DEVELOPMENT OF USER-FRIENDLY TOOLS AND DECISION-MAKING ALGORITHMS FOR SERVICE LIFE DESIGN OF ABC BRIDGES

Quarterly Progress Report
For the period ending November 30, 2021

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ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

Submitted to:
ABC-UTC
Florida International University
Miami, FL

1. Background and Introduction

Accelerated bridge construction (ABC) is a paradigm shift in the project planning where the necessity to lessen mobility impacts that occur due to onsite construction activities are given to a major priority. ABC techniques use innovative design and construction methods that are advantageous in a cost-effective and safe manner. Among the ABC techniques, prefabricated bridge elements are the most prominent methods. These are structural components that are manufactured offsite and shipped to the site upon the requirement that aims the reduction in onsite construction time, traffic disruption, improvement in product quality, and durability. An ABC application called closure joint is used to connect two adjacent prefabricated deck panels by casting filler material (i.e. normal concrete, polymer concrete, and ultra-high-performance concrete) in between them with the use of different reinforcement details. The connections, however, can be affected by environmental and structural degradations. Consequently, durability issues have been encountered in closure joints. There are proof tested and approved ABC design methods available in the literature. The recent publication by ABC-UTC discussed the closure joint design methods to mitigate the durability in a comprehensive manner (Jahromi et al., 2020).

This project will design and implement a prototype web-based decision support tool to facilitate the use of existing manuals and bridge specifications in practice. We first derive decision-making algorithms and criteria presented in the guideline for service life design of longitudinal deck closure joints. We then translate them into UML (Unified Modeling Language) use cases and develop a series of well-designed interactive questions and user interfaces. This will allow users to walk through the service life process with the aids of visual elements, suggestions and tips, and make final design decisions, without much knowledge of probabilistic approaches.

2. Problem Statement

Implementation of ABC technology has been gaining great momentum by Federal Highway Administration (FHWA) and several state DOTs during the last two decades (Culmo, 2011). ABC methods minimize the construction activities performed in the field, reduce the detour time and traffic disruptions, and improve the safety of workers and the public. Methods typically used for ABC include prefabricated bridge elements and systems (PBES), lateral slides, and self-propelled modular transporters (SPMT). Prefabricated elements used for ABC will be connected using longitudinal or transverse closure joints. It is noted that many prefabricated decks with longitudinal closure joints have performed well. Connections of PBES are critical as the performance of connections under loads and natural environmental conditions can affect the service life of the bridges. In addition, some issues like leakage and cracking in prefabricated deck connections have been identified with respect to operational or production defects. Different ABC design methods have been developed to connect prefabricated deck panels (e.g. Jahromi et al., 2020; Haber and Graybeal, 2018; Graybeal, 2014; Li et al., 2009). These design methods and new solutions are in progress to be incorporated in AASHTO LRFD Bridge Design Specifications for ABC but are not available yet. However, the methods have been proof tested and verified by the bridge community including bridge engineering research group in FHWA, ABC-UTC, and several state DOTs.

Recently, ABC-UTC has published a guideline for service life design of longitudinal deck closure joints (Jahromi et al., 2020) which was a customized version of a project for Bridges with Service Life Beyond 100 Years. While the published ABC-UTC Guide is comprehensive, it is not user friendly for bridge engineers and state DOTs to be used and implemented in their design. Therefore, a reliable decision support tool is required to assist stakeholders and engineers in choosing appropriate design options and solutions. To this end, we will develop a prototype web-based tool that provides customized design by applying the decision-making algorithm focusing primarily on service life and durability of closure joints. The proposed decision support tool will be implemented based on the general steps presented in the ABC-UTC design guide. It will be visual and allow users to easily navigate through the design options, design steps, on-site requirements, geometry, material properties, and modes of failures.

3. Objectives and Research Approach

- Develop a prototype web-based tool that will contain in a data base the entire information listed in the ABC-UTC Guide for Service Life Design of Longitudinal Deck Closure Joints and host it at FIU in a dedicated server.
- Develop a series of well-designed interactive questions and user interfaces that will allow the user to walk through service life process with the aids of visual elements, suggestions, and tips.
- Allow, easily, the information in the data base, such as reported closure joint service life performance and types to be updated as information becomes available
- Develop decision making tools that will assist the user to make final design decisions, without having to know fully the theory behind probabilistic approaches that will be used in the decision-making process.

The project team first translates the design solutions, presented in the ABC-UTC Guide, into UML use case and state charts, and designs the interactive questions based on the decision-making criteria and probabilistic approaches. We then organize preliminary meetings with the research advisory panel to solicit their feedback and update the use case diagrams for the decision support tool. Once the information flow, decision algorithms, and system functionality are approved, we use Python, an object-oriented programming language, and available open-source libraries (e.g. Pandas, Scikit, Numpy, SQLite) to implement the user interfaces and algorithms. To facilitate the decision support tool deployment on FIU server, the project team works closely with the Office of Information Technology to allocate the required space and maintenance resources.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Architecture Design

The system architecture is the optimum way to understand the interaction among components. Our architecture comprises three components which include GUI, application server, and database server. The main components are shown in Fig. 1.

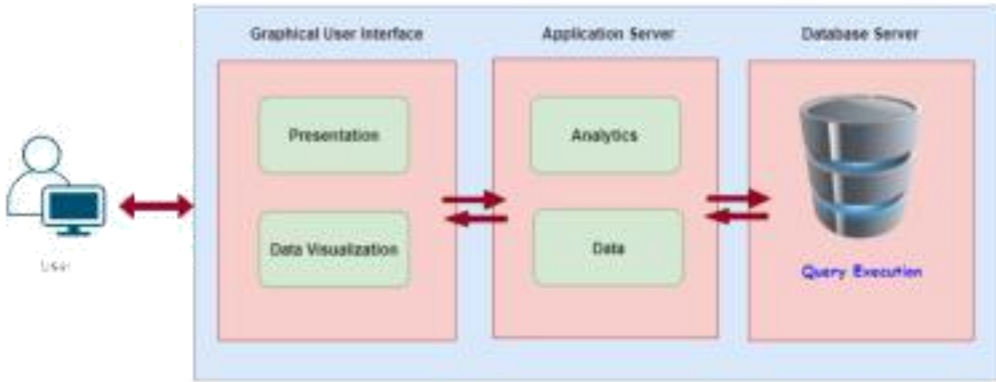


Fig. 1. System Architecture

<u>Graphical User Interface:</u> The user is provided with an interface or frontend where the specific parameters need to be given by the user to assist in identifying the list of closure joints. The interface helps to establish the environment where the user can interact with the system by providing necessary inputs and getting the desired output.

<u>Application Server:</u> The application server is the middle tier of the system. It is a business logic application or set of applications on the local network. When an application server gets a request from the user, it then performs logical operations based on the designed algorithm.

<u>Database Server:</u> It is a crucial component where the query requested by the user will be processed at this stage. The database will be populated with the required information that allows the algorithm to process the data and make appropriate decisions.

The decision support tool will be deployed on the FIU server. The OU research team will initiate communication with the Office of Information Technology at FIU to identify software requirements and allocate the required space and maintenance resources.

Task 2 – Content/Information Flow Identification, Algorithms and Analytics, Dashboard Design.

We designed UML use case diagrams, based on the published ABC-UTC Guide for service life design of longitudinal deck closure joints, to define interactive questions, systems functionalities, and required underlying decision algorithms.
Research team focused on the identification of content flow and decision-making algorithms. Fig. 2 illustrates the system use case diagram. The user is a primary actor who initiates the system. In our project, the database is the secondary actor which provides the necessary details to process the request. In this diagram, tasks or use cases are represented in three different colors to differentiate among tasks. Use cases represented in blue color are nothing but inputs/specifications that the user is required to provide in order to interact with the system. Use cases represented in orange color are outputs that the user receives as the result of the requested query. Rest of the use cases represents internal working process of the query.

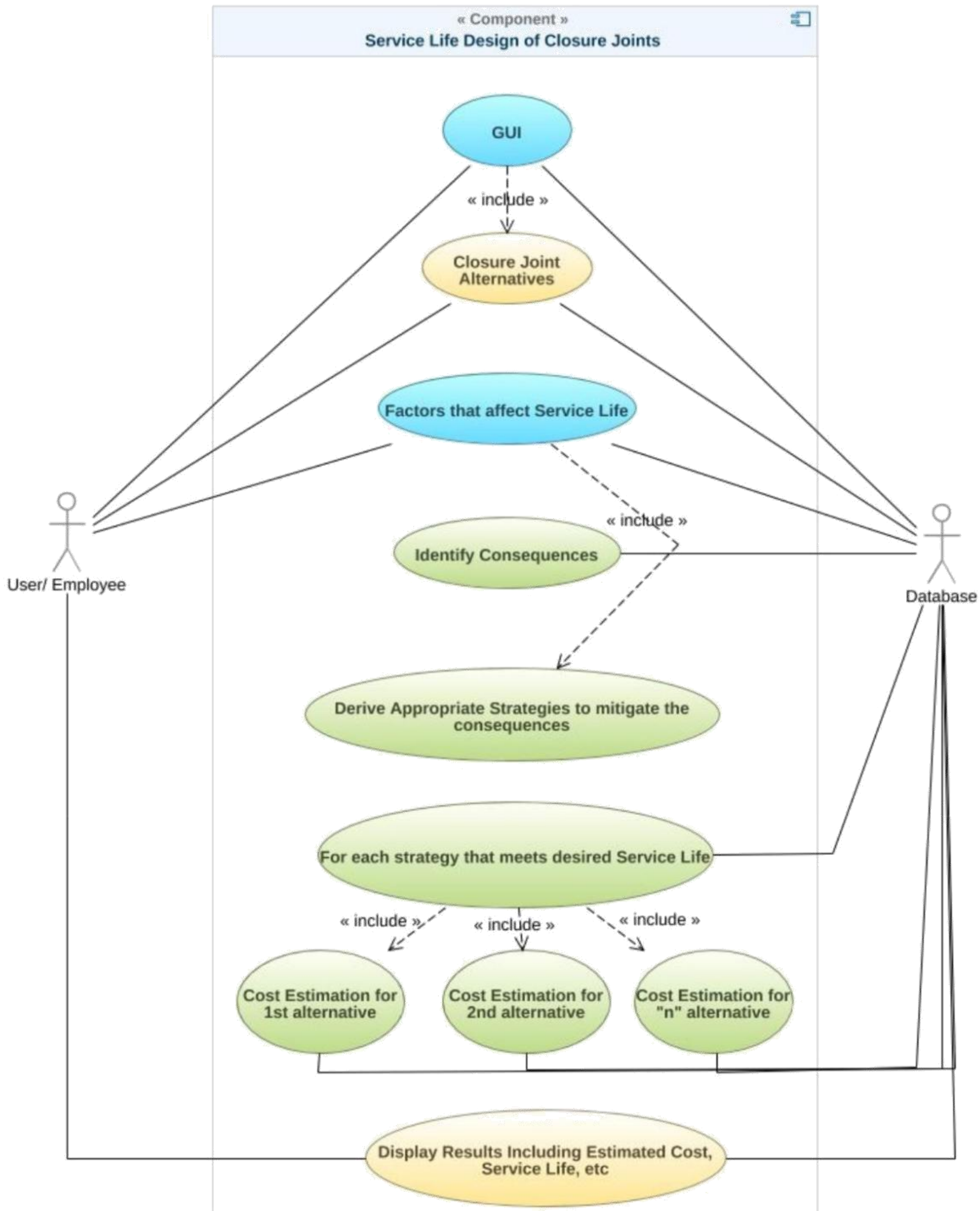


Fig. 2: UML Use case Diagram

Flow of Use cases: The interaction with the system starts once the user initiates the request through GUI by providing specifications through parameters. For each identified closure joint, with provided factors such as service loads, natural or manmade hazards that affect the service life of closure joints, the algorithm will determine appropriate mitigation strategies available in the guideline. For each derived alternative, the service life will be calculated based on Fick's law. For all alternatives, the estimated cost will be calculated and displayed along with the estimated service life. This allows for trade-off analysis and assists the user in making decisions.

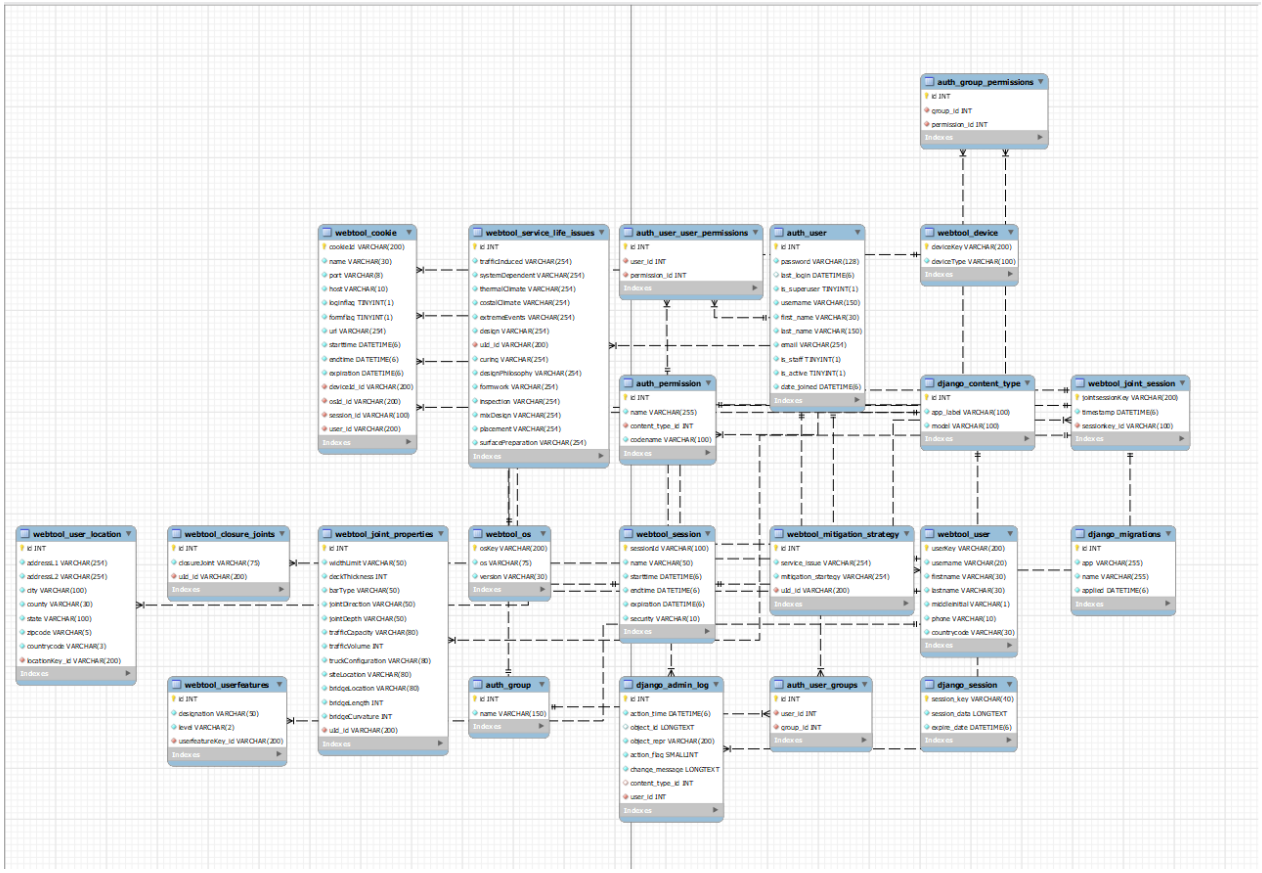


Fig. 3: Designed Relational Database supporting spatiotemporal data

Fig. 3 illustrates the detailed relational database diagram such that each rectangular represents classes and their attributes. The number of classes of a system indicates the number of objects and its corresponding attributes. It can be observed that the above database diagram has main attributes such as user session, closure joints and their properties, mitigation strategies, service life issues etc. Functions performs the operations of specific tasks.
To better understand the relationship between input parameters and mitigation strategies, the research team designed, developed, and tested an excel-based decision support tool based on the use case diagrams and identified attributes. The spreadsheet forms are presented in Appendix A. This tool has served as our reference point for developing the web-based tool in Task 3.

Task 3 – Prototype Implementation.

We chose and utilized Django as our web-based platform, which is a Python-based open source framework. Its architecture is based on the model-view-controller design pattern. Django is a flexible and comprehensive platform which gives us the opportunity to add different levels of computational intelligence to the application. Django consist of front-end interface templates which play a major role in providing user-friendly environment. The View Logic component decides what kind of data to be delivered to the template by responding to inputs from the user. View holds functions with an associated template. Model is a primary source of information about stored data which contains the data fields and behavior of the stored data. Each attribute in the model also represents a database field. The database is then queried using the attributes.

Updated GUIs: To enhance user's interaction, we improved GUIs (Graphical User Interfaces) including inputs, closure joints selection, and categories/ factors affecting the service life. Some fields that were not necessary for calculating the cost and service life were removed. This created space for better performance in terms of caching. All the fields in forms are backed by a local Redis Cache that temporarily store the data until the end of the process is reached.
The new versions of simplified GUIs are presented in Appendix B. Some specific features we used for designing the forms are: (a) displaying the closure joints geometry/shape upon choosing the specific type of closure joint, (b) reducing/disabling duplicate parameters based on the chosen factors by the user, and (c) reducing the issue of global declarations and extra queries using Redis, a Python library, to share data among forms fields. In addition, we added a new dynamic form which produces all possible mitigation strategies based on user's inputs. Logging has also been introduced to collect information about the functionality of the application for various use cases.

Database Implementation: The application is backed by a My Sql server that stores data from a user session, closure joint properties and spatial-temporal standpoints. The main purpose of the database design is to emphasize on tracking the user progress and storing data with respect to time and location. This accumulated data can be utilized for training models that could be used as an end-to-end solution towards best mitigation strategy. The database is currently used to manage and establish a control flow structure and authorization purposes. The database contains all the necessary components to support user registration and provide level-based access. There are three main business rules that the database represents:

- ➔ User Session
    - Contains all attributes to capture user related information
    - Supports data collection for both demographic and environment related information
    - Foundation for tracking and saving progress
- ➔ Closure Joints
    - Provides the infrastructure to collect all the features of closure joints required for computing initial costs and service life
    - It is the data centered backbone of the entire Closure Joint related business process
- ➔ Joint Session
    - A joint session is used to bind the user and session information with a specific closure joint
    - Adds room for improvement and flexibility in terms of database design
    - Simplifies the database schema

Service Life Calculation: Team discussed different methods to calculate the service life of each alternative using Fick's second law and decided to use the time to start the corrosion, assuming one-dimensional ingress of chloride through the concrete deck. The model uses Fick's second law and chloride diffusion coefficient to predict the initiation period (see equation 1). It should be noted that Fick's second law is not sufficient to calculate service life when an overlay is used (e.g., UHPC overlay).

$$C_{crit} = C(x = a, t) = C_0 + (C_s - C_0)\left[1 - erf\,\frac{a}{2\sqrt{D_{app}.t}}\right] \tag{1}$$

Where:

C_{crit} = Critical chloride concentration
C_0 = Initial chloride content of concrete, taken as a constant
a = concrete cover
C_s = Chloride concentration at surface
erf = error function
t = time
D_{app} = apparent chloride diffusion coefficient

Equation for calculating apparent diffusion coefficient is given below.

$$D_{app} = k_e D_c\ .\mathrm{A(t)} \tag{2}$$

Where:

A(t): aging function
k_e: environmental factor to account for temperature
D_c: chloride migration rate

Aging function can be calculated using equation (3).

$$\mathrm{A(t)} = \left(\frac{t_0}{t}\right)^{\alpha} \tag{3}$$

Where:

α =aging exponent
t_0 = reference point of time (28days=0.0767 yrs)

In order to calculate the weighted average to account for chloride buildup over 7 years period, we use the following equation.

$$C_s = \frac{\frac{C_s}{2} * 7 + C_s * \mathrm{t}}{t} \tag{4}$$

The Pseudo code for calculating service life using above equations is given in Algorithm (1). NCHRP report along with existing works in the literature were reviewed by the team to find state-specific values and ranges for the chloride diffusion coefficient. The web-based tool suggests these values to the user, and the user can input the parameters to calculate the service life.

Initial Costs Calculation: The OU research team collected construction cost information for pay items associated with longitudinal and transverse deck joints from state DOT bid records to supplement data available in the ABC-UTC Guide for Service Life Design of Longitudinal Deck Closure Joints. States examined included Oklahoma, New York, Texas, and Tennessee to identify regional differences in construction costs. Oklahoma DOT personnel were also consulted directly to obtain guidance on obtaining the most accurate cost data.

Algorithm 1. Calculating service life (initiation period) based on the one-dimensional ingress of chloride through the concrete deck

Begin Input: C_{crit} , C_s ,a, D_c
Output: initiation period
While ($C_{crit(user)} > C_{crit}$)
  Calculate Aging coefficient(A(t) from equation (3) for time t.
  Calculate D_{app}[t] from equation (2) for time t
  Initialize $C_s = 0$
  If(t<8) **then**
    Using equation (1) and considering $C_s\ as\ C_s * t$
    C_s=$C_s + C_s/7$
  Else
    Using equation (4) to calculate C_s
    Using equation (1) calculate C_{crit}
  End if
  Increment t by 1
End while
Initiation period =t

<u>Multi-criteria decision-making:</u> To find the best mitigation solution for the selected closure joint, we implemented a multi-criteria decision-making algorithm using TOPSIS (Technique for Order of Preference by Similarity). The algorithm utilizes users' preferences as weights to perform trade-off analysis between costs and service life. The user decides whether to give a priority to service life or costs. The algorithm then ranks the options based on the user's preference, and the web-based tool displays the first- and second-best options. The main steps are listed below:

1. Create an evaluation matrix for costs and service life.
2. Normalize the evaluation matrix.
3. Calculate the weighted normalized decision matrix.
4. Determine the best and the worst alternative for each criterion.
5. Calculate the Euclidean distance between the target alternative and the best/worst
6. For each alternative calculate the similarity to the worst alternative.
7. Rank alternatives according to the TOPSIS score by descending order.

<u>Inspection Data:</u> A new form was designed to collect component-level inspection data regarding the condition of closure joints. Based on the condition, the user can select from 5 different categories ranging from excellent to poor.

<u>Meeting with Research advisory board</u>: Two members representing Oklahoma DOT and a consulting company were invited and joined the advisory panel. In addition, PI Mohebbi met with Dr. Azizinamini, Mr. Bruce Johnson, and Ms. Mary Lou Ralls Newman to receive their feedback about the prototype web-based tool. The team will meet with Oklahoma advisory board members in mid-December to solicit their inputs and feedback bout the designed tool.

5. Expected Results and Specific Deliverables

The expected deliverables are: (a) a prototype web-based tool; and (b) a manual (software documentation) which will guide users to make final design decisions, listed in the ABC-UTC Guide for Service Life Design of Longitudinal Deck Closure Joints. The interactive user interfaces will provide effective visual elements and suggestions to guide users, without fully knowing the theory behind probabilistic approaches.

6. Schedule

This project started in May, and the progress of tasks is shown in the table below.

	Year 2021-2022									
Project Tasks	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
T1. Architecture design										
T2. Content identificatiion, algorithms, analytics, dashboard										
T3. Prototype Implementation										
T4. Final Report										
	Worked Performed									
	Worked to be Performed									

Item	% Completed
Percentage of Completion of this project to Date	% 80

7. References

M. Culmo, (2011), “Accelerated Bridge Construction: Experience in Design, Fabrication and Erection of Prefabricated Bridge Elements and Systems: Final Manual”, Federal Highway Administration, Office of Bridge Technology (Rep. No. FHWA-HIF-12-013). United States.

B. Graybeal, (2014), “Design and construction of field-cast UHPC connections”, Federal Highway Administration (Rep. No. FHWA-HRT-14-084; HRDI-40/10-14 (750) E). United States.

Z. Haber, B. Graybeal, (2018), “Performance of Grouted Connections for Prefabricated Bridge Deck Elements”, Federal Highway Administration (Rep. No. FHWA-HIF-19-003), United States.

A. Jaberi Jahromi, A. Valikhani, I.M. Mantawy, A. Azizinamini, (2020), “Service Life Design of Deck Closure Joints in ABC Bridges: Guidelines and Practical Implementations” Frontiers in Built Environment, https://doi.org/10.3389/fbuil.2019.00152.

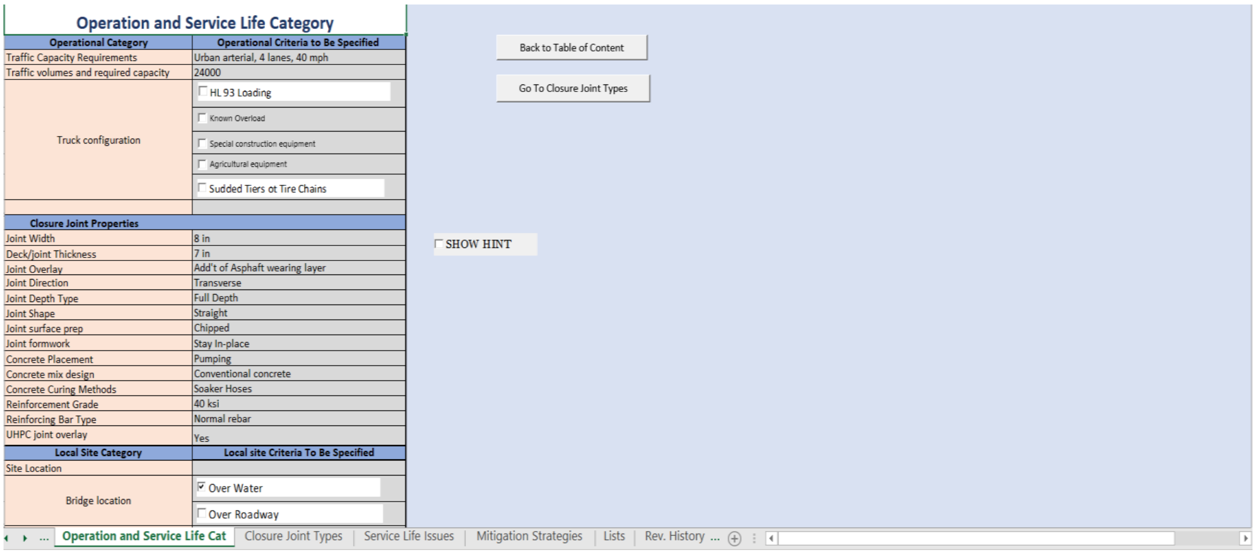
Li, L., Ma, Z., Griffey, M. E., & Oesterle, R. G, (2009), “Improved Longitudinal Joint Details in Decked Bulb Tees for Accelerated Bridge Construction: Concept Development”, ASCE Journal of Bridge Engineering, 15(3), 327-336.

NCHRP Web-Only Document 269: Guide Specification for Service Life Design of Highway Bridges, 2019.

Appendix A

The following forms illustrate the excel-based decision support tool.

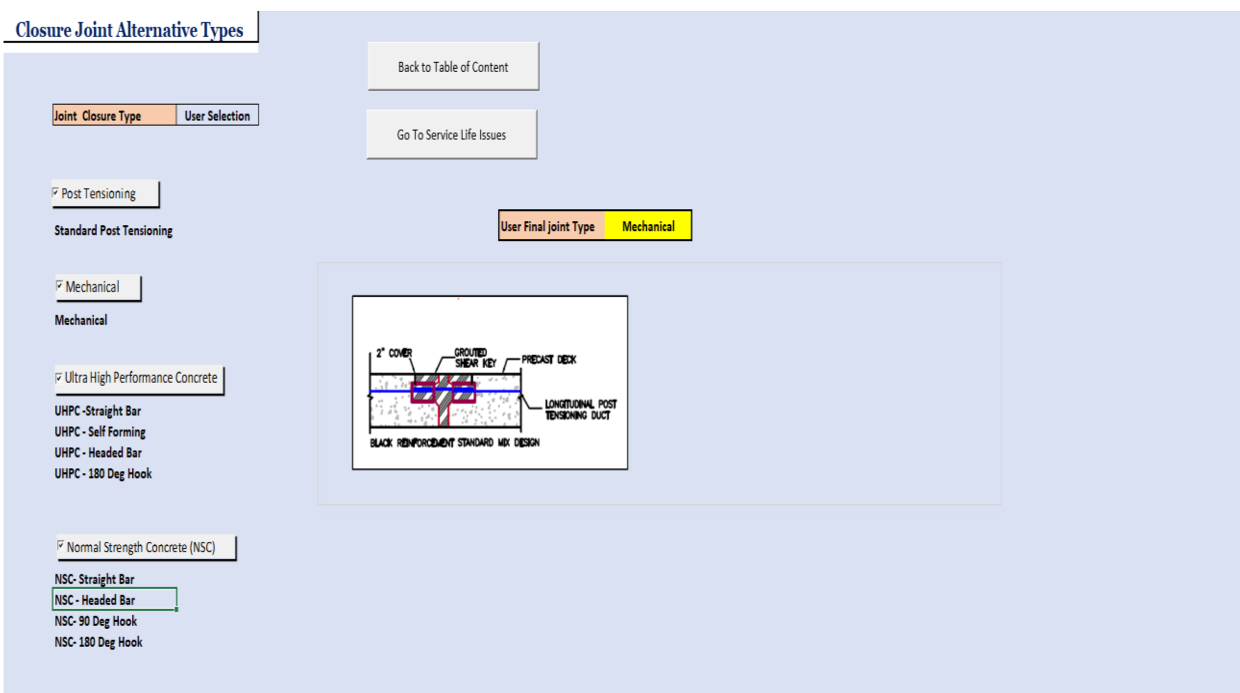
Form 1: Operational and Service Life Category



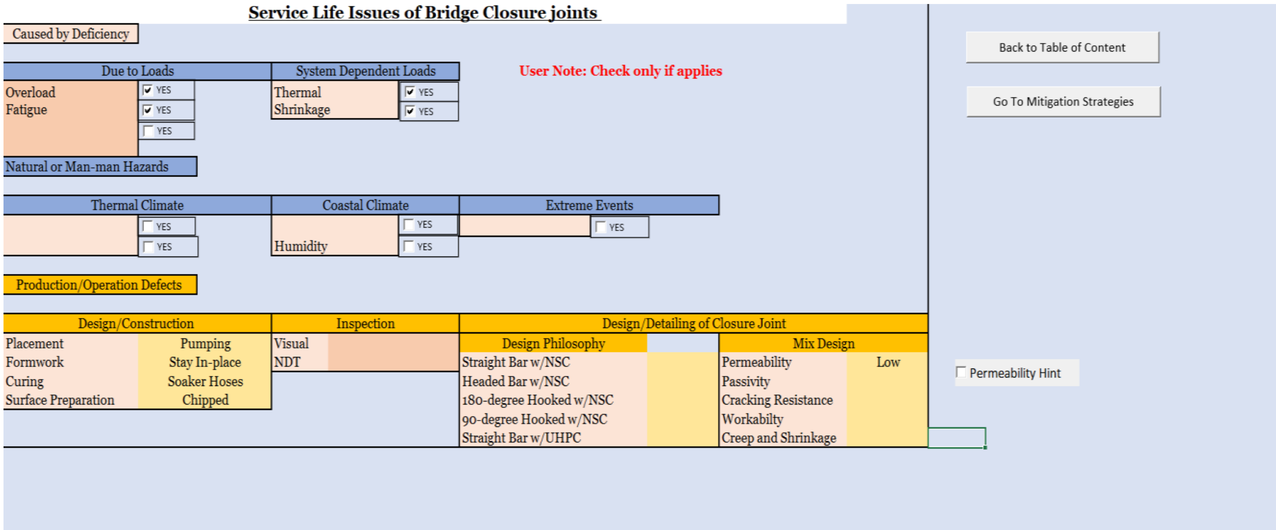
Operation and Service Life Category

Operational Category	Operational Criteria to Be Specified
Traffic Capacity Requirements	Urban arterial, 4 lanes, 40 mph
Traffic volumes and required capacity	24000
Truck configuration	HL 93 Loading Known Overload Special construction equipment Agricultural equipment Sudded Tiers ot Tire Chains
Closure Joint Properties	
Joint Width	8 in
Deck/joint Thickness	7 in
Joint Overlay	Add't of Asphaft wearing layer
Joint Direction	Transverse
Joint Depth Type	Full Depth
Joint Shape	Straight
Joint surface prep	Chipped
Joint formwork	Stay In-place
Concrete Placement	Pumping
Concrete mix design	Conventional concrete
Concrete Curing Methods	Soaker Hoses
Reinforcement Grade	40 ksi
Reinforcing Bar Type	Normal rebar
UHPC joint overlay	Yes
Local Site Category	**Local site Criteria To Be Specified**
Site Location	
Bridge location	Over Water Over Roadway

Form 2: Closure Joint Alternatives



Form 3: Service Life Issues of Closure Joints



Service Life Issues of Bridge Closure joints

Caused by Deficiency

User Note: Check only if applies

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Go To Mitigation Strategies

Due to Loads		System Dependent Loads	
Overload	☑ YES	Thermal	☑ YES
Fatigue	☑ YES	Shrinkage	☑ YES
	☐ YES		

Natural or Man-man Hazards

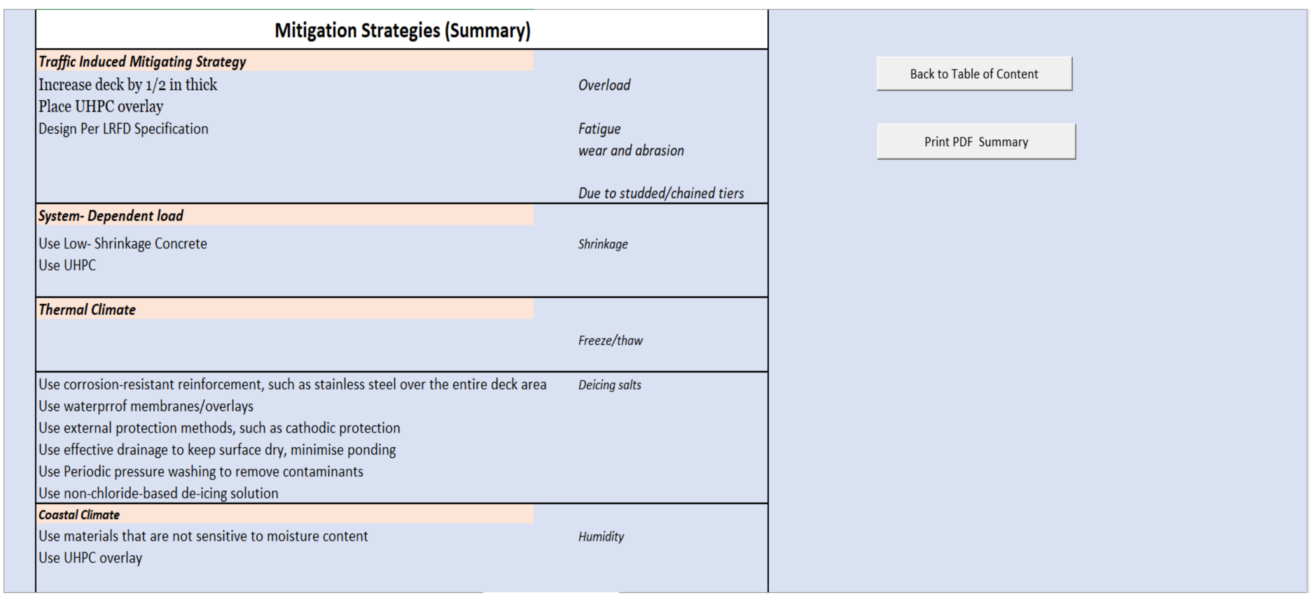
Thermal Climate		Coastal Climate		Extreme Events	
	☐ YES		☐ YES		☐ YES
	☐ YES	Humidity	☐ YES		

Production/Operation Defects

Design/Construction		Inspection	Design/Detailing of Closure Joint: Design Philosophy	Design/Detailing of Closure Joint: Mix Design	
Placement	Pumping	Visual			
Formwork	Stay In-place	NDT	Straight Bar w/NSC	Permeability	Low
Curing	Soaker Hoses		Headed Bar w/NSC	Passivity	
Surface Preparation	Chipped		180-degree Hooked w/NSC	Cracking Resistance	
			90-degree Hooked w/NSC	Workabilty	
			Straight Bar w/UHPC	Creep and Shrinkage	

☐ Permeability Hint

Form 4: Mitigation Strategies



Mitigation Strategies (Summary)

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Print PDF Summary

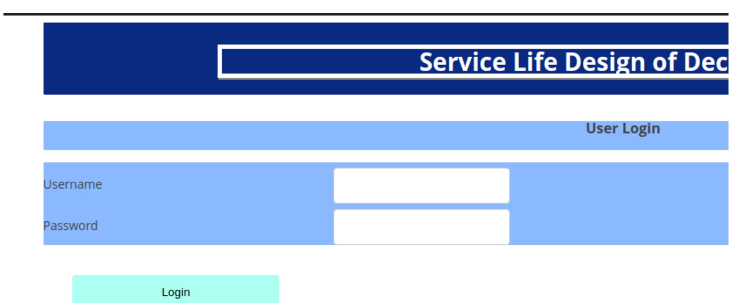
Traffic Induced Mitigating Strategy	
Increase deck by 1/2 in thick	*Overload*
Place UHPC overlay	
Design Per LRFD Specification	*Fatigue*
	wear and abrasion
	Due to studded/chained tiers
System- Dependent load	
Use Low- Shrinkage Concrete	*Shrinkage*
Use UHPC	
Thermal Climate	
	Freeze/thaw
Use corrosion-resistant reinforcement, such as stainless steel over the entire deck area	*Deicing salts*
Use waterprrof membranes/overlays	
Use external protection methods, such as cathodic protection	
Use effective drainage to keep surface dry, minimise ponding	
Use Periodic pressure washing to remove contaminants	
Use non-chloride-based de-icing solution	
Coastal Climate	
Use materials that are not sensitive to moisture content	*Humidity*
Use UHPC overlay	

Appendix B

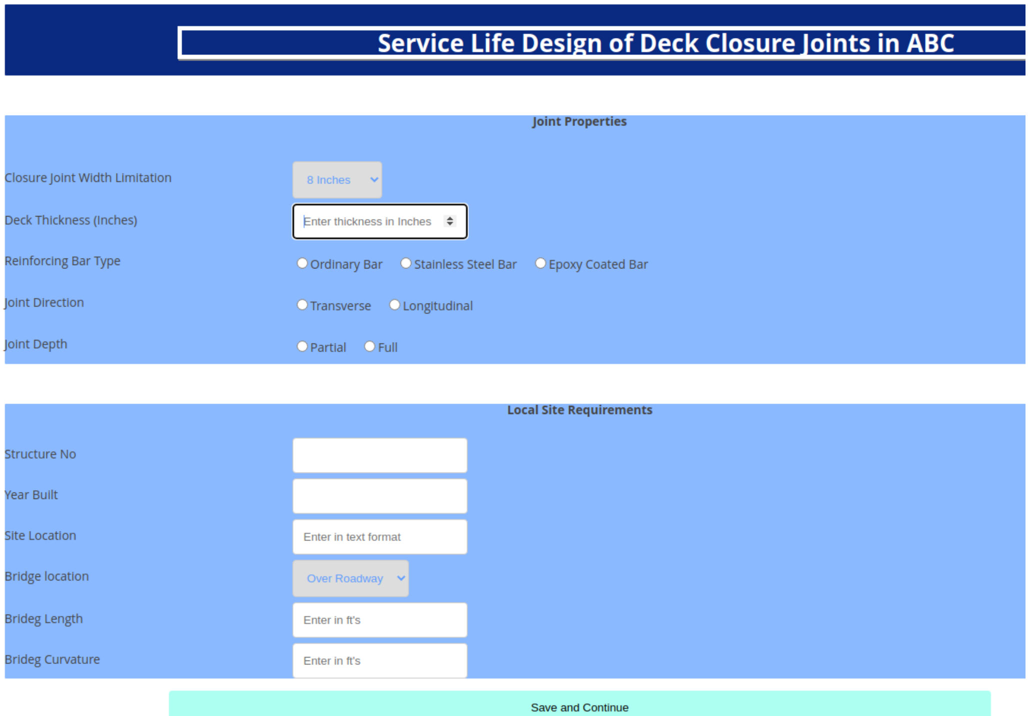
The following forms illustrate the web-based decision support tool.

User Registration Form

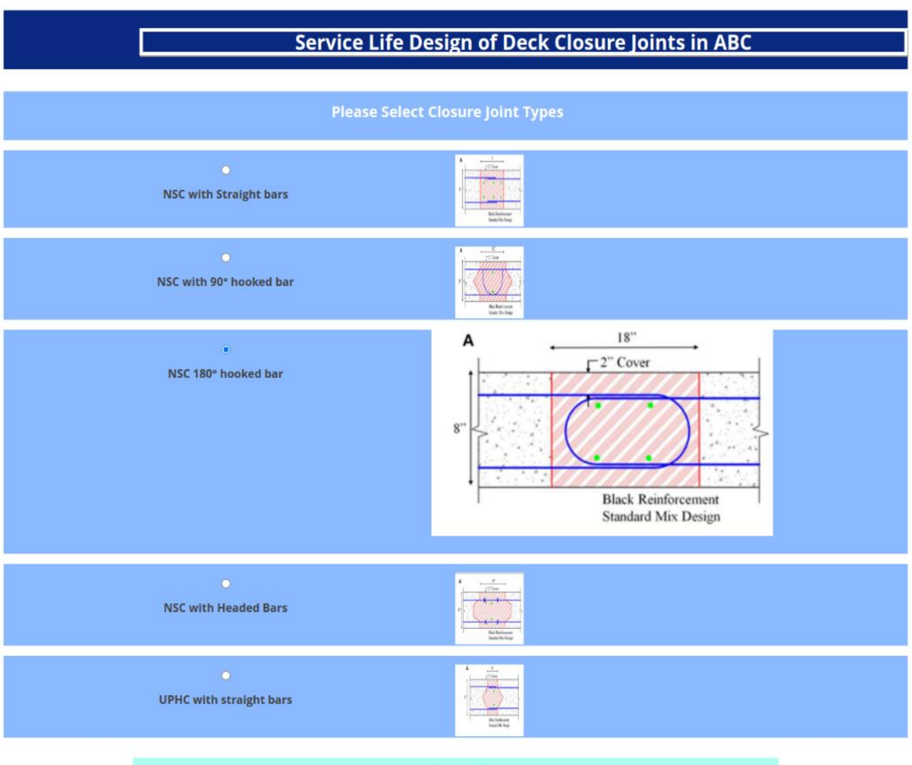
Login



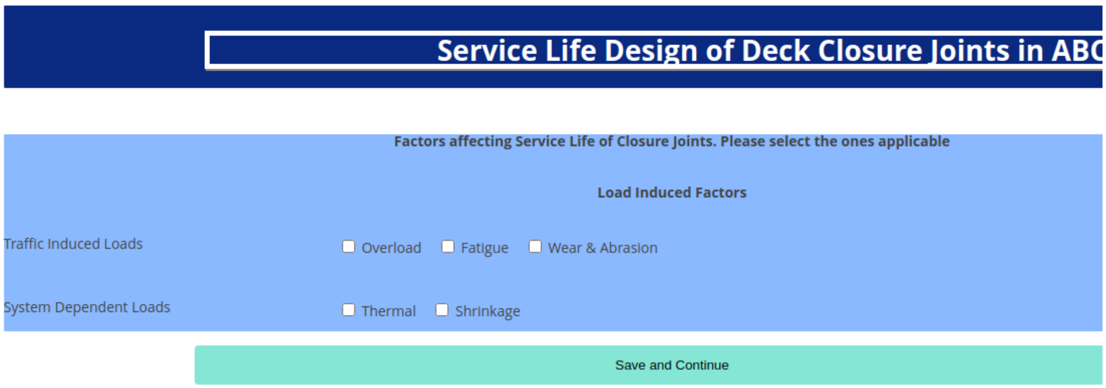
Joint Properties and Local Site Requirements Form

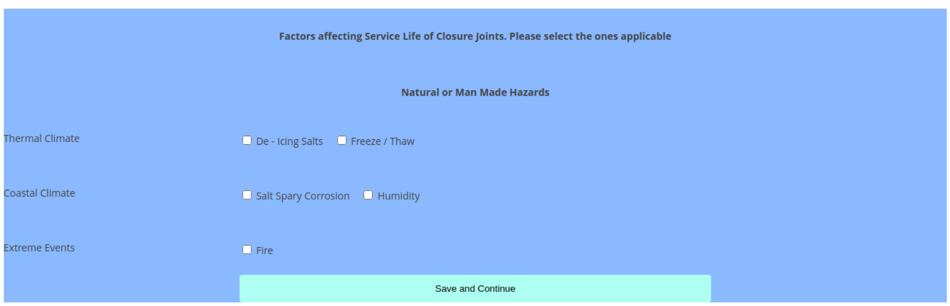


Selection of Closure Joints

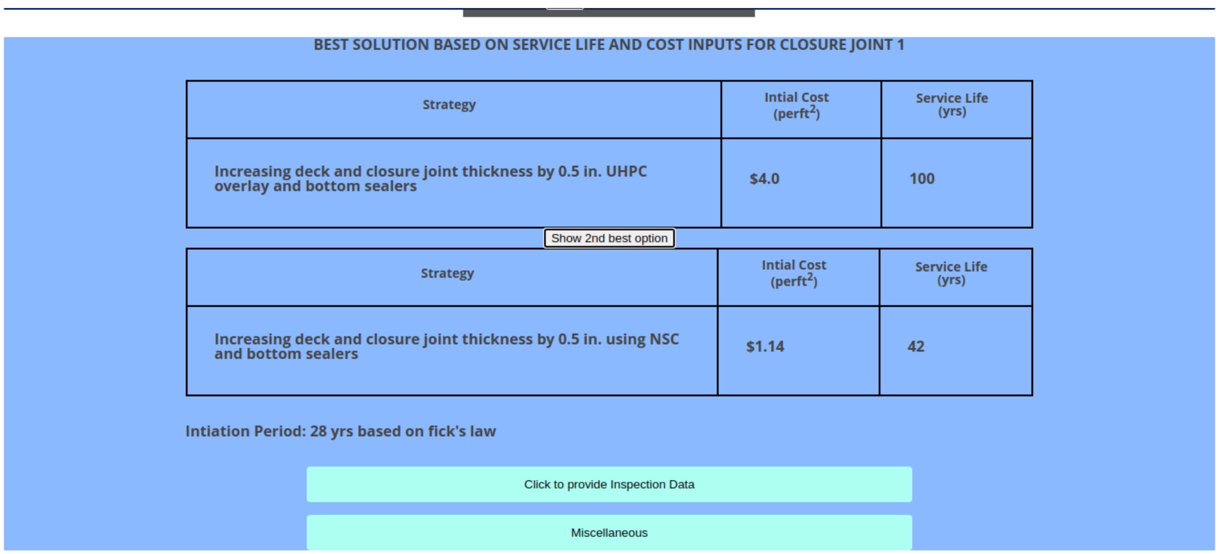


Selection of factors affecting the service life of closure joints





Output (Mitigation Strategies)



Inspection data collection form