
Budget = $\$1.50 \times 10^9$



Case Study Results

Avg. SR after replacement = 83
Budget = $\$1.00 \times 10^9$

Avg. SR after replacement = 95
Budget = $\$1.25 \times 10^9$



- With 25% more budget, the program decides to invest on a new bridge (M_b) to be replaced (Bridge 6) with the fastest ABC technique (ID1), raising SR to 95. Also a faster technique for bridge 3 (ID4).

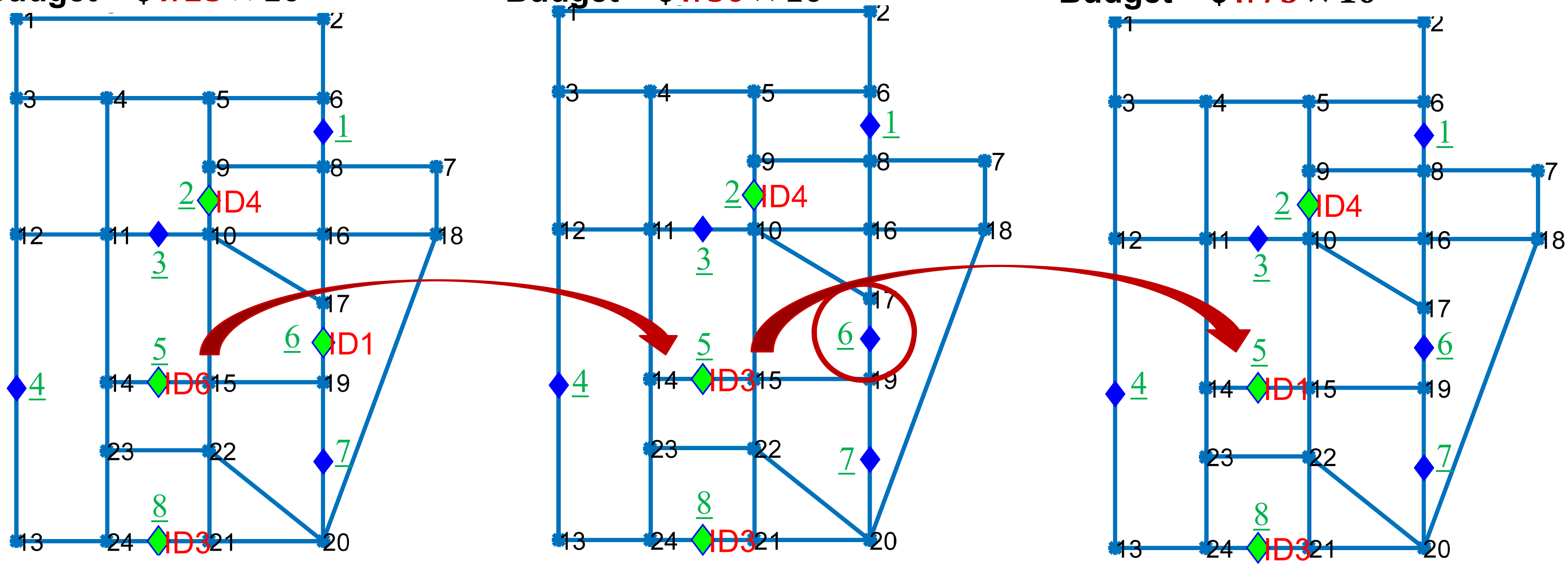
- With $1.0B budget the program optimizes to first replace the bridges that definitely need replacement.
- Two of the bridges are being replaced with the slowest ABC technique (ID6 for bridges 2 &5) and one is replaced with a medium speed (ID3 for bridge 8).
- Resulting in average network SR of 83(>60)

Case Study Results

Avg. SR after replacement = 95
Budget = $$1.25 \times 10^9$

Avg. SR after replacement = 83
Budget = $$1.50 \times 10^9$

Avg. SR after replacement = 83
Budget = $$1.75 \times 10^9$



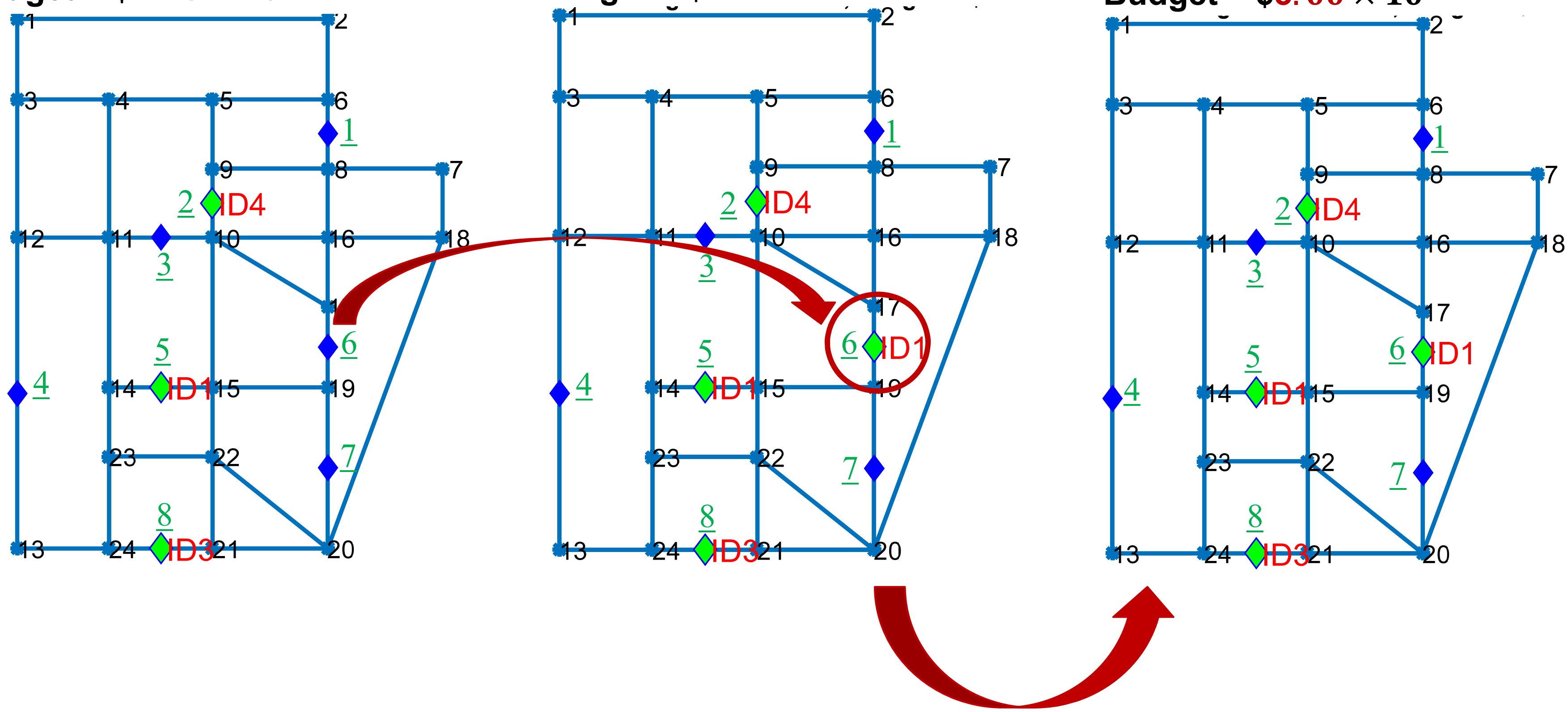
- With more budget the program eliminates the fourth bridge replacement and opts to use a much faster ABC technique for bridge 5 (ID6→ID3)
- Resulting in average network SR of 83(>60)
- Still doing the same with more budget bridge 5 (ID3→ID1)
- **Bridge 5 is a critical bridge**

Case Study Results

Avg. SR after replacement = 83
Budget = $$1.75 \times 10^9$

Avg. SR after replacement = 95
Budget = $$2.00 \times 10^9$

Avg. SR after replacement = 83
Budget = $$3.00 \times 10^9$



No change!

Computational Case Study

Investment ($Billion)	Optimal total direct cost ($Billion)	Bridge optimal closure time (days) Bridge: [1, 2, 3, 4, 5, 6, 7, 8]	Network traffic time after all replacements ($\times 10^{10}$ hours)
1.00	0.9355	[0, 225, 0, 0, 250, 0, 0, 126]	2.93
1.25	1.2348	[0, 153, 0, 0, 250, 32, 0, 126]	2.62
1.50	1.4976	[0, 153, 0, 0, 140, 0, 0, 126]	2.05
1.75	1.7394	[0, 153, 0, 0, 80, 0, 0, 126]	1.91
2.00	1.7991	[0, 153, 0, 0, 80, 32, 0, 126]	1.90
3.00	1.7991	[0, 153, 0, 0, 80, 32, 0, 126]	1.90

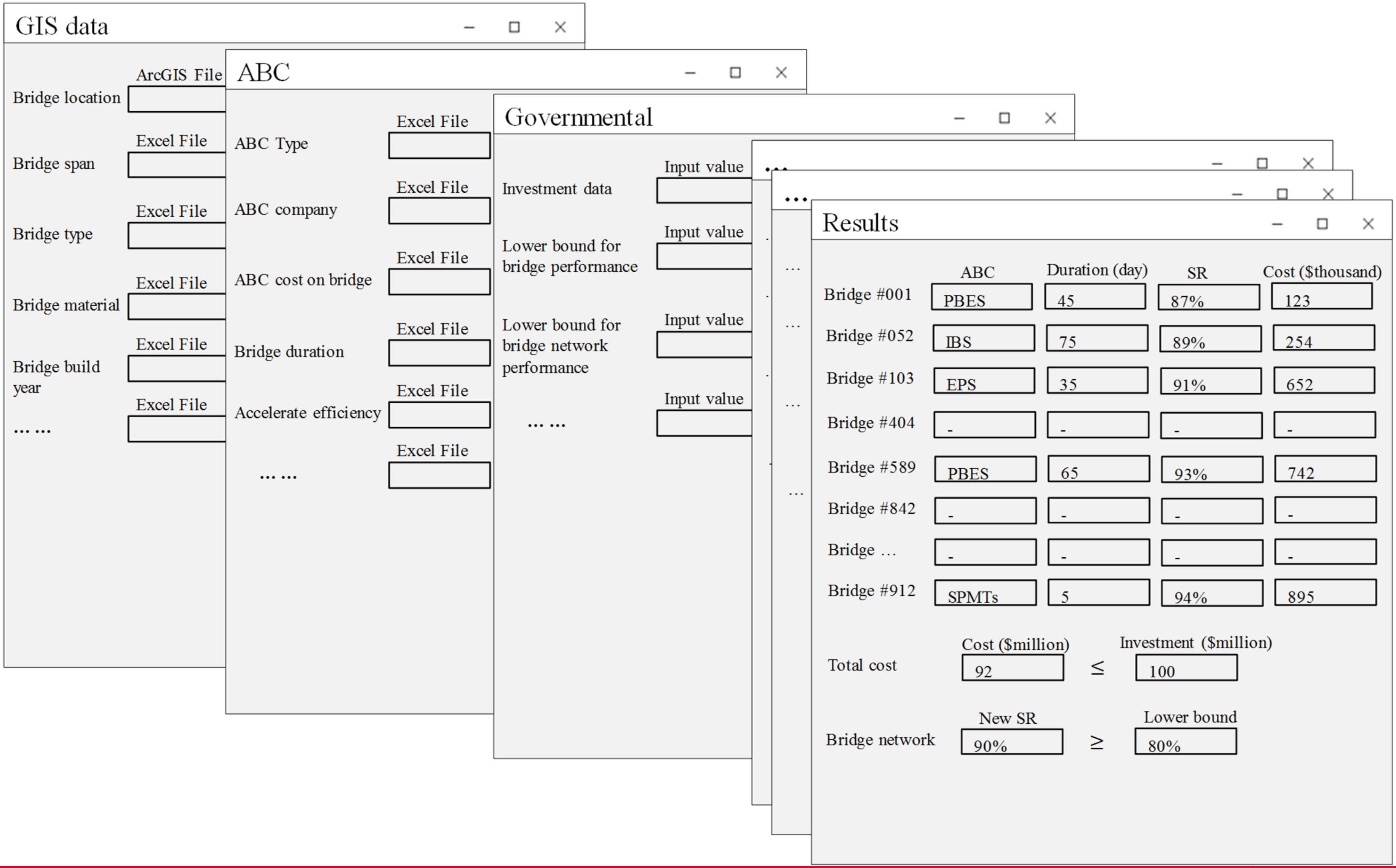
Conclusions

- A holistic decision making framework is developed for the network-level prioritization of candidate bridges, in addition to the project-level selection of the cost-efficient ABC technique for each bridge.
- The key point of this model is to provide an optimal solution considering the two levels of decision making in one process.
- The objective function of is defined to find the minimum cost of the entire network not only on at each target bridge site (direct cost) but also at the network level (indirect cost).
- Constraints from decision makers, bridge sites, and traffic operations are accounted for.

Future Work

- Enhance the technique for future applications to larger scale and more realistic network of bridges
- Consider the potential to extend the framework for network resilience enhancement using optimized pre- and post-event replacement and repair of bridges
- Develop a user interface for the developed technique so that it could be implemented by state agencies

User Interface Visualization



Thank you!

For questions contact: alipour@iastate.edu