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Agent-Based Modeling of ABC Methods for Decision-Making in Highway Bridge Projects Including Uncertainty and Several Stakeholders

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AGENT-BASED MODELING OF ABC METHODS FOR DECISION-MAKING IN HIGHWAY BRIDGE PROJECTS INCLUDING UNCERTAINTY AND SEVERAL STAKEHOLDERS

by

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Accelerated Bridge Construction (ABC) methods that were recently introduced in the U.S. to reduce the on-site construction duration furnish several benefits to the public and highway agencies. Further, the traffic growth in addition to increasing number of functionally obsolete and structurally deficient bridges necessitates the increased implementation of ABC methods. In recent years, several Departments of Transportation (DOTs) in the U.S. have developed decision-making models to compare broadly ABC to conventional bridge construction for a particular site. However, with increased implementation and advancements in ABC methods, there is a need for specifying a particular ABC method and a superstructure system for a site by means of evaluating the associated uncertainty. The uncertainty arises because of the activities associated with ABC methods, and constructability and durability of superstructure systems with respect to site-specific conditions. Moreover, the interactions among the internal stakeholders such as the DOT, Designer, Contractors, Consultants, etc., while delivering a project using an ABC method contribute to the uncertainty. Understanding the need, a decision-making model is required that enables the evaluation of ABC methods and the associated superstructure systems in order to achieve optimal constructability and durability of a bridge. The agent-based complex systems approach enables modeling and simulating the activities and stakeholder interactions in order to evaluate the impact of the uncertainty on the ABC project performance. The uncertainty can be quantified by identifying the parameters that contribute to uncertainty, and establishing parameter correlations with the site-specific data. The following outline the specific tasks performed during the research: (1) Documenting potential superstructure systems that can be used with the ABC methods for a particular region, (2) Documenting major activities and internal stakeholders of ABC methods, (3) Documenting parameters that contribute to uncertainty

of the activities, (4) Developing the parameter correlations with site-specific data for a particular region, (5) Formulating the decision-making framework and demonstrating the framework using an example, and (6) Developing recommendations for future research to extend the framework to an automated decision-making model/tool.

Keywords: Accelerated Bridge Construction (ABC), ABC Methods, Agent-Based Modeling and Simulation, Complex Systems Approach, Bridge Superstructure Elements, Decision-Making Framework, Decision-Making with Uncertainty.

Dedicated to my beloved father Dr. Mohammed Abdul Wajid, mother Tasneem Fathima, and wife Dr. Siddiqua Fathima.

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Abdul Wahed Mohammed

TABLE OF CONTENTS

Table of Contents – Continued

Table of Contents – Continued

Table of Contents – Continued

CHAPTER

LIST OF TABLES

List of Tables – Continued

LIST OF FIGURES

List of Figures – Continued

CHAPTER I

INTRODUCTION

Problem statement

Bridges are the key nodes in the roadway network. Highway agencies strive to manage bridge projects in order to maintain a safe and serviceable highway infrastructure while assuring mobility. The U.S. has 610,749 bridges and 61,365 (10%) are deemed structurally deficient while 84,525 (14%) are declared functionally obsolete and call for bridge rehabilitation or replacement projects (Federal Highway Administration (FHWA) 2015a). Bridge rehabilitation or replacement with conventional approaches will lead to more outrageous conditions for the commuters. The ongoing growth in traffic coupled with the public's demand for uninterrupted travel and improved safety has led to the evolution of state-of-the-art bridge construction methods characterized as Accelerated Bridge Construction (ABC). ABC is in early stages of development and the bridge construction industry is gaining experience with it the new methods through limited implementations such as demonstration projects. The strict time constraints will always be a part of ABC projects in order to reduce the mobility impact time. ABC methods are highly valued because of their inherent advantages of perceived higher quality, short onsite construction duration, lower life-cycle cost, improved work zone safety to workers and traffic, and reduced users' costs (FHWA 2013).

In order to build longer lasting highway infrastructure using innovations along with achieving the fast construction of highways and bridges, the FHWA is promoting use of ABC methods in regular practice through its initiative *Highways for Life* program. Thus, highway agencies are developing policy statements for specifying ABC methods for appropriate sites as part of their regular business process. The policy statements require that in a project selection, ABC is always included as a bridge construction method.

Also, if an ABC method is not utilized for a project, a rationale is required (Aktan et al. 2014a).

Currently, popular ABC methods are (a) assembling bridge structural elements at final bridge alignment, termed as Prefabricated Bridge Elements and Systems (PBES), (b) constructing replacement superstructure at a staging area and moving it from the staging area into final alignment, termed as Self-Propelled Modular Transporter (SPMT) move, and (c) constructing replacement superstructure on temporary supports adjacent to the final bridge alignment and sliding it in place, termed as Slide-In Bridge Construction (SIBC). Research is being conducted to make the implementation of ABC methods more efficient and effective. One such effort is to compile the lessons learned from already implemented ABC projects. The FHWA developed a web-based repository for ABC projects in the U.S. (FHWA 2015b). This repository consists of folders for states that have implemented ABC projects. Each project folder consists of sub-folders that may include contract plans, specifications, bid tabs, and other related information such as photos and videos. As of April 2015, a review of ABC projects from the FHWA repository showed a total of 123 ABC projects were compiled including 76 PBES, 30 SIBC, and 11 SPMT moves.

The construction method selection for a bridge rehabilitation or replacement project is generally based on available funding and proposals from contractors or design-bid-build contracts. Moreover, in regular practice the decision group comprising of representatives of owner and contractor with differing preferences, experiences, and backgrounds do not have a rational approach to make an informed decision. Thus, to evaluate the bridge construction methods, FHWA and several state Departments of Transportation (DOTs) are in the process of developing and improving decision-making models. The basic decision-making models for bridge projects are limited to flowcharts that are not facilitated with project specific qualitative/quantitative data to help in the judgments, such as the ones developed by Ralls (2005) and MassDOT (2009). These models also lack tangible mathematical background. Few of the decision-making models use scoring models with predefined weight factors, such as the ones developed by UDOT (2010) and WisDOT (2013). However, these models lack background to assist the highway agencies in developing standardized procedures for a region/state. On the other hand, some of the recent decision-making models implement the Analytical Hierarchy Process (AHP) that allows qualitative pair-wise comparisons of the decision-making parameters, such as the ones developed by Salem and Miller (2006), Doolen et al. (2011) and Saeedi et al. (2013). However, such models restrict the decision makers to provide judgments without specific knowledge of the project site. The decisions are not properly articulated and the information provided by the project team may not yield to a coherent decision.

To overcome the limitations in the available decision-making models, a decision-making model was developed by the author as a part of Michigan Department of Transportation (MDOT) research project MDOT RC-1602 (Aktan and Attanayake 2013). The model incorporates quantitative data, qualitative data obtained as preference ratings on an ordinal scale, and the AHP. Project managers, scoping engineers, and bridge committee members are the potential users to provide preference ratings. The quantitative data is grouped as site-specific data, traffic data, and cost data, and is made available to the users during the decision-making process. The preference ratings for the quantitative parameters on an ordinal scale are calculated based on site-specific data, traffic data, life-cycle cost data, and common site characteristics and economic indicators for a state/region. Later, the ordinal scale ratings of the qualitative and quantitative parameters are converted into pair-wise comparison ratings to be used in the AHP. The conversion process includes calculating a pair-wise comparison rating (on AHP scale) based on the ordinal scale rating differential of the two parameters being compared. The calculated pair-wise comparison rating is assigned to the parameter with larger ordinal scale rating, while the inverse of the pair-wise comparison rating is assigned to the parameter with smaller ordinal scale rating. Implementing ordinal scale ratings in conjunction with Eigenvalue analysis to eliminate the concern of pair-wise comparing unrelated parameters and associated consistency control in the classic AHP, the decision-making model is considered as hybrid. The results from the model are presented as the distribution of decision-making parameter preferences and bridge construction method preferences.

The hybrid decision-making model addresses many shortcomings of the other available models for ABC decision-making. However, the hybrid decision-making model addresses only one of the several challenges that state DOTs encounter during scoping of ABC projects. The most common challenges include the following: (1) justification of initial project costs for ABC implementation and a rational process for evaluating ABC methods for a given site, (2) specifying a particular superstructure system to be used with an ABC method, and (3) evaluating constructability and durability of ABC methods and the superstructure systems with respect to site-specific conditions (Aktan et al. 2014a). The hybrid decision-making model addresses the first challenge. However, further research is necessary to address the second and third challenges.

For each ABC method selected for a site, there are several superstructure systems that can be implemented. The superstructure systems include elements such as prefabricated girders, prefabricated deck panels or cast-in-place deck, and prefabricated modules. Recommendations of bridge superstructure elements and a combination thereof for implementation in ABC methods have been developed by Aktan and Attanayake (2013). The recommendations are based on a critical review of the connection and continuity details of the systems utilized in past projects, considering the durability and constructability of the systems. Understanding the current and future needs of the state DOTs, it is essential to select an ABC method and an associated superstructure system for a site in order to achieve optimal constructability and durability of the bridge.

Typically, bridge superstructure systems used in ABC methods consist of superstructure elements connected using innovative materials and details. Though individual superstructure component performance data is available, being relatively new in the field of construction, the performance data of the bridge structural systems used in ABC methods is scarce. An investigation of some of the bridges constructed using ABC methods showed structural system performance in terms of durability (Issa et al. 1995, 2003; Dye 2005; Ackermann 2007, Culmo 2009, 2010, 2011, 2013). The constructability and durability of a bridge is affected by the site-specific conditions and the uncertainty associated with the activities of ABC methods (Aktan et al. 2014a, b). Incorporating structural system performance in terms of constructability and durability in the decision-making process is essential to predict the risk/uncertainty associated with the superstructure systems and the ABC methods. Failing to incorporate structural system performance may lead to an inferior decision.

The international technology scanning program conducted under the sponsorship of FHWA to improve construction management practices in the U.S. (Ashley et al. 2006) noted that the collaboration of internal stakeholders during a project affects the project performance. The internal stakeholders include the owner, contractors, designers, etc. that are involved with delivering a project. Hence, in evaluating ABC methods for a site, it is essential to consider the interactions among internal stakeholders during the project delivery process. In the future several DOTs intend to implement ABC at sites using the historical design-bid-build contract procurement method (Aktan et al. 2014a). This contract procurement method is preferred because of its wide applicability and well-established roles for the stakeholders. The design-bid-build contract procurement method offers the owner, such as a DOT, a significant control over the process because the facility carried features are completely determined and specified prior to selection of the contractor. The owner can use competition among the contractors to establish reasonable prices and quality standards for a project. Also, as shown in Figure 1.1, the internal stakeholders interact with each other particularly through the owner's agreement in the process of delivering a project.

In order to address the aforementioned needs, a decision-making model is required that enables specifying a particular ABC method and a superstructure system for a site by means of evaluating the associated uncertainty. Also, the decision-making model needs to include the interactions among the internal stakeholders in the evaluation. By implementing such a decision-making model during scoping of ABC projects, optimal constructability and durability of bridges can be achieved.

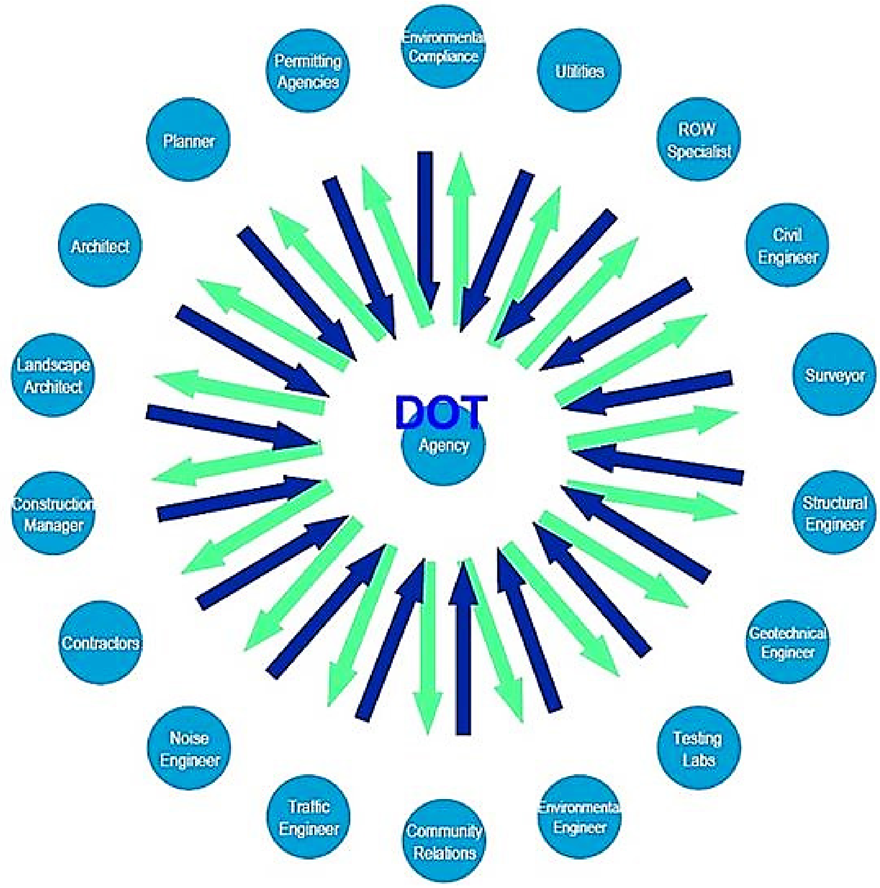


Figure 1.1. Interactions among stakeholders with DOT as controlling entity (Source: FTA 2009)

Objective of the study

Understanding the need described in the previous section, the objective of the research is to develop a decision-making model that enables selecting an ABC method and an associated superstructure system for a site based on the following:

1) Evaluating ABC methods and the associated superstructure systems for a site
2) Evaluating uncertainty associated with the activities of ABC methods
3) Evaluating interactions among the internal stakeholders while delivering a project using the ABC methods.

The research outcome aims to make the decision-making model widely available to the internal stakeholders so that optimal constructability and durability of a bridge can be achieved. To achieve the objective, a research methodology is developed and will be described in Chapter 2.

Scope of the study

The scope of this study is limited to developing a decision-making framework for evaluating specific ABC methods (PBES, SPMT move, and SIBC) for a site in a particular region. The DOT is assumed as the owner, and is considered to maintain overall project control and transfer detailed engineering design/construction activities to design/construction contractors. Further, key internal stakeholders involved with the ABC methods are considered.

To gauge the impact of the risk/uncertainty and the interactions on an ABC project performance, two metrics are used: (1) project cost and (2) construction duration. These are termed as measures of performance of the project, and are defined as the following:

- Project cost: The project cost is defined as the cost incurred to the agency for an ABC project including the design and specialty cost for ABC specific activities (FHWA 2015b).
- Construction duration: The construction duration considered in this research refers to the *mobility impact time*. The mobility impact time is defined as the period of time the traffic flow of the transportation network is reduced due to onsite construction activities (FHWA 2015b).

Specific tasks of the study include the following:

1) Documenting potential superstructure systems that can be used with ABC methods for a particular region
2) Documenting major activities and internal stakeholders of ABC methods
3) Documenting parameters that contribute to uncertainty of the activities
4) Developing the parameter correlations with site-specific data for a particular region
5) Formulating the decision-making framework and demonstrating the framework using an example
6) Developing recommendations for future research to extend the framework to an automated decision-making model/tool.

CHAPTER II

METHODOLOGY

In order to achieve the study's objective, a research methodology is developed as shown in Figure 2.1. According to the methodology, five tasks need to be accomplished to develop and illustrate the decision-making framework (Tasks 1 to 5). Afterwards, the framework can be extended to an automated decision-making model or tool.

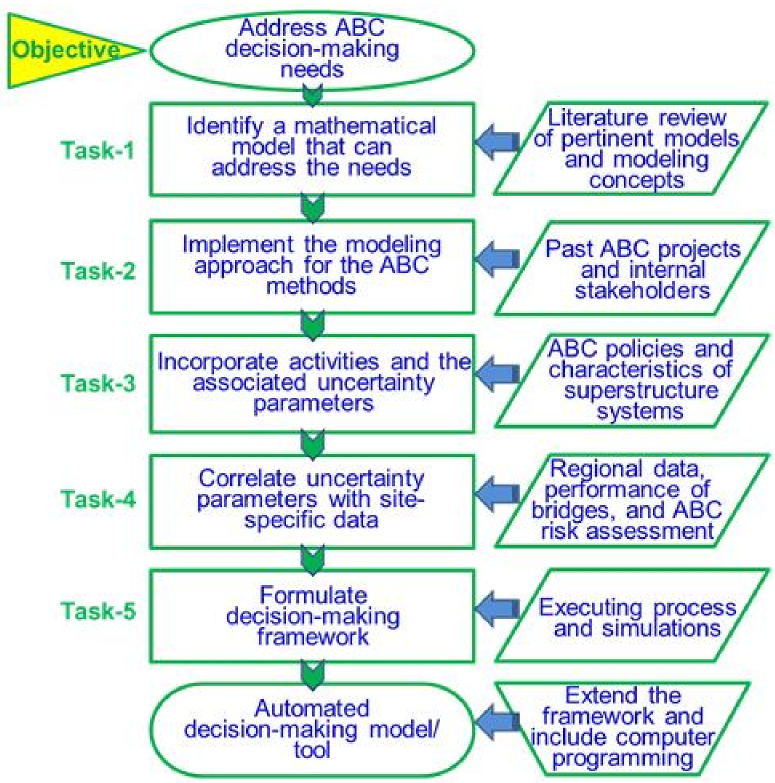


Figure 2.1. Research methodology

Task-1 is to identify a mathematical model that can address the ABC decision-making need for selecting ABC methods and the associated superstructure systems by means of evaluating the associated uncertainty and the interactions of internal stakeholders. This calls for a comprehensive literature review of mathematical models used in the decision-making process and the associated modeling concepts. The literature review will be presented in Chapter 3 and Chapter 4.

Task-2 is to implement the modeling approach to develop mathematical models for ABC methods that provide an interface for the internal stakeholders to interact during a project. This requires necessary concepts of the modeling approach to be linked with processes included in an ABC method; details of this are presented in Chapter 5. Further, past ABC projects need to be reviewed and the internal stakeholders involved with delivering ABC projects need to be identified during Task-2. Subsequently, the activities and the associated parameters that contribute to uncertainty need to be incorporated in the model, which represents Task-3. In order to incorporate the parameters that affect the constructability and durability of a bridge, completed ABC projects, ABC policies of DOTs, and potential superstructure systems and their characteristics need to be considered.

Task-4 is to develop parameter correlations with site-specific data that can serve as the knowledgebase for the decision-making model. This task requires consideration of the regional data, performance of superstructure systems, and risk assessment of ABC projects.

Task-5 is to formulate the decision-making framework based on the previous tasks. This task includes a series of modeling and simulation steps that will be described in Chapter 6.

After formulation, the decision-making framework is implemented to evaluate ABC methods and the associated superstructure systems (collectively termed as alternatives) for a bridge replacement project located in Kent County, Michigan. The decision-making framework is implemented by employing manual calculations and an available computer tool, such as Microsoft Excel®. The implementation example will be presented in Chapter 7.

Summary of the research, conclusions, and recommendations for further studies to extend the framework to an automated decision-making model will be provided in Chapter 8.

CHAPTER III

STATE-OF-THE-ART LITERATURE REVIEW

Overview

Many state Departments of Transportation (DOTs) including Federal Highway Administration (FHWA) have undertaken efforts to develop decision-making models for bridge construction decision-making. A literature review is performed and will be described in this chapter in order to identify the state-of-the-art decision-making models for bridge projects and their relevance to address the Accelerated Bridge Construction (ABC) decision-making need. In addition, there are several mathematical models used by industries and management organizations for decision-making to achieve optimal performance of a process or a project. A literature review of such mathematical models is also performed considering the capabilities and limitations with respect to ABC decision-making need, and will be presented in this chapter.

State-of-the-art decision-making models for bridge projects

With the advent of Accelerated Bridge Construction (ABC) in 2005, several state DOTs developed decision-making models for evaluating sites for ABC. The review of decision-making models used by DOTs demonstrated that most of them developed their decision-making models using of a flowchart that requires *Yes/No* type decisions in order to select a bridge construction method, such as the ones developed by Ralls (2005) and MassDOT (2009). Several of the decision-making models include overloaded information that is difficult to be managed and assessed appropriately, such as the ones developed by UDOT (2010), WisDOT (2013), Salem and Miller (2006), Doolen et al. (2011), and Saeedi et al. (2013). On the other hand, the FHWA emphasized the consideration of applicability of design, ability of contractors and suppliers, access to project site, and effect of construction requirements on cost and schedule in order to make the decision to use ABC in a project. Thus, in 2013, a decision-making tool was developed under the research project of Aktan and Attanayake (2013) for Michigan DOT. The tool is titled Michigan Accelerated Bridge Construction Decision-Making (Mi-ABCD). The Mi-ABCD tool overcomes the limitations of previous decision-making models. A detailed discussion of decision-making models prior to the Mi-ABCD tool is discussed in the Master's thesis of the author (Mohammed 2011). The Mi-ABCD considers tangible quantitative and qualitative parameters for decision-making among conventional construction (CC) and ABC. However, the Mi-ABCD tool addresses only one of the several challenges that state DOTs encounter during scoping of ABC projects. A more thorough discussion of the tool including its advantages and limitations follows.

Michigan accelerated bridge construction decision-making tool

The Michigan Accelerated Bridge Construction Decision-Making (Mi-ABCD) tool includes a decision-making methodology that is an improvement to the earlier decision-making models for bridge projects. The Mi-ABCD tool addresses the following deficiencies in the earlier models:

- The decision-making parameters were evaluated using naive Yes/No type user choices, a weighted scoring model with predefined weights, or qualitative pair-wise comparisons of the parameters using Analytical Hierarchy Process (AHP) without considering quantitative project specific data.
- The AHP pair-wise comparisons in earlier models often led to issues of comparing two unrelated parameters and thus creating ambiguity for the users in providing input.
- Project specific data was not provided to the user while performing the AHP pair-wise comparisons in earlier models. The users were left in the dark and needed to rely upon their own knowledge to make judgments during the pair-wise comparison process.
- Cost was considered in the earlier models using qualitative pair-wise comparisons rather than using project specific cost data.
- The earlier models did not provide a collaborative platform to leverage knowledge from the users involved with the decision-making process.

Significance of AHP in Decision-Making for Bridge Projects

In decision-making for bridge projects, it is essential to identify the parameters that have greater influence on selecting the optimal bridge construction method. The AHP includes representing a problem in terms of parameters and establishing a hierarchy. This provides the ability to group the parameters into several levels, such as categorizing the parameters into major-parameters and associated sub-parameters. This categorization enables identifying not only the optimal decision alternative, but also the major-parameters that highly influence the problem and the decision. The details of the process are provided under the *Mathematical Models* discussion (following section). Therefore, specific to decision-making for bridge projects, a 4-level hierarchy is typically established for the AHP such that the first level includes the objective, the second level includes the major-parameters, the third level includes the sub-parameters, and the fourth level includes the decision alternatives. The key part of the hierarchy consists of major-parameters, sub-parameters, and decision alternatives. After establishing the hierarchy, the AHP includes performing pair-wise comparisons. In the decision-making for bridge projects, the pair-wise comparisons are among (1) major-parameters, (2) sub-parameters under the respective major-parameter, and (3) decision alternatives with respect to each sub-parameter. This process develops three sets of pair-wise comparison matrices. The normalized preferences for the major-parameters and the decision alternatives are calculated from the pair-wise comparison matrices.

Mi-ABCD Advances and Limitations

In Mi-ABCD, the methodology incorporates quantitative and qualitative parameters with hybrid AHP. The AHP hierarchy is retained consisting of major-parameters, sub-parameters, and decision alternatives. The methodology implements Ordinal Scale Ratings (OSRs) to generate AHP pair-wise comparison matrices, which eliminates the typical pair-wise comparisons. Because the approach incorporates OSRs rather than pair-wise comparisons, it is termed “hybrid.” The methodology includes a process wherein the OSRs of the quantitative parameters are calculated based on project specific data, as well as general data for a state or region (Aktan and Attanayake 2013).

The decision-making parameters incorporated in Mi-ABCD for evaluating the bridge construction methods are presented in Figure 3.1. The decision-making parameters include quantitative and qualitative parameters. Mi-ABCD provides the users with the ability to incorporate additional decision-making parameters based on the project. The quantitative parameters are obtained from project-specific data that is available or calculated during the project planning stages. Several of the quantitative parameters, such as *life-cycle cost*, *user cost*, and *significance of level of service*, are calculated using computational models adapted from literature: Ehlen and Marshall (1996), Walls and Smith (1998), HCM (2000), and FHWA (2004). The project-specific quantitative data is utilized in the calculations. The quantitative data is grouped as site-specific data, traffic data, and life-cycle cost data (Figure 3.2).

Decision-Making Parameters for Highway over Highway Project						
Major-Parameters	Site and Structure Considerations (S&ST)	Cost	Work Zone Mobility (WZM)	Technical Feasibility and Risk (TF&R)	Environmental Considerations (EC)	Seasonal Constraints and Project Schedule (SC&PS)
Sub-Parameters	Precaster/Ready-mix supplier proximity	Initial Construction cost	Significance of maintenance of traffic on facility carried	Contractor experience	Environmental protection (e.g., wet land)	Seasonal limitations
	Availability of staging area	Life-cycle cost	Significance of maintenance of traffic on feature intersected	Manufacturer/ Precast plant experience	Aesthetic requirements	Construction duration
	Existing structure type and foundations	User cost	Length of detour	Work zone traffic risk		Stakeholder(s') limitations
Sub-Parameters	Terrain to traverse	Economic impact on surrounding businesses	Significance of level of service on detour route	Construction risks		
	Access and mobility of construction equipment	Economic impact on surrounding communities	Impact on nearby major intersection due to traffic on facility carried			
	Number of similar spans		Impact on nearby major intersection due to traffic on feature intersected			

Project Details Menu

Add Sub-Parameters

Figure 3.1. Decision-making parameters for evaluating CC and ABC

Site-Specific Data for Highway over Highway Project

Advanced User Menu

Description	Data
County of the project	Kalamazoo
Distance to ready-mix concrete plant	11–20 miles
Distance to prefabrication plant	≤ 10 miles
Distance to a potential staging area	≤ 10 miles
Number of major intersections for facility carried	2
Number of major intersections for feature intersected	1
Number of similar spans	2

Description	Facility Carried	Feature Intersected
Functional class	Urban freeway (Peak hou	Urban freeway (Peak hou
Traffic directionality	2	2
Number of lanes in each direction	3	3
Speed limit (mph)	45	70

(a)

Traffic Data for Highway over Highway Project

Advanced User Menu

Description	Data
Average queue length on feature intersected due to work zone (mi)	1.13
Duration of queue on feature intersected due to work zone (hr/day)	4.00
Detour length (mi)	1.24
Detour route speed limit (mph)	45

Description	Facility Carried	Feature Intersected
Recent ADT	41774	52085
Recent ADTT (% of ADT)	3	12
Work zone length (mi)	0.00	1.00
Work zone speed limit (mph)	NONE (Full Closure)	45
LOS during construction	NONE (Full Closure)	C

Description	Before Construction	During Construction using CC	During Construction using ABC
LOS on detour route	B	D	D
LOS on nearby major intersection-1 due to traffic on facility carried	B	D	D
LOS on nearby major intersection-2 due to traffic on facility carried	B	C	C
LOS on nearby major intersection-1 due to traffic on feature intersected	A	B	B
LOS on nearby major intersection-2 due to traffic on feature intersected	N/A	N/A	N/A

(b)

Life-Cycle Cost Data — Advanced User Menu

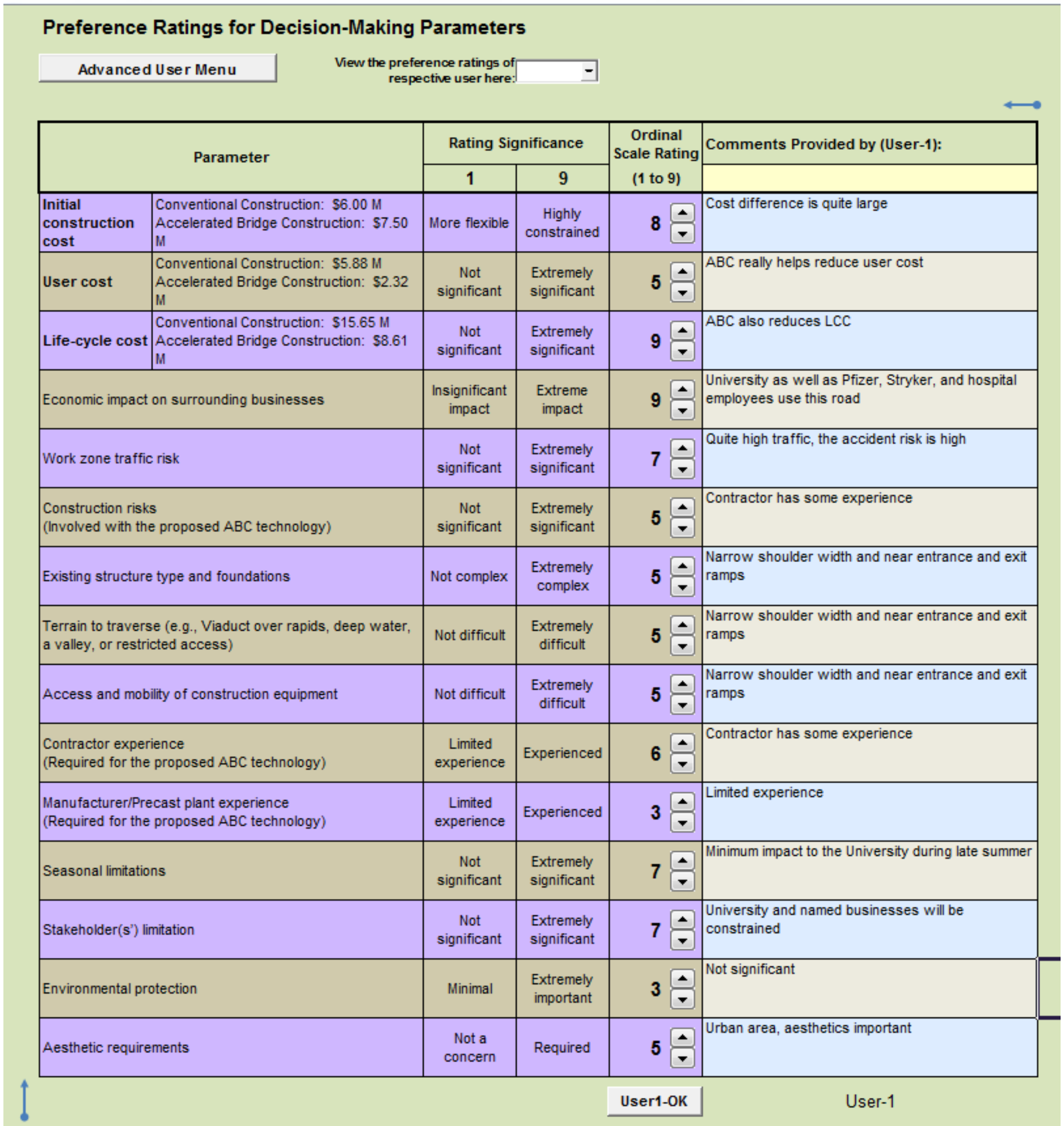
Description	Data
Number of years for life-cycle cost analysis	75
Discount factor (%) *Note: A high discount factor will make the life-cycle cost less important than a low discount factor, and vice-versa. Generally, a discount factor around **3%** to **5%** is considered reasonable with average close to **4%** (FHWA 1998; Thoft-Christensen 2009).*	3%

Description	Conventional Construction (CC)	Accelerated Bridge Construction (ABC)
Construction duration (days)	152	60
Initial construction cost ($)	$6,000,000	$7,500,000
Cost per each maintenance/repair activity ($)	$120,000	$150,000
Average duration between the maintenance/repair activities (year)	15	35
Disposal cost or salvage value ($) *Note: At the end of life-cycle cost analysis period, if the structure has either a residual life or a slavage value, the input amount should be negative.*	$600,000	-$750,000

(c)

Figure 3.2. Quantitative data: (a) site specific data, (b) traffic data, and (c) life-cycle cost data

For the qualitative parameters, judgments are obtained on an ordinal scale that represents the OSRs from users (i.e., decision makers) who are planning, design, transportation, or construction experts (Figure 3.3). This process allows a parameter to be rated by the user based on their experiences gained from recent projects. The users are also allowed to provide their reasoning for respective preferences (i.e., OSRs), which are available to subsequent users. This process helps leveraging the experience gained from past projects to enhance the decision-making process by developing a user knowledgebase within the process.



Preference Ratings for Decision-Making Parameters

Advanced User Menu — View the preference ratings of respective user here:

Parameter		Rating Significance 1	Rating Significance 9	Ordinal Scale Rating (1 to 9)	Comments Provided by (User-1):
Initial construction cost	Conventional Construction: $6.00 M Accelerated Bridge Construction: $7.50 M	More flexible	Highly constrained	8	Cost difference is quite large
User cost	Conventional Construction: $5.88 M Accelerated Bridge Construction: $2.32 M	Not significant	Extremely significant	5	ABC really helps reduce user cost
Life-cycle cost	Conventional Construction: $15.65 M Accelerated Bridge Construction: $8.61 M	Not significant	Extremely significant	9	ABC also reduces LCC
Economic impact on surrounding businesses		Insignificant impact	Extreme impact	9	University as well as Pfizer, Stryker, and hospital employees use this road
Work zone traffic risk		Not significant	Extremely significant	7	Quite high traffic, the accident risk is high
Construction risks (Involved with the proposed ABC technology)		Not significant	Extremely significant	5	Contractor has some experience
Existing structure type and foundations		Not complex	Extremely complex	5	Narrow shoulder width and near entrance and exit ramps
Terrain to traverse (e.g., Viaduct over rapids, deep water, a valley, or restricted access)		Not difficult	Extremely difficult	5	Narrow shoulder width and near entrance and exit ramps
Access and mobility of construction equipment		Not difficult	Extremely difficult	5	Narrow shoulder width and near entrance and exit ramps
Contractor experience (Required for the proposed ABC technology)		Limited experience	Experienced	6	Contractor has some experience
Manufacturer/Precast plant experience (Required for the proposed ABC technology)		Limited experience	Experienced	3	Limited experience
Seasonal limitations		Not significant	Extremely significant	7	Minimum impact to the University during late summer
Stakeholder(s') limitation		Not significant	Extremely significant	7	University and named businesses will be constrained
Environmental protection		Minimal	Extremely important	3	Not significant
Aesthetic requirements		Not a concern	Required	5	Urban area, aesthetics important

User1-OK User-1

Figure 3.3. Qualitative data: preference ratings and comments

In Mi-ABCD, matrices for major-parameters, sub-parameters, and bridge construction methods are developed using the hybrid AHP process. A theoretically sound method utilized in several computing algorithms (like Mathcad Hessenberg form coupled with a QR Decomposition algorithm) is implemented in Mi-ABCD to calculate the normalized preferences for the decision-making parameters and the bridge construction methods. This method is called the Eigenvalue method. The method manages inconsistencies in the matrices and eliminates the need of verifying the consistency ratio or repeating the pair-wise comparisons in earlier AHP decision-making models (Mohammed 2011). The results from the model are presented in Figure 3.4. The upper and lower bound preference ratings (Figure 3.4a) provide variability in the normalized preferences of the bridge construction methods. The distribution of decision-making parameter preferences (Figure 3.4b) is helpful in identifying parameters that had significantly different opinions among the users, and can be a subject of review. The normalized preferences for bridge construction methods (Figure 3.4c) include contribution of the major-parameter preferences (refer to color coding). This information helps in identifying the major-parameter and its underlying sub-parameters with greater influence towards the final decision. The advanced features of the Mi-ABCD are summarized as the following:

- The Mi-ABCD incorporates project information, general data, site-specific data, traffic data, and life-cycle cost data, which assists the users during the process of providing preferences.
- The Mi-ABCD simply requires the users to provide preferences for a set of parameters based on their experience from previous recent projects, rather than pair-wise comparisons.
- The analysis procedure of Mi-ABCD to determine normalized preferences for bridge construction methods is based on Eigenvalue method that assures the consistency of preference ratings from a user.
- The strength of Mi-ABCD methodology is the integration of quantitative data to help the user make qualitative decisions. An additional strength is eliminating the pair-wise comparison of parameters and obtaining judgments from users on an ordinal scale.

Although Mi-ABCD is an improvement from the earlier decision-making models for bridge projects, it lacks to address the following needs:

- Evaluate the risk/uncertainty associated with the ABC systems and the activities of bridge construction methods.
- Incorporate interactions among the internal stakeholders in the evaluation process and identify the impact on project performance.

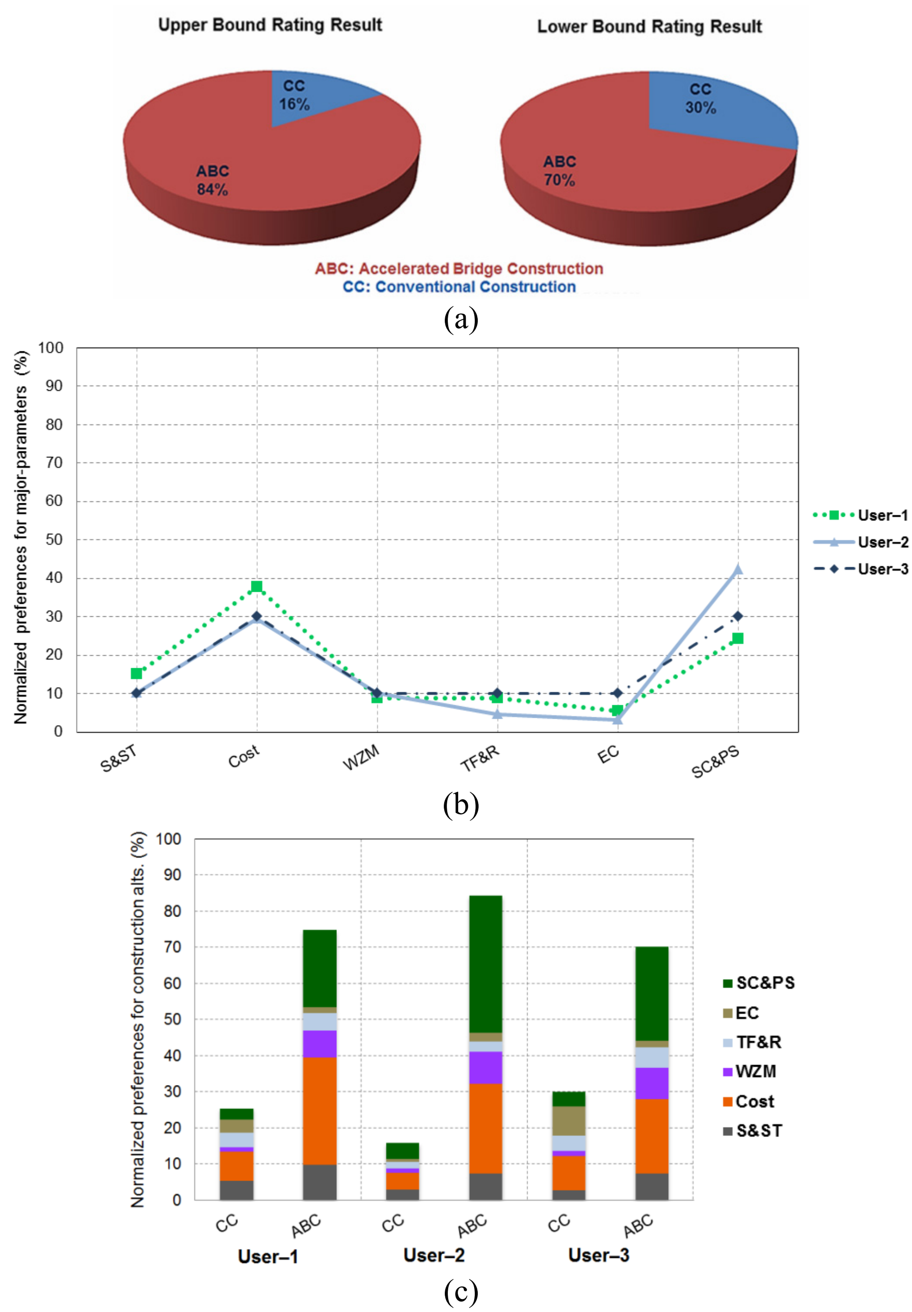


Figure 3.4. Results from Mi-ABCD model

Mathematical models used in decision-making

Analytical hierarchy process

The Analytical Hierarchy Process (AHP) was developed by Saaty (1980) for selecting an optimal alternative among several decision alternatives that address the objective. The AHP, also known as the standard AHP, was developed to overcome limitations of earlier multi-criteria decision-making models, such as the weighted sum model and the weighted product model that produced the weighted algebraic average of the performance value as the overall performance score. The standard AHP method is widely used for solving multi-criteria decision-making problems (Mohammed 2011; SU 2013; Balali et al. 2014). As mentioned in the previous section, the AHP includes representing a problem in terms of parameters and establishing a hierarchy. After establishing a hierarchy, the AHP includes performing pair-wise comparisons. The AHP scale of 1 to 9 is used for the pair-wise comparison ratings, where 1 represents an equal importance and 9 represents an extreme importance. The pair-wise comparisons enable the development of pair-wise comparison matrices. Each matrix is a unit positive reciprocal matrix, where the diagonal elements are unity and the lower triangular elements are reciprocal to the corresponding upper triangular elements. The AHP synthesis process is implemented to calculate the normalized preference ratings for the decision alternatives. The process also enables the calculation of the normalized preference ratings of the decision-making parameters, and the performance of a sensitivity analysis. Additional information regarding the standard AHP is presented in the author's Master's thesis (Mohammed 2011). The literature review presented in the following paragraphs deals with tailored AHP processes for specific implementations.

Based on the requirements of decision-making for specific cases, the standard AHP method is modified to develop hybrid AHP methods. Examples of novel hybrid AHP implementations are the following:

1) The Michigan Accelerated Bridge Construction Decision-Making (Mi-ABCD) tool: As described in the previous section, the hybrid AHP process used in Mi-ABCD incorporated ordinal scale ratings to eliminate typical AHP pair-wise comparisons that created ambiguity for the decision makers while comparing

unrelated parameters. Also, the process incorporated the Eigenvalue analysis to manage inconsistency in the unit positive reciprocal matrices and eliminate the need for verifying the consistency ratio (Aktan and Attanayake 2013).

2) Decision making in equipment selection: Dagdeviren (2008) integrated AHP and the preference ranking organization method for enrichment evaluation (PROMOTHEE) methods for decision-making in equipment selection. The PROMETHEE method allows defining the preference functions of the parameters. The preference functions of the decision-making parameters define the accuracy of the final decision. On the other hand, the AHP method allows for the analysis of the structure of a problem and the determination of parameter weights (normalized ratings). Thus, AHP was used to determine the weights of the parameters, and PROMETHEE was used to obtain the final rankings of the equipment (Dagdeviren 2008).
3) Improving the uncertainty estimate of the embodied-energy of construction materials: The data quality indicator (DQI) method was integrated with AHP in order to obtain an improved estimate of the embodied-energy of construction materials. In the process, the DQI method was used to qualitatively handle uncertainty in the life-cycle analysis, and the AHP was used to obtain the weights of the quality indicators (Wang and Shen 2012).
4) Coal suppliers evaluation model: The AHP and PROMETHEE methods were integrated in order to evaluate coal suppliers for thermal power plants so that the cost of power generation can be reduced. In the process, AHP was used to obtain the weight of each criterion according to practical importance, and the ranking of the alternatives was obtained using PROMETHEE. The AHP was used to obtain the criteria weight because PROMETHEE compares alternatives according to difference between each criterion, which is unsuitable for calculating the criteria weight with full compensation (Dong 2015).

The AHP has been criticized for its inability to incorporate the uncertainty associated with a decision maker's judgment in the decision-making process. Therefore, several fuzzy AHP methods have been developed and implemented for specific cases, such as the following: (1) the selection of a global supplier for a supply chain (Chan et al. 2008), (2) the selection of a suitable bridge construction method (Pan 2008), (3) the selection of a computer integrated manufacturing system (Bozdag et al. 2003), (4) the selection of a level of faulty behavior risk in manufacturing systems (Dagdeviren and Yuksel 2007). Fuzzy AHP is essentially the combination of the two concepts: fuzzy set theory and the AHP method (Saaty 1980). The fuzzy set theory (Zadeh 1965) enables one to mathematically represent uncertainty in the judgment of decision makers during the decision-making process. In the fuzzy approach, the decision maker's preference can be expressed with a quantitative value by using a membership function [$\mu N(x)$] that takes a real value between 0 and 1. The fuzzy approach can be implemented using the membership function of triangular fuzzy numbers or trapezoidal fuzzy numbers.

Typical steps in a fuzzy AHP are summarized here using the fuzzy AHP implementation by Chan et al. (2008) that used triangular fuzzy numbers (TFN). To identify the range of numerical values for the set of TFN, general terms such as large, medium, and small are typically used. An example TFN denoted as a triplet (n_1, n_2, n_3) is shown in Figure 3.5.

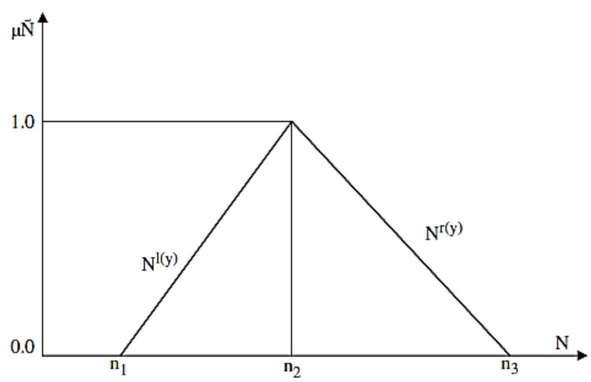


Figure 3.5. Triangular fuzzy number (Source: Chan et al. 2008)

The first step in the process is forming the hierarchy of the selection criteria and decision alternatives similar to a standard AHP. The hierarchy may consist of sub level of criteria (sub-criteria), however, the discussion here is limited to one level of criteria and decision alternatives. The criteria are denoted by C_i and the alternatives by A_j (where i, j = 1, 2,......). Next, the fuzzy evaluation matrix for the criteria is formed that consists of fuzzy numbers as elements. An example of the fuzzy evaluation matrix consisting of TFN is shown in Figure 3.6. The fuzzy numbers are obtained based on qualitative pair-wise comparisons provided by the decision maker in terms of equal, fairly strong, very strong, or absolute importance. For each of the qualitative judgments, fuzzy numbers are defined based on the specific problem. For example, in Figure 3.6 the TFN (1.0, 1.0, 1.0) represents equal importance, the TFN (1.5, 2.0, 2.5) represents fairly strong importance, the TFN (2.5, 3.0, 3.5) represents very strong importance, and the TFN (3.5, 4.0, 4.5) represents absolute importance. In Figure 3.6, the lower triangular elements of the matrix are reciprocal to the corresponding upper triangular elements.

O	C_1	C_2	C_3	C_4	C_5
C_1	(1.0, 1.0, 1.0)	(1.5, 2.0, 2.5)	(2.5, 3.0, 3.5)	(2.5, 3.0, 3.5)	(3.5, 4.0, 4.5)
C_2	(0.4, 0.5, 0.67)	(1.0, 1.0, 1.0)	(1.5, 2.0, 2.5)	(1.5, 2.0, 2.5)	(2.5, 3.0, 3.5)
C_3	(0.28, 0.33, 0.4)	(0.4, 0.5, 0.67)	(1.0, 1.0, 1.0)	(0.67, 1.0, 1.5)	(1.5, 2.0, 2.5)
C_4	(0.28, 0.33, 0.4)	(0.4, 0.5, 0.67)	(0.67, 1.0, 1.5)	(1.0, 1.0, 1.0)	(1.5, 2.0, 2.5)
C_5	(0.22, 0.25, 0.28)	(0.28, 0.33, 0.4)	(0.4, 0.5, 0.67)	(0.4, 0.5, 0.67)	(1.0, 1.0, 1.0)

Figure 3.6. Sample fuzzy evaluation matrix

The next step is to determine the fuzzy synthetic extent value (F_i) with respect to the each criterion using the following equation:

$$F_i = \sum_{j=1}^{m} N_{oi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} N_{oi}^{j} \right]^{-1}$$

where N_{oi}^{j} is a fuzzy number in the matrix with size n×m. If $N_1 = (n_{11}, n_{12}, n_{13})$ and $N_2 = (n_{21}, n_{22}, n_{23})$ are two TFN, then the fuzzy sum (⊕), fuzzy subtraction (Θ), fuzzy multiplication (⊗), and fuzzy inverse are expressed as the following:

$$\tilde{N}_1 \oplus \tilde{N}_2 = (n_{11} + n_{21}, n_{12} + n_{22}, n_{13} + n_{23})$$

$$\tilde{N}_1 \Theta \tilde{N}_2 = (n_{11} - n_{21}, n_{12} - n_{22}, n_{13} - n_{23})$$

$$\tilde{N}_1 \otimes \tilde{N}_2 \cong (n_{11} n_{21}, n_{12} n_{22}, n_{13} n_{23})$$

$$\lambda \otimes \tilde{N}_1 = (\lambda n_{11}, \lambda n_{12}, \lambda n_{13}), \quad \text{where } \lambda > 0, \lambda \in R$$

$$\tilde{N}_1^{-1} = \left(\frac{1}{n_{11}}, \frac{1}{n_{12}}, \frac{1}{n_{13}} \right)$$

The next step is to determine the degree of possibility of the superiority (V) of each criterion over other (i.e., F_i over F_k, such that i ≠ k). The following equations are used in the process:

$$V\left(F_i \geq F_k \mid i \neq k\right) = \begin{cases} 1, & \text{if } f_{i1} \geq f_{k1} \\ \dfrac{f_{i1} - f_{k3}}{\left(f_{k2} - f_{k3}\right) - \left(f_{i2} - f_{i1}\right)}, & \text{otherwise} \end{cases}$$

$$\text{where: } i, k = 1, 2, \ldots\ldots, n$$

The next step is to obtain the minimum degree of possibility of the superiority, *m(Ci)*, using the following equation:

$$m(C_i) = \min V\left(F \geq F_i\right) \quad \rightarrow \text{ for criterion } i, \; i = 1,2,\ldots\ldots,k$$

$$\text{where}: V\left(F \geq F_1, F_2, \ldots\ldots, F_k\right) = V\left[(F \geq F_1) \text{ and } (F \geq F_2) \text{ and } \ldots\ldots \text{ and } (F \geq F_k)\right]$$

The weight vector for the criteria matrix is obtained by aggregating all *m(Ci)* as the following:

$$W_p = (m(C_1), m(C_2), \ldots, m(C_n))^T$$

The normalized weight vector (W) for the criteria matrix is obtained by normalizing the W_p vector. The weights in vector *W* are used for further calculations. Next, the fuzzy evaluation matrices of decision alternatives with respect to each criterion are formulated, and the normalized weight vectors for the matrices are obtained using the process discussed above. The final priority weights of decision alternatives are calculated by the summation of weights per decision alternative multiplied by the weights of the corresponding criterion. The decision alternative with the highest score is considered the optimal alternative to address the problem.

Considering the ABC decision-making need, the standard AHP, the hybrid AHP and the fuzzy AHP implementations are unsuitable because of the following limitations:

- Standard AHP and hybrid AHP methods incorporate the parameters and decision alternatives in the decision-making process without considering the specific processes/activities included in a decision alternative and the associated uncertainty.

- It is impractical to assign preference functions to ABC decision-making parameters, because the ABC methods are in the early stages of implementation and lack performance data. Thus, the hybrid AHP that incorporates the preference functions for the decision-making parameters cannot be implemented.
- Fuzzy AHP incorporates uncertainty associated with a decision maker's judgment and lacks incorporating uncertainty associated with a project itself.
- In fuzzy AHP, predefining fuzzy numbers for each qualitative judgment requires careful evaluation of the included criteria and the perspective of the decision makers. Predefining fuzzy numbers that can be widely applicable to all bridge construction methods is impractical because the activities and stakeholders are not the same.
- The outcome of standard AHP, hybrid AHP, and fuzzy AHP methods is a deterministic result that restricts the decision makers to obtain a range of possible inferences for decision-making.
- None of the AHP implementations are capable of incorporating the interactions of the stakeholders involved in a project in the evaluation.

Elimination and choice expressing the reality

The Elimination and Choice Expressing the Reality (ELECTRE) method was developed by Benayoun et al. (1966). ELECTRE is considered one of the most widely used methods to outrank a set of alternatives instead of ranking a set of criteria (Balali et al. 2014). The concept of outranking can be interpreted as a fuzzy relation. ELECTRE considers judgments including preference, indifference, and veto (rejection) thresholds. The alternatives are evaluated with pair-wise comparisons and ineffective alternatives are neglected in the process (Roy 1973). An extension of the ELECTRE was presented by Lopez and Gonzalez (2003) to assist a group of decision makers in achieving a consensus on a set of possible alternatives. The proposed method performed relatively better than other multi-criteria decision-making models that utilized net outranking flow (Lopez and Gonzalez 2003). Balali et al. (2014) combined ELECTRE with another outranking methodology (PROMETHEE, discussed next) to select appropriate an structural system for a low-rise multi-housing project. In this case, ELECTRE was used to consider uncertainties in the judgments of the decision makers.

Typical steps in ELECTRE implementation are summarized in this section referring to Balali et al. (2014). The procedure starts with a pair-wise comparison of the alternatives with respect to each criterion g_j in order to determine the concordance index c_j and the discordance index d_j using the following equations:

$$c_j(a_i, a_k) = \begin{cases} 1 & \text{if } g_j(a_k) - g_j(a_i) \le q_j \\ 0 & \text{if } g_j(a_k) - g_j(a_i) \ge p_j \\ \dfrac{p_j + g_j(a_i) - g_j(a_k)}{p_j - q_j} & \text{otherwise} \end{cases}$$

$$d_j(a_i, a_k) = \begin{cases} 0 & \text{if } g_j(a_k) - g_j(a_i) \le p_j \\ 1 & \text{if } g_j(a_k) - g_j(a_i) \ge v_j \\ \dfrac{g_j(a_k) - g_j(a_i) - p_j}{v_j - p_j} & \text{otherwise} \end{cases}$$

where a_i and a_k are the alternatives, p_j is the threshold of preference for criterion g_j, q_j is the threshold of indifference for criterion g_j, and v_j is the threshold of rejection (veto threshold) for criterion g_j.

The concordance indicates the dominance of one alternative over another. The concordance index varies from 0 to 1; where the value 0 indicates that alternative a_i is worse than alternative a_k for all criteria, and the value 1 indicates that there is no criterion for which a_k is better than a_i. The discordance of a criterion g_j considers that the criterion more or less disagrees with the declaration a_i outranks a_k. The discordance index reaches its maximum when criterion g_j puts its veto (rejection) to the outranking relation; it reaches minimum when the criterion g_j agrees with the outranking relation.

In the next step, an overall concordance index $C(a_i,a_k)$ for the alternatives is calculated by considering all the criteria using the following equation:

$$C(a_i, a_k) = \frac{\sum_{j=1}^{n} c_j(a_i, a_k)\ w_j}{\sum_{j=1}^{n} w_j}$$

where w_j is the weight of criterion g_j.

In the next step, a *credibility index* ($S(a_i,a_k)$) is determined for the alternatives, which describes the credibility of the declaration a_i outranks a_k. The following equation is used to determine $S(a_i,a_k)$:

$$S(a_i, a_k) = \begin{cases} C(a_i, a_k) & if\ \ d_j(a_i, a_k) \le C(a_i, a_k) \\ C(a_i, a_k) - \prod_{j \in J(a_i, a_k)} \frac{1 - d_j(a_i, a_k)}{1 - C(a_i, a_k)} & if\ \ d_j(a_i, a_k) \ge C(a_i, a_k) \end{cases}$$

where $J(a_i,a_k)$ is set of criteria for which $d_j(a_i,a_k)$ is greater than $C(a_i,a_k)$.

Then, the results are used to develop a partial preorder for the alternatives. The process includes creating two preorders Z_1 and Z_2 using a descending and ascending distillation process respectively, and combining them to produce a partial preorder $Z = Z_1 \cap Z_2$. In the descending distillation process, a square matrix **T** is defined with the following elements:

$$T(a_i, a_k) = \begin{cases} 1 & if\ \ S(a_i, a_k) > \lambda - s(\lambda) \\ 0 & otherwise \end{cases}$$

where λ is a credibility value determined so that only values of $S(a_i,a_k)$ that are sufficiently close to λ are considered.

Then, qualification of each alternative, $Q(a_i)$, is determined by subtracting the number of alternatives that outrank the alternative a_i from the number of alternatives that are outranked by a_i. In matrix **T**, $Q(a_i)$ is the row *i* minus the column *i* sum. The criteria having the largest qualification are selected in descending order. The outcome is the preorder Z_1. The ascending distillation to determine Z_2 is performed in a similar manner with the exception of selecting the smallest qualification criteria in ascending order. The outputs are a set of rankings that provide the concordance of the alternatives.

ELECTRE has been considered a useful tool for stochastic decision-making problems as it has a fuzzy view towards the judgments of decision makers. Also, the decision makers are able to provide their preferences by means of criteria weights and thresholds. However, considering the ABC decision-making need to incorporate the uncertainty associated with respective activities and stakeholder interactions, the ELECTRE family of methods are unsuitable because of the following:

- ELECTRE methods are complicated because they require fixing values for criteria such as concordance, discordance, and veto thresholds that are not easily understood by practitioners (Brans and Vincke 1985). Also, the impact of criteria on the results is not well understood.
- For the ABC decision-making parameters, defining the concordance, discordance, and veto thresholds is impractical because the ABC methods are in early stages of implementation and the performance data of the systems constructed using ABC methods is limited.
- ELECTRE is able to consider uncertainties in the judgments of the decision makers, but it lacks the incorporation of the uncertainty associated with a project itself.
- In the ABC decision-making process, the bridge construction methods need to be evaluated by incorporating the associated activities and stakeholder interactions and the formulations used in ELECTRE cannot incorporate these aspects.

Preference ranking organization method for enrich evaluation

The Preference Ranking Organization Method for Enrich Evaluation (PROMETHEE) was developed by Brans and Vincke (1985). The procedure establishes a partial or total preorder for the alternatives. The preorder for an alternative is defined as the intensity by which it outranks other alternatives. The fundamental principle is based on predetermining the weight of each criterion, assigning statistical distributions termed as preference functions to each criterion, and pair-wise comparing the alternatives. The method is software-driven and appropriate for problems involving criteria that need to be either maximized or minimized. Cox (2003) implemented the PROMETHEE procedure to analyze the planning process for two Reforestation and Multiple Use state forest units in order to improve the process and management quality. The research by SU (2013) adapted PROMETHEE to develop a multi-criteria decision-making framework for Expected Opportunity Loss (EOL) based risk criterion in a decision-making problem including uncertainty. In this case, PROMETHEE was adopted for its compatibility with the decision logic and the mathematical formulation including the EOL concept. Balali et al. (2014) tailored PROMETHEE by combining it with ELECTRE to rank structural systems for a low-rise multi-housing project including 16 decision-making criteria. In this case, PROMETHEE was used to identify the alternative that can maximize 12 criteria and minimize 4 criteria.

The typical steps in PROMETHEE implementation are summarized here referring to Brans and Vincke (1985) and Balali et al. (2014). The procedure starts with determining deviations based on pair-wise comparisons of the alternatives with respect to each criterion and assigning preference functions to each criterion as shown below:

$$d_k(a_i, a_j) = f_k(a_i) - f_k(a_j)$$

$$P_k(a_i, a_j) = F_k[d_k(a_i, a_j)]$$

where k is the number of criteria, d_k is the deviation of criterion f_k for alternatives a_i and a_j, P_k is the preference of a_i over a_j for criterion k based on the preference function F_k.

Each criterion needs to be assigned a preference function from the available 6 functions (Figure 3.7): (1) Usual Function, (2) Quasi Function, (3) Linear Function, (4) Level Function, (5) Linear Function with Indifference Area, and (6) Gaussian Function.

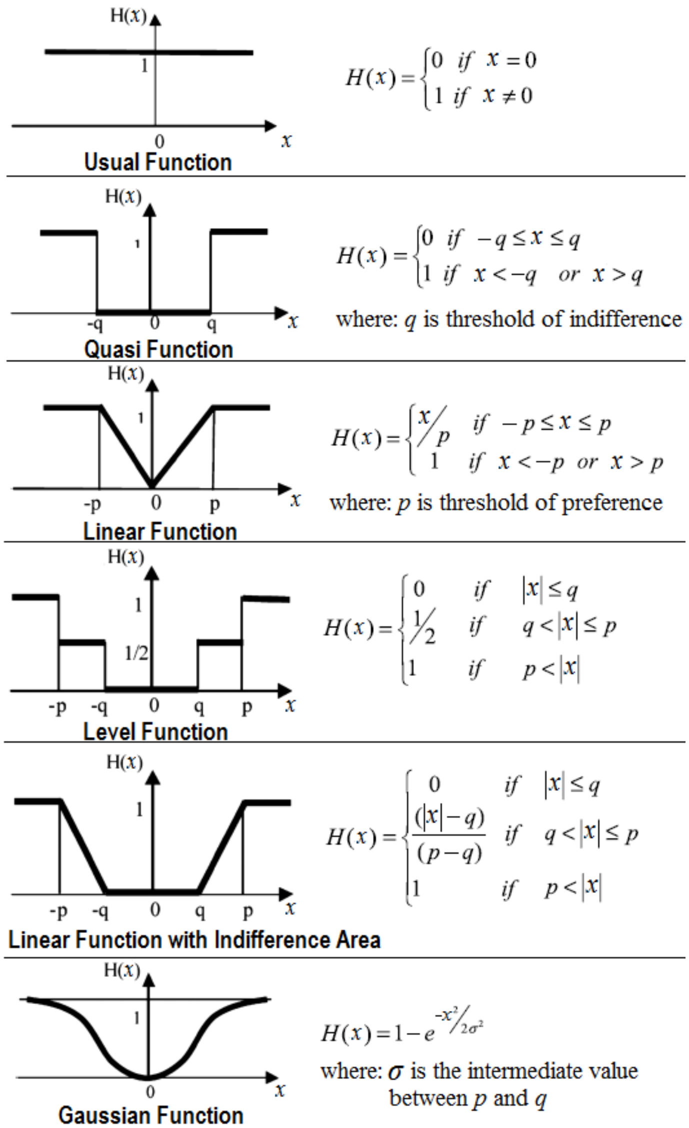


Figure 3.7. Preference functions for criteria (Source: Brans et al. 1986)

Next, global preference index π of a_i over a_j is calculated by a pair-wise comparison of the alternatives using the equation below:

$$\pi(a_i,a_j)=\sum_{k=1}^{n}P_k(a_i,a_j)\ w_k$$

where w_k is the weight associated with k criterion.

The net outranking flow, $\phi(a_i)$, for each alternative in the set of alternatives, A, is calculated based on the positive outranking flow, $\phi^+(a_i)$, and negative outranking flow, $\phi^-(a_i)$, as shown below:

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i)$$

$$\text{where: } \phi^+(a_i) = \sum_{x \in A} \pi(a_i, x); \quad \phi^-(a_i) = \sum_{x \in A} \pi(x, a_i)$$

The positive outranking flow expresses how an alternative is outranking all the other alternatives in set A. The higher positive outranking flow represents the better alternative. The negative outranking flow expresses how an alternative is outranked by all the others; the lower negative outranking flow represents the better alternative. The maximum amount of net flow denotes the best alternative.

The PROMETHEE sensitivity analysis provides the most effective criteria in the decision making process. In a sensitivity analysis, a stability interval is computed for each criterion that indicates the range in which the weights of the criterion can be modified without affecting the complete ranking (results). The preference functions for the criteria are not changed during the analysis. The criterion with the smallest interval will be the most sensitive in affecting the results.

The PROMETHEE family of outranking methods includes the PROMETHEE I, PROMETHEE II, PROMETHEE III, PROMETHEE IV, PROMETHEE V, PROMETHEE VI, PROMETHEE Group Decision Support System (GDSS), PROMETHEE Geometrical Analysis for Interactive Aid (GAIA), PROMETHEE TRI, and PROMETHEE CLUSTER (Balali et al. 2014). Each of the PROMETHEE methods can be implemented based on their mathematical properties and their particular user friendly application. For example, PROMETHEE GAIA is suitable for visualization of problem characteristics through geometrical interpretations (Brans and Mareschal 2005). Graphical GAIA displays the relative position of the alternatives in terms of contributions to various criteria. In this case, a two-dimensional plot is generated wherein the alternatives and the criteria are represented in the same plot. The criteria expressing similar preferences for an alternative are oriented in the same direction, while the conflicting criteria are oriented in the opposite direction.

The PROMETHEE is preferred because it is consistent and requires little interaction with decision makers. However, considering the ABC decision-making need to evaluate bridge construction methods by incorporating the uncertainty associated with the activities and stakeholder interactions, PROMETHEE or tailored PROMETHEE methods are unsuitable for the following reasons:

- The method is applicable to parameters that need to be either maximized or minimized. In evaluating bridge construction methods, parameters do not need to be maximized or minimized, rather they need to be satisfied in terms of constructability and durability.
- One of the important steps in utilizing PROMETHEE is to select the preference function, which is very difficult for decision makers. Predefining preference functions for the ABC decision-making parameters is impractical because the ABC methods are in the early stages of implementation and the lack performance data that is required to predict the behavior of each parameter. Also, the following values need to be defined for each parameter: (1) Indifference threshold (q), (2) Strict preference threshold (p), and (3) Intermediate value (σ) between p and q.
- PROMETHEE lacks a process to incorporate project-specific activities and stakeholder interactions in the evaluation.

Artificial neural network

An Artificial Neural Network (ANN) is an information processing methodology that was inspired by the human brain. The ANN is a type of artificial intelligence system that was developed to overcome the limitations of expert systems, genetic algorithms, and object oriented models. The major limitation of this method is considered their dependence on rules that need to be predefined based on experiences. The mathematical formulation of ANNs is developed based on the following assumptions using human cognition (Tabarak and William 2003):

- *Information processing occurs at many simple elements called neurons.*
- *Signals are passed between neurons over connection links.*
- *Each connection link has an associated weight which in a typical neural net multiplies the signal transmitted.*
- *Each neuron applies an activation function to its net or gross input to determine its output signal.*

The ANN is typically implemented in decision-making to predict the future performance of a system. However, a large amount of past performance information of the system is required to implement the ANN. Tabarak and William (2003) implemented ANN to represent the heuristic design knowledge and buildability requirements at the preliminary design stage of a building construction project. The data in this case was extracted from previously completed building projects compiled by Building Cost Information Service (BCIS) of Royal Institution of Chartered Surveyors (RICS). In another research, the ANN was implemented to estimate future stress values for structural health monitoring of a bridge (Mansiz 2012). The data in this case was obtained from the vibrating wire sensors mounted in the bridge deck.

The typical procedure included in the ANN is summarized here referring to Hagan (1996), Tabarak and William (2003), and Mansiz (2012). ANN consists of a network of neurons that processes data to produce an output. A single layer of ANN consists of i number neurons. Each neuron i requires x_{ij} inputs, where j is the size of the input matrix. Each input in neuron i is weighed w_{ij}. Then, each neuron is summed with weighted inputs and the associated bias ϕ as shown below:

$$n_i = \sum (w_{ij}\ x_{ij}) + \phi_i$$

The output of each neuron O_{ni} is calculated as a function of n_i, i.e., $f(n_i)$. The f represents a transfer function. The transfer function generates outputs between 0 to 1 for a range of inputs between $-\infty$ to $+\infty$. Available transfer functions for ANN are the following: (1) Hard limit, (2) Symmetrical hard limit, (3) Linear, (4) Saturating linear, (5) Symmetric saturating linear, (6) Log-sigmoid, (7) Hyperbolic tangent sigmoid, (8) Positive linear, and (9) Competitive. Among the transfer functions, Log-sigmoid and Hyperbolic tangent sigmoid functions are most commonly used and are represented as the following (Mansiz 2012):

$$O_{ni} = f_{\text{log-sigmoid}}(n_i) = \frac{1}{1+e^{-n_i}}$$

$$O_{ni} = f_{\substack{\text{hyperbolic} \\ \text{tan-sigmoid}}}(n_i) = \frac{e^{n_i} - e^{-n_i}}{e^{n_i} + e^{-n_i}}$$

An output matrix, $\boldsymbol{O}$, is developed for the set of neurons using the following transfer functions. The matrix will represent the output of a single layer in the ANN. The multi-layer network can have several hidden layers and only one output layer. Each layer has a weight matrix, $\boldsymbol{W}$, bias matrix, $\boldsymbol{\phi}$, and an output matrix, $\boldsymbol{O}$. The output from one layer becomes the input for the subsequent layer in the network. The number of matrices and complexity in ANN increases with the size of the network. An example multi-layer network with 3 layers is shown in Figure 3.8. In Figure 3.8, the first and second layers are hidden layers and the third layer is the output layer.

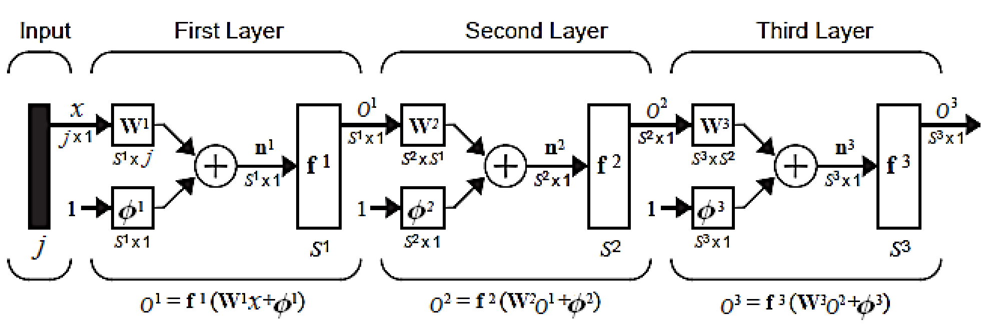


Figure 3.8. Multi-layer artificial neural network (Source: Matlab User's Guide 2000)

The fundamental property of ANN is its learning capability. The learning process includes discovering similarities and regularities among input parameters. The back-propagation learning algorithm, which is a supervised learning process, is typically implemented when the log-sigmoid transfer function is used in the layers (Mansiz 2012). A supervised learning process (training) of ANN typically includes application of the input and corresponding output vectors. The back-propagation learning process includes modifying weights of the inputs after the determination of error associated with each layer. A cyclic process is implemented wherein each layer in the network is trained by the consequent modification of respective weights. In the process, a learning constant and gradient of total error are estimated for each input unit. The process is repeated several thousand times until the error is reduced to a certain level. After the learning constant and gradient of total error are fixed, the input data of known output is fed into the trained ANN for validation. Finally, new input data is fed into the trained ANN to obtain results. Available tools such as Matlab® can be used for implementing ANN (Mansiz 2012).

The benefits of ANNs are their ability to self-organize, generalize, tolerate error, and provide extensive parallelism. However, considering the ABC decision-making need, implementing ANN is unsuitable because of the following:

- ABC methods are in early stages of implementation and a large amount of the past performance data that can form the base for future predictions is unavailable.
- In predicting a system performance, the ANN merely depends on the pattern of the data that is used for training, and lacks incorporating the uncertainty associated with the system specific-activities/processes.

Combinatorial optimization methods

The optimization methods include approaches that optimize an objective function with respect to certain conditions, such as linear programming and nonlinear programming. The combinatorial optimization methods refer to the optimization methods that have been developed by tailoring the existing ones in order to deal with a specific problem in the decision-making process. The combinatorial optimization methods include goal programming, data envelopment analysis, stochastic linear programming, generalized fuzzy linear programming, and decision theory. Goal programming presented by Charnes and Cooper (1961) is applied to multiple-objective linear programming problems to select the best alternative from a set of discrete alternatives. Data envelopment analysis was proposed by Charnes et al. (1978) and is used to maximize the efficiency of an alternative by categorizing the parameters as input terms and yield terms; the efficiency of an alternative is obtained as the ratio of total yield to total input.

The stochastic linear programming implemented by Wu (2008) incorporated random variables in the optimization formulation to include stochastic constraints in the problem. The stochastic linear programming formulation is written as the following:

Maximize F(X)

Subject to: $P_r\{g_i(X) \le \beta_i(\eta)\} \ge \alpha_i; \quad i = 1, 2, ...m$

where *F(X)* is the objective function, *X* is the decision variable vector, η is the stochastic distribution, $g_i(X)$ is the left-hand function for i^{th} stochastic constraint, $\beta_i(\eta)$ is the right-hand function with stochastic distribution η for i^{th} stochastic constraint, α_i is the prescribed confidence level for i^{th} stochastic constraint, and $P_r\{.\}$ is the probability of the event *{.}*.

The stochastic linear programming can deal with various probabilistic uncertainties and the shapes of the functions determine the uncertainty behavior. However, the data requirement for specifying the behavior of each parameter affects the practical applicability of stochastic linear programming. The implementation by Wu (2008) assumes that $\beta_i(\eta)$ is normally distributed and incorporates the weighting sum method to obtain the optimal solution set.

In another research study, Fan et al. (2013) developed a generalized fuzzy linear programming (GFLP) method considering that probabilistic methods were unable to quantify various uncertainties when data is insufficient. The GFLP reflects uncertain information in management problems. A typical GFLP is formulated as the following:

Maximize $f = c \times X$

Subject to: $\mathbf{A} \times X \le b\,; \quad X \ge 0$

$$c = (c_1, c_2, ..., c_n), X^T = (x_1, x_2, ..., x_n), b^T = (b_1, b_2, ..., b_n),$$

$$\mathbf{A} = (a_{ij})_{m \times n}, \forall i \in m, j \in n$$

$$c_j \in \{\mathbf{R}\}^{1 \times n},\ x_j \in \{\mathbf{R}\}^{n \times 1},\ b_j \in \{\mathbf{R}\}^{m \times 1},\ \mathbf{A} \in \{\mathbf{R}\}^{m \times n}$$

where *f* is a fuzzy set representing the objective function, *c* is a fuzzy set representing the fuzzy coefficients, *X* is a fuzzy set representing the decision variable vectors, **A** is a fuzzy matrix, b is a fuzzy set representing the lower or upper bound of the constraint, and **R** is a matrix including a set of fuzzy sets.

The GFLP method allows all parameters to be expressed as fuzzy sets and generate fuzzy solutions. Several alternatives can be evaluated and the alternative that satisfies the objective efficiently can be selected as the ideal one. Implementation of fuzzy set theory is beneficial when uncertainties can be intentionally assumed by decision makers (Fan et al. 2013). The uncertainty considered in this case is for the parameters.

Another combinatorial optimization method, decision theory includes decision rules to achieve an objective based on the decision maker's opinion (Ceausu 1972). Situations of uncertainty can also be evaluated with decision theory (Rotarescu 2011). In this case, for analyzing the decisions for a problem, decision matrices are developed. Decision variables (i.e., alternatives) represent the row elements and the nature states represent the column elements. Nature states are the possible outcomes that the problem can attain. Similar to pair-wise comparison matrices, the decision matrix elements are filled by pair-wise comparing decision variables with the nature state. The elements in the matrix will be the probability that the decision variable will satisfy the respective nature state. Unlike the AHP pair-wise comparison matrix, the matrix will not be a unit positive reciprocal matrix. If the nature state is known, the decision maker can choose a decision variable that efficiently satisfies the nature state by examining the information in the decision matrix. On the other hand, if uncertainty exists in determining the nature state, other decision rules are implemented. Several decision rules exist, such as the following: (1) Maxi-Min criterion (Abraham Walt's criterion), (2) Maxi-Max criterion, (3) Pessimistic-optimistic criterion (Hurwicz's criterion), (4) Savage's criterion, and (5) Laplace criterion. The decision rules have respective objective functions that need to be satisfied in the process. For example, the Laplace criterion has the following formulation:

$$D_0 = \max\{E_i\} = \max\left\{e \sum_{j=1}^{n} a_{ij}\right\}; \quad e = {}^{1}\!/_{S_j^2}$$

where i and j vary from 1 to m, m is the size of the matrix, a is the element in the matrix, e is the coefficient of equivalent probability, and S_j is the number of nature states.

When using Laplace criterion, it is considered that all nature states of the objective function have equivalent probabilities. The equivalent probability is distributed to each nature state. The expected value E_i is calculated, which characterizes each decision variable i. Then, from the $\boldsymbol{E_i}$ vector, the decision variable with the maximum expected value is selected. The major limitation of this method is that it is unrealistic that all the probabilities will be equal for the nature states (Rotarescu 2011). The decision rules only provide judgments based on the pessimistic and optimistic outcomes. A decision rule among the ones listed above cannot be declared to be the best. If the decision makers have a similar vision of solving a problem, each of the decision rules can have the same effectiveness for different decision makers (Rotarescu 2011; SU 2013).

Considering the ABC decision-making need, implementing combinatorial optimization methods is unsuitable because of the following:

- The combinatorial optimization methods mainly focus on maximizing or minimizing the objective function while incorporating uncertainty. The uncertainty associated with activities of ABC methods cannot be incorporated in such formulation.
- The outcomes associated with each activity of the ABC methods cannot be formulated as constraints in the optimization formulation.
- All the decision rules are based on single variable optimization and they cannot evaluate inter-relations among the entities or individuals of the system while addressing the objective.

Structured modeling technology

The Structured Modeling Technology (SMT) is a mathematical model developed to meet the requirements of modeling activities undertaken to support intergovernmental negotiations for complex problems in Europe (Makowski 2005). C++ language programming is implemented for modeling the elements of SMT. The methodology is applicable to a wide class of complex problems that can be represented by algebraic expressions. The complexity considered here is in terms of the number of components in a system or the number of combinations one must consider in making a decision; this complexity is termed as detail complexity. Detail complexity is a typical property of mechanical systems whose parts play a well-defined role and have a defined set of possible relations. One of the SMT models known as RAINS is used in decision-making to improve European air quality. RAINS provides a framework for the analysis of cost-effective emission reduction strategies. The quality of air is assessed by several indicators computed at a few hundred grids in which Europe is divided for the purpose of air-quality assessment. The air quality indicator value depends on its location on the grid and the amount of emissions at that location. The decision variables are emissions that are input into the model. The output variables are the costs for reducing emissions and a set of various air-quality indicators. Each indicator is represented by a vector of values. The current version of RAINS consists of approximately 30,000 variables and 30,000 constraints formulated as a nonlinear algebraic expression (Schopp et al. 1999).

The summary of SMT model is presented here referring to Geoffrion (1987) and Makowski (2005). The SMT model specification consists of declaring all the variables and constraints. The specification includes declaring mathematical programming types (e.g., real, integer, binary), variable types (e.g., decision, outcome, auxiliary), and respective variable lower bound, upper bound, and zero tolerance. An example state equation of a control problem is presented in the matrix form as the following:

$$\begin{aligned} &\mathbf{A}\,\mathbf{x} + \mathbf{B}\,\mathbf{u} = \mathbf{c} \\ &\rightarrow \sum_{i \in I} a_{ij} x_i + \sum_{k \in K} b_{kj} u_k = c_j;\;\; j \in J \end{aligned}$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ are matrices of variable coefficients, $\boldsymbol{c}$ is a vector of output variables, $\boldsymbol{x}$ and $\boldsymbol{u}$ are vectors of state and control variables, respectively, $\boldsymbol{I, K, J}$ are sets of indices for state variables, control variables, and state equations, respectively.

The left hand sides of constraints in the formulation are treated as function $\boldsymbol{g(x)}$, where the vector $\boldsymbol{x}$ is composed of all variables. The constraint is represented as the following:

$$\mathbf{l} \leq \mathbf{g(x)} \leq \mathbf{u}$$

$$J_{ik} = \frac{\partial g_i(x)}{\partial x_k}$$

where ***l*** and ***u*** are vectors including lower and upper bound values of corresponding function, J_{ik} represents the elements of Jacobian matrix (***J(x)***), *i* represents indices of functions, and *k* represents indices of variables.

Model instances are defined after specifying the state equation and its associated variables. Each model instance requires the selection of two objects: (1) model specification and (2) set of data to be used for defining all associated variables. For each instance, analysis is performed following the steps below:

- Select a type of analysis among simulation, single-criterion optimization, soft simulation, and multi-criteria model analysis.
- Select a suitable solver and a variable standard for solving.
- Generate a computational task using a programming language.
- Monitor the progress of the computational task.
- Translate the results in a form presentable to the users.

The final analysis includes generating several instances and comparing the results from various instances. The benefits of SMT are the following:

- Algebraic expressions are used to represent relations in the problem state equation and constraints, which are commonly known among modelers and users.
- The structure of the problem can be easily verified.
- The methodology enables evaluating problems with detail complexity and alleviates the challenge of combining specifications of two or more models.
- The instances allow experimenting with various modifications to the model specification without actually changing the original state of the problem.

Even with the above benefits, implementing SMT modeling is unsuitable for addressing the ABC decision-making need because of the following:

- The SMT deals with problems involving detailed complexity, whereas the complexity in delivering a project using an ABC method is dynamic complexity.
- The outcomes associated with each activity of the ABC methods cannot be formulated as constraints in the SMT model specification.
- In the SMT, incorporating uncertainty in the problem formulation requires defining a set of possible relations/variables. However, defining algebraic relations for the activities and the stakeholder interactions in an ABC method is impractical.

Complex systems modeling

Something complex is considered something difficult to understand or to manage. Complex System Modeling (CSM) addresses complex problems involving dynamic complexity. Dynamic complexity can arise even in simple systems (i.e., with low detailed complexity) because of exchanges among the system components over time. The science of dynamic complexity takes into account the study of chaotic phenomena and helps in understanding collective phenomena such as the turbulence in fluids, evolution of weather conditions, spontaneous formation of organized structures in societies, traffic flow patterns, urban development, epidemics, and the behavior of people in groups.

Simon (1962) termed a complex system to consist of a large number of parts that interact in an uncertain way. He emphasized that a complex system is composed of interrelated subsystems that in turn can consist of several sub-systems and can therefore be represented using the hierarchical structural scheme. Another complex systems researcher, Simon (2006), defined a complex system as a system that includes the following: (1) Several different types of components, (2) Continuous feedback loops, i.e., the output of a component is input to another component, (3) Organized structure, i.e., contains hierarchies and subsystems that can be seen as complex systems themselves, and (4) Shows emergence, i.e., the behavior of the system cannot be predicted by observing the behavior of lower level components. In general, complex systems can be considered to have the following characteristics:

- Large numbers of interacting components acting in parallel with dispersed control
- Ability of components to alter the outcome based on feedback from interacting components
- Self-organizing collective behavior of the components to produce an outcome that is difficult to be anticipated from an individual component's behavior
- Components react to the environment using internal models and affect the system outcome.

The dynamics of a complex system is evaluated using experimental modeling. Simulation models that include computer simulations are utilized to develop a complex system model (Birta and Ozmizrak 1996; Ford 1999; Banks et al. 2010). A distinctive aspect of a simulation model is that it is developed to capture the relevant features of a system's dynamic behavior. A model has parameters that ultimately need to be measured and are termed as *measures of performance* of the system. The simulation models utilize numerical methods that are *simulated* rather than *solved* to analyze the output and estimate the *measures of performance*. This process contradicts with optimization/analytical methods. Complex system modeling requires comprehensive knowledge of the modeling concepts. Also, the modeler should be able to tailor the modeling process for obtaining the desired format of output results while preserving the main idea of complex system theory.

Considering the ABC decision-making need, implementing the complex system modeling methodology is deemed appropriate because of the following:

- The ABC decision-making need is to evaluate the ABC methods and the associated ABC systems for a project by incorporating the activities of ABC methods, characteristics of ABC systems, and the involvement of internal stakeholders. The evaluation process characterizes dynamic complexity.
- Complex system modeling enables us to understand the behavior within a system and the interactions between its components (Boccara 2004). The process allows evaluating stakeholder interactions included in delivering a project.
- A distinctive aspect of a simulation model is that it is developed to capture relevant features of a system's dynamic behavior (Banks et al. 2010). Therefore,

simulation modeling is suitable to incorporate project-specific activities in the evaluation process.

- Complex system modeling allows incorporating stochastic formulations within the evaluation process. If data is unavailable, engineered estimates can be implemented to achieve a close-to real world situation (Sanford-Bernhardt and McNeil 2004a,b; Sonnessa 2005). This characteristic of the complex system modeling methodology enables incorporating the uncertainties in the evaluation process.

Nevertheless, complex systems modeling can be performed using several techniques. A review of contemporary complex system modeling techniques is essential in order to implement the methodology for formulating the ABC decision-making model. Also, the review is essential to obtain insight of complex system modeling concepts and their applicability in addressing the needs.

Summary

The state-of-the-art decision-making models for bridge projects and their relevance to address the ABC decision-making need are discussed. A review of mathematical models used in decision-making is performed. A summary of the models including respective capabilities and limitations is provided in Table 3.1. From the review, it is concluded that the complex system modeling methodology is appropriate for addressing the ABC decision-making need. Also, a need is recognized to identify a suitable complex system modeling technique for formulating the ABC decision-making model. This directs to the literature review of complex system modeling techniques, which will be presented in Chapter 4.

Table 3.1. Summary of Mathematical Models Including their Strengths and Limitations

Model	Research Reference (s)	Model Outcome	Procedure Included	Strengths	Limitations w.r.t. ABC Decision-Making Need
Analytical Hierarchy Process (AHP)	Saaty (1980), SU (2013), Balali et al. (2014).	Provides preference ratings for the decision-making parameters and the decision alternatives.	The problem is represented in terms of parameters and a hierarchy is established. AHP pair-wise comparisons are performed in order to develop AHP pair-wise comparison matrices. Normalized preference ratings are calculated for each of the matrices. AHP synthesis process is implemented to calculate preference ratings for the decision alternatives.	• Ability to incorporate qualitative and quantitative parameters in the decision-making process.	• Lacks to consider the specific processes/activities included in a decision alternative and the associated uncertainty. • Lacks to incorporate the interactions of the stakeholders involved in a project in the evaluation.
Hybrid AHP	Mohammed (2011), Dagdeviren (2008), Wang and Shen (2012), Dong (2015).	Provides preference ratings for the decision-making parameters and the decision alternatives.	The standard AHP procedure is modified based on case-specific implementation. Example methodologies include the following: (1) hybrid AHP process that alleviates user input by incorporating ordinal scale ratings and Eigenvalue analysis (Mohammed 2011), and (2) hybrid AHP that combines standard AHP with other mathematical models to incorporate uncertainty in the parameters using predefined distribution functions (Dagdeviren 2008; Wang and Shen 2012; Dong 2015).	• Alleviates user input. • Accommodates uncertainty associated with decision-making parameters.	• Lacks to incorporate project-specific activities and stakeholder interactions in the evaluation.

Table 3.1. — Continued

Model	Research Reference (s)	Model Outcome	Procedure Included	Strengths	Limitations w.r.t. ABC Decision-Making Need
Fuzzy AHP	Chan et al. (2008), Pan (2008), Bozdag et al. (2003), Dagdeviren and Yuksel (2007).	Provides preference ratings for the decision-making parameters and the decision alternatives.	The standard AHP procedure is combined with Fuzzy set theory to incorporate the uncertainty associated with the decision maker's judgment. The procedure is tailored base on case-specific implementation. The procedure requires correlating qualitative judgments with a set of fuzzy numbers.	• Enables incorporating uncertainty in the decision maker's judgment.	• For the qualitative judgments, predefining fuzzy numbers that can be widely applicable to all bridge construction methods is impractical because the activities and stakeholders are not same. • Lacks to incorporate stakeholder interactions in the evaluation. • Results are deterministic and restrict the decision makers to obtain a range of possible inferences.
Elimination and choice expressing the reality (ELECTRE)	Benayoun et al. (1966), Roy (1973), Lopez and Gonzalez (2003), Balali et al. (2014).	Outranks a set of alternatives by considering judgments including preference, indifference, and veto (rejection) thresholds.	The procedure requires pair-wise comparing the alternatives with respect to each criterion in order to determine the concordance index, and the discordance index. Then, overall concordance indices and credibility indices are determined. Finally, partial preorder for the alternatives is determined by calculating qualification of each alternative.	• Useful for stochastic decision-making problems as it has a fuzzy view towards the judgments of decision makers. • Decision makers are able to provide their preferences by means of criteria weights and thresholds.	• For the ABC decision-making parameters, defining the concordance, discordance, and veto thresholds is impractical because the ABC methods are in early stages of implementation and the performance data of the systems constructed using ABC methods is limited. • ELECTRE is able to consider uncertainties in the judgments of the decision makers, but it lacks the incorporation of the uncertainty associated with a project itself.

Table 3.1. — Continued

Model	Research Reference (s)	Model Outcome	Procedure Included	Strengths	Limitations w.r.t. ABC Decision-Making Need
Preference ranking organization method for enrich evaluation (PROMETHEE)	Brans and Vincke (1985), Brans et al. (1986), Brans and Mareschal (2005), Balali et al. (2014).	Provides net outranking flows for each of the decision alternatives. The net outranking flow is calculated by combining positive outranking flow and negative outranking flow.	The procedure establishes a preorder among the alternatives. The procedure requires weights of decision-making parameters and statistical distributions termed as preference functions. Each criterion needs to be assigned a preference function from the available 6 functions: (1) Usual Function, (2) Quasi Function, (3) Linear Function, (4) Level Function, (5) Linear Function with Indifference Area, and (6) Gaussian Function.	• The preference function feature allows incorporating uncertainty in the parameters. • The method is consistent and requires little interaction with the decision makers. • The method allows visualization of problem characteristics through geometrical interpretations.	• The method is applicable to parameters that need to be either maximized or minimized. In evaluating bridge construction methods, parameters do not need to be maximized or minimized, rather they need to be satisfied in terms of constructability and durability. • Predefining preference functions for the ABC decision-making parameters is impractical because the ABC methods are in the early stages of implementation and the lack performance data that is required to predict the behavior of each parameter.

Table 3.1. — Continued

Model	Research Reference (s)	Model Outcome	Procedure Included	Strengths	Limitations w.r.t. ABC Decision-Making Need
Artificial Neural Network (ANN)	Hagan (1996), Tabarak and William (2003), Mansiz (2012).	Predicts the future performance of a system by implementing concept of neurons inspired by the human brain. Past data is used to train and validate the ANN. New input data is required to predict the future performance.	The output of each neuron is obtained by summing weighed inputs and associated bias, and implementing transfer functions. For multi-layered network, output matrix from first layer becomes input for subsequent layer. A cyclic process is implemented for training ANN with known input and output; each layer in the network is trained by consequent modification of respective weights until the error is reduced to a certain level.	• Ability to self-organize, generalize, tolerate error, and provide extensive parallelism.	• ABC methods are in early stages of implementation and a large amount of the past performance data that can form the base for future predictions is unavailable. • In predicting a system performance, the ANN merely depends on the pattern of the data that is used for training, and lacks incorporating the uncertainty associated with the system specific-activities/processes.

Table 3.1. — Continued

Model	Research Reference (s)	Model Outcome	Procedure Included	Strengths	Limitations w.r.t. ABC Decision-Making Need
Combinatorial Optimization Methods	Charnes and Cooper (1961), Charnes et al. (1978), Wu (2008), SU (2013), Fan et al. (2013).	Maximizes the efficiency of an alternative subjected to a set of constraints. Implements tailored optimization methods in order to deal with a specific problem in the decision-making process.	The process includes expressing the objective in terms of a function that needs to be optimized. The parameters governing the objective are formulated as constraints. Probability functions or fuzzy sets are utilized for the constraints and the objective functions in order to incorporate uncertainty associated with the parameters.	• The method can be implemented to reflect uncertain information in the management problems. • Alternative that satisfies the objective efficiently can be identified from a set of alternatives.	• The combinatorial optimization methods mainly focus on maximizing or minimizing the objective function while incorporating uncertainty. The uncertainty associated with activities of ABC methods cannot be incorporated in such formulation. • The outcomes associated with each activity of the ABC methods cannot be formulated as constraints in the optimization formulation. • All the decision rules are based on single variable optimization and they cannot evaluate inter-relations among the entities or individuals of the system while addressing the objective.

Table 3.1. — Continued

Model	Research Reference (s)	Model Outcome	Procedure Included	Strengths	Limitations w.r.t. ABC Decision-Making Need
Structured Modeling Technology (SMT)	Geoffrion (1987), Schopp et al. (1999), Makowski (2005).	Produces a set of indicators in the form of vectors based on input variables. The indicators represent effectiveness of the problem objective or state equation.	Procedure includes representing the problem objective as an algebraic model (i.e., state equation), and specifying variables and constraints. The constraints are treated as functions of variables. Instances are developed by various combinations of model specification and the associated variables. Analysis is performed for each instance and the results are compared.	• Algebraic expressions are used to represent relations in the problem state equation and constraints, which are commonly known among modelers and users. • The methodology enables evaluating problems with detail complexity and alleviates the challenge of combining specifications of two or more models. • The instances allow experimenting with various modifications to the model specification without actually changing the original state of the problem.	• The SMT deals with problems involving detailed complexity, whereas the complexity in delivering a project using an ABC method is dynamic complexity. • The outcomes associated with each activity of the ABC methods cannot be formulated as constraints in the SMT model specification. • In the SMT, incorporating uncertainty in the problem formulation requires defining a set of possible relations/variables. However, defining algebraic relations for the activities and the stakeholder interactions in an ABC method is impractical.

Table 3.1. — Continued

Model	Research Reference (s)	Model Outcome	Procedure Included	Strengths	Limitations w.r.t. ABC Decision-Making Need
Complex Systems Modeling (CSM)	Simon (1962), Birta and Ozmizrak (1996), Axelrod (1997), Dorigo and Gambardella (1997a,b), Bonabeau et al. (1999), Ford (1999), SDG (2000), Boccara (2004), Sanford-Bernhardt and McNeil (2004a,b, 2008), Sonnessa (2005), Simon (2006), Moore et al. (2007), Wang et al. (2007), Hodge et al. (2008), van Dam (2009), Banks et al. (2010),	Evaluates a system performance for a set of system configurations (i.e., alternatives). The outcome can be customized based on case-specific application.	Process includes developing a simulation model to address the problem. The components and their interactions during the process are incorporated using simple mathematical rules. The measures of performance of the system are defined. A framework is implemented to define attributes of the system components and their behavior rules. The simulation process is formulated using computer programming to obtain results in a desired format.	• Allows evaluating the interactions included in a process. • Enables incorporating the activities associated with a process. • Enables evaluating the uncertain nature of a system.	• Requires comprehensive knowledge of complex system modeling concepts and their applicability in addressing the ABC decision-making needs. • The modeler needs to tailor the modeling process for obtaining the desired format of output results while preserving the main idea of complex system theory.

CHAPTER IV

LITERATURE REVIEW OF COMPLEX SYSTEM MODELS AND MODELING TECHNIQUES

Overview

The literature review of mathematical models in Chapter 3 concluded that complex system modeling is a contemporary methodology that is appropriate for addressing the Accelerated Bridge Construction (ABC) decision-making need. Also, Chapter 3 indicated a need to identify a suitable complex system modeling technique for developing an ABC decision-making model. This chapter includes the review of available complex system models and modeling techniques from various disciplines. The findings from the review that can be implemented in developing the ABC decision-making model will be summarized in this chapter.

Complex system models

Model for social influence

The model for social influence developed by Axelrod (1997) simulates the way people tend to change each other in the process of interaction. The model illustrates how local convergence can generate global polarization. The model represents a culture as a 5-digit number. The 5 digits represent the *features* of the culture. Each feature can take any one of 10 *traits* that range from 0 to 9. The formulation means that two individuals have the same culture if they have the same traits for each of the 5 features. The formulation allows defining the degree of cultural similarity between two individuals as the percentage of features that have identical traits. For example, if the cultures of two individuals have 2 out of 5 features with the same traits, their cultural similarity is 40% (i.e., $2/5\times100$).

The basic idea of the simulation is that individuals who are similar to each other are likely to interact and then become even more similar. This is implemented by assuming that the probability of interaction is proportional to the cultural similarity between any two neighbors (individuals). Simple mathematical rules are subjected to simulation in order to allow interactions and explore the results. The following steps are utilized for the model simulation:

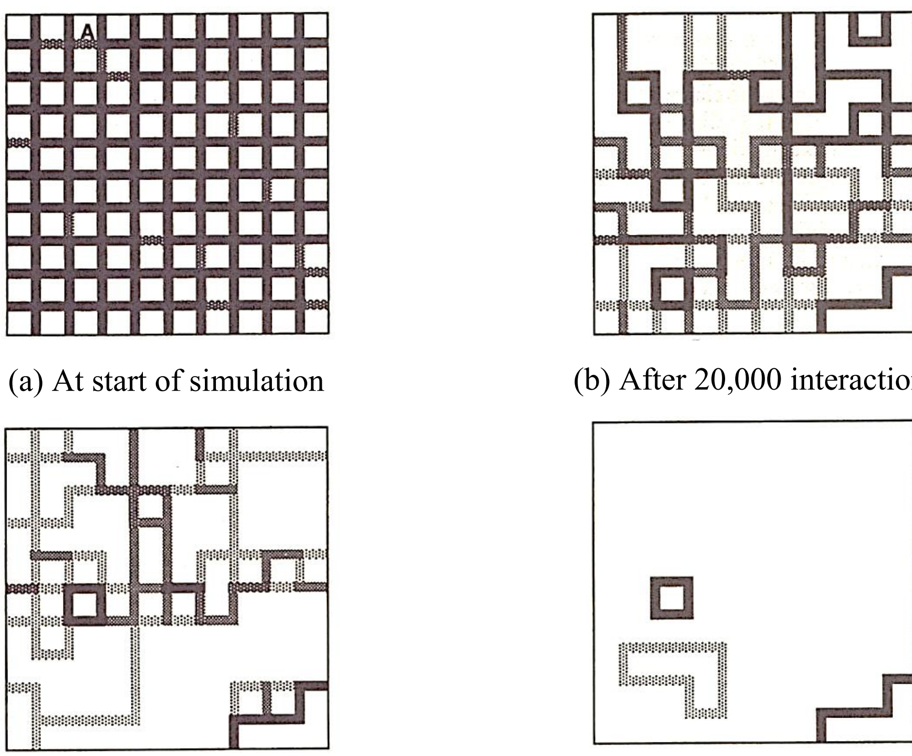
1) A large grid of 5-digit numbers is used to represent a population of individuals with random cultures.
2) An individual (5-digit number) is selected randomly from the grid as active individual. Then, one of the individual's neighbors is selected.
3) The two individuals are allowed to interact with probability equal to their cultural similarity. An interaction consists of selecting a feature that is different for both selected individuals, and changing the active individual's trait (of the selected feature) to the corresponding neighbor's trait.
4) Steps 2 and 3 are repeated numerous times to perform the simulation.

An example simulation model with a set of 100 individuals arrayed on a 10 by 10 grid is shown in Figure 4.1. The numbers shown in Figure 4.1 represent randomly assigned cultures to individuals at the start of a simulation. Except the boundary individuals, each individual has four neighbors called North, East, South, and West neighbors. The underlined individual in Figure 4.1 shares two features with its south neighbor and their cultural similarity is 40%.

74741	87254	82330	17993	22978	82762	87476	26757	99313	32009
01948	09234	67730	89130	34210	85403	69411	81677	06789	24042
49447	46012	42628	86636	27405	39747	97450	71833	07192	87426
22781	85541	51585	84468	18122	60094	71819	51912	32095	11318
09581	89800	72031	19856	08071	97744	42533	33723	24659	03847
56352	34490	48416	55455	88600	78295	69896	96775	86714	02932
46238	38032	34235	45602	39891	84866	38456	78008	27136	50153
88136	21593	77404	17043	39238	81454	29464	74576	41924	43987
35682	19232	80173	81447	22884	58260	53436	13623	05729	43378
57816	55285	66329	30462	36729	13341	43986	45578	64585	47330

Figure 4.1. Typical starting situation with randomly assigned cultures (Source: Axelrod 1997)

The initial grid is developed using random number generators and interactions between the individuals are modeled using the artificial intelligence procedure known as *Genetic Algorithm*. To illustrate the development of cultural regions, the cultural similarities between adjacent individuals were represented using different shades of lines between individuals as shown in Figure 4.2a. The shades of lines range from White to Black, where 100% similarity is shown using White and less than 20% similarity is shown using Black. A set of 100 runs of simulation was performed with different random choices of the grid shown in Figure 4.1. The result from a particular simulation (out of 100 simulations) is shown in Figure 4.2. The maps in Figure 4.2 show the cultural similarities at the end of several interactions within the simulation.



(a) At start of simulation

(b) After 20,000 interactions

(c) After 40,000 interactions

(d) After 80,000 interactions

Figure 4.2. Maps showing cultural similarities between adjacent individuals (Source: Axelrod 1997)

The results from 100 simulations showed that on a median there were 3 stable cultural regions and in 10% of the simulations there were more than 6 stable cultural regions. The results indicated that the process of convergence stopped with several surviving cultural regions that were completely different from one another. Axelrod (1997) implemented the model to explore how the number of stable communities depends on factors such as the scope of cultural possibilities, the range of interactions, and the size of geographic territory.

Model for exploring evolutional patterns

The research conducted by Wang et al. (2007) adopted a multi-agent simulation method to explore the general evolutional pattern of a logistics industrial cluster. The logistics industrial cluster system is considered a complex system. The logistic industries included in the research were logistics parks, logistics centers, and third-party logistics running companies. The external environment included in the research were politics, economy, society, resources, and the natural environment. The entities in the logistics industrial cluster were divided into *agent groups*, such as enterprise agents, social management agents, and environmental agents as shown in Figure 4.3. The agent groups were further divided into *agent subgroups*. The enterprise agents consist of producers and consumers. The social management agents consist of government departments at all levels. The environment agents consist of agents from the service region and from inside the cluster.

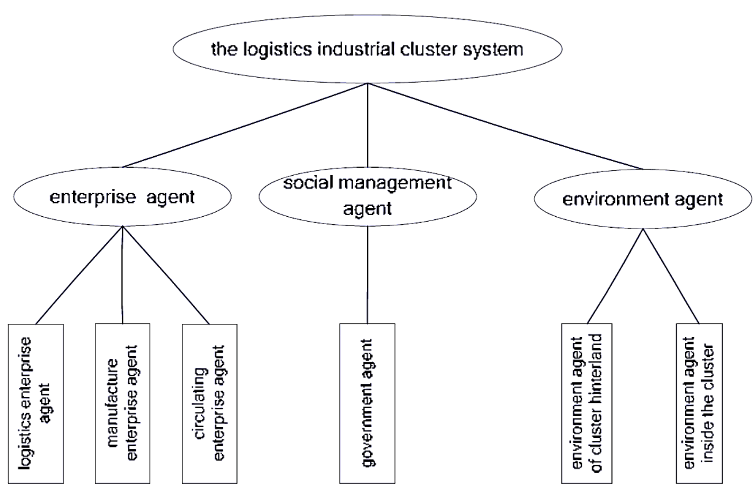


Figure 4.3. Hierarchical structure of logistics industrial cluster agent (Source: Wang et al. 2007)

The major task in this research was to establish a mathematical formulation for the industrial cluster system, so that it can be implemented in an available complex system simulation tool. The task was alleviated by relating the industrial cluster system to the characteristics of the ASPEN mathematical formulation developed by the American

National Laboratory of SANDIA (Wang et al. 2007). The SWARM software platform (SDG 2000) developed by the USA Santa Fe Institute was used to develop the simulation model.

Using the simulation model, the collective behavior of the agents was obtained. The collective behavior of the agents was used to understand the logistics industry planning and management system functioning. To perform the simulation, initial locations were randomly assigned to the agents of agent subgroups. The initial simulation parameters were selected as follows: 100 by 100 space grid, 0.80 probability of effort for the government, 0.002 transition probability for the enterprises, and 1500 step-size for the simulation. Using ASPEN formulation, the strategies of a *cell* in the 100 by 100 grid were associated with the behavior/rule of the respective agent. During the simulation, each agent performed an action and an interaction according to the respective behavior/rule. Figure 4.4 shows the distribution of the agents in the logistics industrial cluster.

(a) At the beginning of simulation (b) After the simulation

Figure 4.4. Distribution of agents in a logistics industrial cluster (Source: Wang et al. 2007)

The conclusions drawn from the simulation results were the following:

- The evolution of the logistics industrial cluster was very slow without the planning of the logistics park. On the other hand, the logistics industrial cluster developed faster with the planning of the logistics park. Thus, the logistics park was concluded as an important entity that affects the development of the logistics industrial cluster.

- The simulation showed that if the cluster scale was too small, the industrial cluster was unable to reach the best effect. However, if the cluster scale was too large, the effect of the industrial cluster was declined. Thus, it was concluded that an optimal cluster scale needed to be identified using multiple simulations.

Model for behavior of civil infrastructure systems

The research conducted by Sanford Bernhardt and McNeil (2004a) considered the pavement network as a complex system. The research recognized that the predictive models used to support decision-making are not always appropriate because the complex system behavior cannot always be controlled by the decision makers. The research also highlighted that in typical pavement management systems the predictions of individual segment condition fail to account for the interactions between system components, such as short segments being rehabilitated because of adjoining site rehabilitation. Therefore, the complex system modeling technique was utilized to capture the interactions and processes included in improving the existing pavement network. The interactions included separate units of the government making decisions about the investment, maintenance, financing, and pricing. The characteristics of a complex system were compared to the pavement network and a simulation model was developed. The model was developed using Microsoft® Excel to demonstrate the behavior of the pavement network as a complex system. Simulations were performed to explore the behavior of the pavement condition, user cost, and agency cost.

In the simulation model, the pavement network and its stakeholders were considered as agents that influence the pavement performance. The model was implemented to simulate the condition of a network of 1000 pavement segments over time with respect to varying environmental conditions and maintenance strategies. At the start of the simulation process, random conditions of the pavements were generated and pavement condition index (PCI) values were assigned to the pavements. The PCI value was assumed to be uniformly distributed between 20 and 95, where 20 represented a deteriorated pavement and 95 represented a new pavement. A *base case* was assumed, wherein rehabilitation of a pavement segment was prompted at a PCI of 30. Also, a linear deterioration function and a life of 25 years was assumed for all the pavement segments. The rehabilitation cost was considered the same for all the pavement segments. A hypothetical case with an unlimited budget was considered for simulation. In this case, the base case was modified to reflect the unlimited budget, termed as *modified case*. The simulation results showed that a pavement segment with an average condition had a PCI of 62.5, and 40 segments needed to be rehabilitated each year. Pairs of simulations (base case and modified case) were used to relate the situation to characteristics of a complex system, and to describe the simulation results in terms of the overall network condition. Similarly, five other modified cases were considered for the simulation. They include the following: (1) Reduced funding, (2) Changing exogenous factors causing accelerated deterioration, (3) Uncertainty in inputs, (4) Changing technology to provide better information, and (5) Recognizing network connectivity. The simulation results from the five cases in comparison to the base case are shown in Figure 4.5. Finally, the simulation results were correlated to the characteristics of a complex system in order to demonstrate that a pavement network behaves as a complex system (Sanford Bernhardt and McNeil 2004a, b).

Case	Attribute/ Simulation	Many agents/ decision-makers with dispersed control	Many organizational levels	Ability of agents to adapt	Internal models to anticipate the future	Condition	Agency cost	User costs
Reduced funding	One year deferral	✓	✓			⇩	⇩	⇧
	Lower trigger	✓	✓			⇩	-	⇧
	Budget cut	✓	✓			⇩	⇩	⇧
Changing exogenous factors	Accelerating deterioration rates	✓	✓	✓	✓	⇩	⇩	⇧
	Traffic growth	✓	✓	✓	✓	-	⇧	-
Changing technology	Inspection data	✓	✓	✓	✓	⇧	⇧	⇩
	Feedback	✓	✓	✓	✓	⇧	⇧	⇩
Uncertainty	Random failures – unlimited budget	✓	✓	✓	✓	⇧	⇧	⇩
	Random failures – constrained budget	✓	✓	✓	✓	⇩	-	⇧
Networked Segments	Opportunistic scheduling	✓	✓	✓	✓	⇧	-	⇩

Figure 4.5. Simulation results (Source: Sanford Bernhardt and McNeil 2004a)

The above research was extended by Moore et al. (2007) by developing the simulation model in MathWorks® MATLAB software. The simulation model included the following five agent types: (1) pavements, (2) users, (3) politicians, (4) engineers, and (5) work crews. A data set from Oregon Department of Transportation was used in the simulation model. The data set included 1468 pavement segments, 4 million users, 10 politicians, 5 engineers, and 35 work crews. The agents were represented as vectors with different values in MATLAB. Different agent classes for pavement segments, users, politicians, engineers, and work crews were defined. The individual agents in an agent class were grouped in a matrix. For example, the engineer matrix consisted of 5 vectors to represent 5 engineers. Each of the engineer's vector consisted of the following three values: (1) the ID of first pavement in the range the engineer was responsible, (2) the ID of last pavement in the range the engineer was responsible, and (3) the amount of funding allocated to the engineer.

In the MATLAB simulation process, a user cost was calculated in each time step (assumed 1 year) of the simulation. The user cost was calculated for each pavement segment based on the associated Average Daily Traffic. The user costs represented the level of dissatisfaction of the user agents with respective pavement segments. The level of dissatisfaction was reported to the politician agent representing the users. The politicians were modeled with fixed thresholds at the beginning of the simulation that governed their voting decisions. If the change in user complaints (based on user costs) was greater than the predetermined threshold, the politician increased its vote for funding. If the total vote of all the politicians was greater than a threshold, the funding increased. The funding level was calculated as a weighted average of the votes and the mean of the previous five years of funding. The funding was then divided among the 5 engineers according to the number of lane-miles of pavement for which they were responsible. Based on either the Worst-First or Benefit-Cost Analysis algorithm, each engineer selected the project location and repair techniques. Work crews were then assigned to a project based on specialization. If a pavement was not scheduled for repair, its condition deteriorated. The simulation was repeated for the next time step, i.e., for the following year. The simulation data for each time step was stored, which reflects the pavement network condition in the respective year. The simulation data was exported to

Microsoft® Excel using a MATLAB function in order to store and analyze the data. Finally, the simulation results were plotted using a Microsoft® Excel spreadsheet. The results captured the agent behaviors, such as pavement deterioration and pavement segment selection for rehabilitation. However, the behavior of other agents was understood qualitatively (Moore et al. 2007; Sanford-Bernhardt and McNeil 2008).

Complex system modeling techniques

Discrete-event systems approach

The discrete-event systems approach is one of the most widely used and accepted techniques in operations research and system analysis. The authors of the discrete-event systems approach highlight that it is virtually impossible to solve many complex real world systems mathematically using differential calculus or algebraic methods. Thus, the discrete-event systems approach considers computer programming languages as a means to describe a complex system. The discrete-event systems approach implements numerical simulations and considers that a system changes its condition or system state due to events at discrete points in time. The use of numerical solutions is recognized as essential in modeling the dynamics of complex systems (Sonnessa 2005). Numerical simulations using computers assist in imitating the behavior of a complex system and inferring the operating characteristics of the complex system (Banks et al. 2010).

A discrete-event simulation proceeds by creating a sequence of system snapshots that represent the evolution of the system. A snapshot at a particular time provides all the associated attributes of that particular system state, and it can be used to obtain model outputs at that instance. Discrete-event simulations typically consist of performing the following (Banks et al. 2010):

- Developing simulation tables that assist in tracking the system's state over time. The tables are custom designed for a particular problem.
- Incorporating random numbers to represent uncertainty in the real world system.
- Predicting the system performance by collecting and analyzing the descriptive statistics of the *measures of performance* of the system.

- Incorporating model automation using a programming language in order to assist in generating an output by processing the inputs, activities, and events that change the system state.

The three important processes included in discrete-event simulation modeling are the following: (1) event scheduling, (2) process interaction, and (3) activity scanning. Lists are used to keep a record of the events that occur during the simulation, and are termed the Future Event List (FEL). The FEL also contains the data required to execute an event. Based on the duration of activities, FELs generate respective activity completion times. The FELs will dynamically change during the simulation. Therefore, optimal computer runtime requires efficient management of FELs. The process of managing FELs is known as *List Processing.* The interaction between the events or activities is modeled using "logical conditions." Logical conditions include programming statements that become true/false or that are executed upon satisfying a specific condition. As complex systems change over time due to events, its entities and associated attributes are all functions of time. Thus, the time needs to be tracked using an independent variable. In the simulation model, FELs and *Event Scheduling/Time Advance Algorithm Procedure* are used for advancing simulation time and ensuring appropriate sequence is followed during the simulation.

In the Event Scheduling/Time Advance Algorithm Procedure, all future events and their associated event times are included in the FEL. Each entry in the FEL is termed as a "notice." The FEL is then organized based on time sequencing as shown below:

$$t < t_1 < t_2 < \ldots. < t_n$$

where t is the value of the computer clock and is considered the current value of simulated time, t_1 is the time of the imminent event which is the event that occurs next, t_2 is the time of the second subsequent event, and t_n is the time of the n^{th} subsequent event.

Then, the system state is updated at time t and the simulation is advanced to time t_1. The imminent event is executed at time t_1 and its notice is removed from the FEL. The event execution process includes updating the system state based on the previous system state and the operation/behavior of the event. At time t_1 future events are generated and the FEL is updated and organized again. Generating a future event includes computing the duration of an ongoing event from the statistical distribution of the respective operation/behavior, and placing an end-event on the FEL at the corresponding time. Later, the simulation proceeds to the next subsequent event time and a similar procedure is repeated until the simulation is completed.

As mentioned earlier, List Processing is required for efficient management of FELs. List Processing includes removing or adding an event notice from the top or bottom of the FEL within a minimum time. *Pointers* are used to perform this process. A pointer is an identifier that points to the next notice or the previous notice. Pointers allow traversing the FEL from top to bottom or bottom to top. A pointer to a notice can be considered a physical or logical address in the computer memory. In procedural programming languages different notations are used for referring data from pointer variables. For example, in Visual Basic the "next pointer" is "Next i" where "i" is a variable used dynamically during a runtime. An entity (X) in a procedural programming language is represented as the following:

X: [ID, attribute 1, attribute 2,……., attribute n, next pointer]

In the above equation, the "next pointer" field refers to a subsequent notice in the FEL. Along with "next pointer" field, "tail pointer" field can be implemented for concise and efficient list processing. The "tail pointer" points to the ID of last notice in the FEL. Also, removing or adding an event from an arbitrary position in the FEL requires "searching the list." For this purpose, the following two popular techniques can be implemented:

1) Store all notices in arrays that can be referenced by a respective array index. This is similar to pointing to a row number in a matrix.
2) Represent and track all entities and event notices using *classes* allocated from computer RAM memory. In this case, procedural programming languages such as C++, Visual Basic, Java, etc. can be used.

The first technique that uses arrays requires pre-dimensioned arrays. The dimensions of the arrays shall be estimated based on the maximum possible number of notices for any FELs during the simulation. This process will require excessive amounts of computer memory and in some instances will be challenging to estimate the maximum possible number of notices for a FEL. In contrast, the second approach that uses Classes will be more efficient. The procedural programming languages dynamically create classes for event notices when needed. After an event is executed, the respective class is released. This helps in the efficient management of computer memory.

More often discrete-event simulation models are developed using simulation packages that are based on procedural programming languages. Simulation packages used in the manufacturing industry are ProModel, Arena, etc., and the simulation packages used in business, technology, network theory, economics, and the social sciences are Anylogic, Starlogo, Swarm, Repast, etc. All the simulation packages are developed for specific applications (Banks et al. 2010).

Swarm intelligent systems approach

Swarm intelligence theory deals with contemplating natural systems, such as ant colony, flock of birds, etc. and their social behavior to solve a complex system problem. For example, an ant colony is considered to be a self-organized and decentralized problem-solving system comprised of many relatively simple interacting agents. A swarm intelligent system is a system that self-organizes to solve problems, and is based on self-organization and decentralized problem-solving techniques. The swarm intelligence theory imitates the way of nature to solve problems. The theory has been implemented to design artificial neural networks that solve problems and has been used in the development of genetic algorithms for optimization. One possible way to develop a swarm intelligent system is to list all the collective behaviors that can be generated with simple interacting agents.

The self-organization technique is a set of dynamical relations that result in a global configuration of a system. The relations among lower-level components of the system are termed as interactions. The rules specifying the interactions among the components are executed based on exclusively local information without reference to the global configuration. Self-organization relies on the amplification of variations because of randomness. Variations can be treated as *seeds* from which system configuration evolves. Seeds are integer values that initialize random number sequences. The interactions are simple rules of thumb that promote the creation of various configurations of the system. In natural systems there are two types of interactions among the agents, which are direct and indirect interactions. The indirect interaction is a promising tool in the design of artificial agents because it enables the design of simple agents with interacting rules (Bonabeau et al. 1999). In one example of the ant-based algorithm models, the researcher conducted an experiment and showed that path selection to a food source in an ant species is based on self-organization (Deneubourg et al. 1987). The researcher then developed a simulation model to represent that phenomenon. In the experiment a food source was separated from the nest by a bridge with two equally long branches, *A* and *B*. In the simulation model, the probability of choosing a branch at a certain time was assigned based on the total number of ants that used the branch at the particular time. A_i and B_i were considered the number of ants that used branches *A* and *B* respectively after *i* number of ants. The probability P_A that the $(i+1)^{th}$ ant selected branch *A* was represented by the following equation:

$$P_A = \frac{(k + A_i)^n}{(k + A_i)^n + (k + B_i)^n} = 1 - P_B$$

where *n* determines the degree of nonlinearity of the choice function, i.e., if *n* is large and branch *A* has more *pheromone* than branch *B*, the next ant will have high probability of choosing branch *A*; *k* quantifies the degree of attraction of an unmarked branch, i.e., a greater *k* leads to a greater amount of pheromone which makes the choice non-random.

Pheromone is a chemical factor that activates a social response in ants. In the research, the values of the parameters *n* and *k* were obtained by calibrating probability P_A with experimental results. A best-fit curve to the experimental results was used for calibration. The model used the Monte Carlo simulation procedure for running the simulation.

The decentralized problem-solving technique underlying all ant-based algorithms is the use of Positive Feedback and Negative Feedback mechanisms in order to strengthen those portions of the good solutions that contribute to the quality of the solutions. Two important aspects of ant foraging strategies that can be used in real world complex problem solving are the following: (1) Emergent effect from the actions of many ants, and (2) Discovering and maintaining a shortest path between two or more locations. A Traveling Salesman Problem (TSP) is used as an example to explain one such ant-based algorithm (Dorigo and Gambardella 1997a, b). In the case of TSP, the goal was to find a closed tour of minimal length connecting a number of given cities and each city was to be visited once. The problem was defined in Euclidean space. The cities were defined as *nodes* and connections between them as *edges* on a graph. The distance (d_{ij}) between any two cities i and j was represented as the following:

$$d_{ij} = \left[\left(x_i - x_j \right)^2 + \left(y_i - y_j \right)^2 \right]^{1/2}; \quad d_{ij} \neq d_{ji}$$

where x_i and y_i are the coordinates of city i.

A distance matrix was developed for all possible connections between the cities. The length of an edge connecting two cities i and j depended on whether the salesman traveled from i to j or from j to i. Initially, the Ant System (AS) algorithm was implemented to solve the TSP, wherein the ants built solutions by moving on the problem graph from one city to another until they complete a tour. However, the AS algorithm led to the amplification of the initial random fluctuations and could not perform well without pheromone decay. Thus, the researchers introduced the Ant Colony System (ACS) algorithm by considering the requirements for improved performance of the algorithm. The ACS algorithm is based on following four modifications of the AS algorithm: (1) Modified transition rule, (2) Modified pheromone trail with updated rule, (3) Local updates of pheromone trail to favor exploration, and (4) Use of a candidate list to restrict the choice of the next city to visit. Finally, the researchers recommended combining ACS with procedures that can iteratively improve a solution, such as linear programming/ optimization procedures (Dorigo and Gambardella 1997a, b).

Agent-based modeling approach

Agent-based modeling is a method for modeling and simulating the processes and interactions of autonomous individuals in a system. The goal of agent-based modeling is to assess the effect of the processes and the interactions on the entire system. In this method, the model of an individual (that performs actions) or a group of individuals is termed as an *agent*. Agents can be people or entities that actively make decisions and exhibit learning based on past events/activities. Each agent's behavior is governed by a set of local rules; i.e., an agent responds or makes decisions in a manner prescribed with respect to local/nearby conditions. The interest of agent-based modeling is in the patterns of behavior that emerge for the total group of agents called *emergent behavior.* Emergent behavior is not explicitly programmed, rather it emerges from a set of simple rules of interaction. The behavior of an agent can be formalized using mathematical rules. The key feature that distinguishes agent-based models from other models is the focus on modeling individuals who can make decisions or provide responses. Agents can exist in several levels of hierarchy. The agents can communicate and link with other agents based on the behavioral rules. Thus, different networks can be created by altering the behavioral rules. The bottom-up nature of agent-based modeling allows simulating dynamic systems where the configuration needs to be changed during a simulation run. Thus, different configurations of a system can be established in a simulated environment, and the response of agents to the emergent system behavior can be observed. Agent-based models are useful in the decision-making process when dynamic changes in the system during its performance need to be evaluated, or when the interaction between system elements needs to be evaluated. Another advantage of agent-based modeling lies in reusing the elements of previously developed models because of its bottom-up nature and the possibility of implementing *ontology* as an interface between system elements. Agent-based modeling facilitates the explanation of model structure and model results by offering a representation for the entities and their interactions in the system. The available literature emphasizes that an agent-based model is not mysterious, but rather a clearly defined computational model capable of producing results that can be replicated using the same input data and configuration (Boccara 2004; van Dam 2009; Banks et al. 2010).

An agent-based model was developed by Hodge et al. (2008) for simulating energy systems. The model was specifically developed for the energy domain. The goals of the model were the following: (1) Evaluate the impact of energy policies on new technology growth and integration into the current energy system, (2) Identify the mechanisms that alter the energy systems, (3) Understand new technologies while considering market adoption, and (4) Inspect the role of research in technological improvements. In this particular agent-based model, the agents made independent decisions based on information they received and the communication network among the agents. A network view of the world was considered, wherein the agents were represented with *nodes* and the lines of communication were represented with *edges* (discussed in next section). Each individual involved with the system process was considered an agent and its behavior was modeled with a set of rules. The interactions among the agents were modeled as "take it" or "leave it" based on products and prices. The illustrative case study by Hodge et al. (2008) proved that the model can be extended and validated on a real system.

van Dam (2009) developed an integrated agent-based model for capturing the characteristics of a complex socio-technical infrastructure system. Specifically, van Dam focused on to developing an integrated model for capturing physical and social reality, inter-relations, and external dynamic environment of a socio-technical infrastructure system. The research started with considering the major challenges encountered by strategic decision makers in large scale network systems. One of the challenge was that each decision making entity was situated in a dynamic, multi-actor, multi-objective and multi-level environment. The environment was a part of a bigger system that constantly changed to cope up with the actions of entities. The entities operated on different levels of the hierarchy in the system. For example, considering an oil refinery supply chain from a socio-technical infrastructure system perspective, it contains distributed, intelligent, autonomous entities that interact with complex production technologies. Each entity in the system has its own dynamics and goals. An overview of the agent-based modeling methodology adapted by van Dam is presented in the following paragraphs.

van Dam reviewed potentially interesting modeling approaches that described complex infrastructure framework, and that were closely related to socio-technical infrastructure systems. From the review, van Dam concluded that agent-based modeling is the best approach for modeling socio-technical systems and developed a framework to combine social and physical systems. van Dam extended the approach used by Hodge et al. (2008) of considering the network view of the world, wherein the nodes represent the agents and the edges represent the lines of communication. To enable flexibility of experimenting with different configurations of the social network, physical network or both, the framework was modeled similar to *building blocks* that can be connected and reused. An ontology was used for modeling the interface and shared world model. Modeling the interface refers to describing the components, and modeling the shared world model refers to prescribing the interactions of the components. An ontology includes formal descriptions of entities and their properties, relationships, constraints, and behavior that are machine readable and understandable. Specifically, an ontology offers the following: (1) Class structure, (2) Interface, and (3) Language for system definition. A complex system and its process can be easily expressed using the ontology and stored in a knowledgebase. The tool used by van Dam (2009) for developing the specific ontology was developed by Stanford Center for Biomedical Informatics Research at the Stanford University School of Medicine in California. The tool supports several web storage languages for storing an ontology that are based on XML (Extensible Markup Language). The tool uses a Graphical User Interface (GUI) for entering class definitions and for knowledge acquisition using user-defined forms.

The ontology developed for socio-technical systems considers the agents and physical systems as nodes with different *classes* (social node class and physical node class). The network in the ontology was defined using edges by connecting nodes together. Edges were designed to have only one *"from"* node and one *"to"* node. A small fraction of socio-technical system ontology is shown in Figure 4.6 that illustrates the classes. As shown in Figure 4.6, each class (property box) includes property labels in the left column, value type in the middle column, and the specific property in the right column. The agent in Figure 4.6 belongs to the social node class and thus, it inherits all properties of the social node class. The agent represents an actor in the system and can be a single person, a group of people, or an organization.

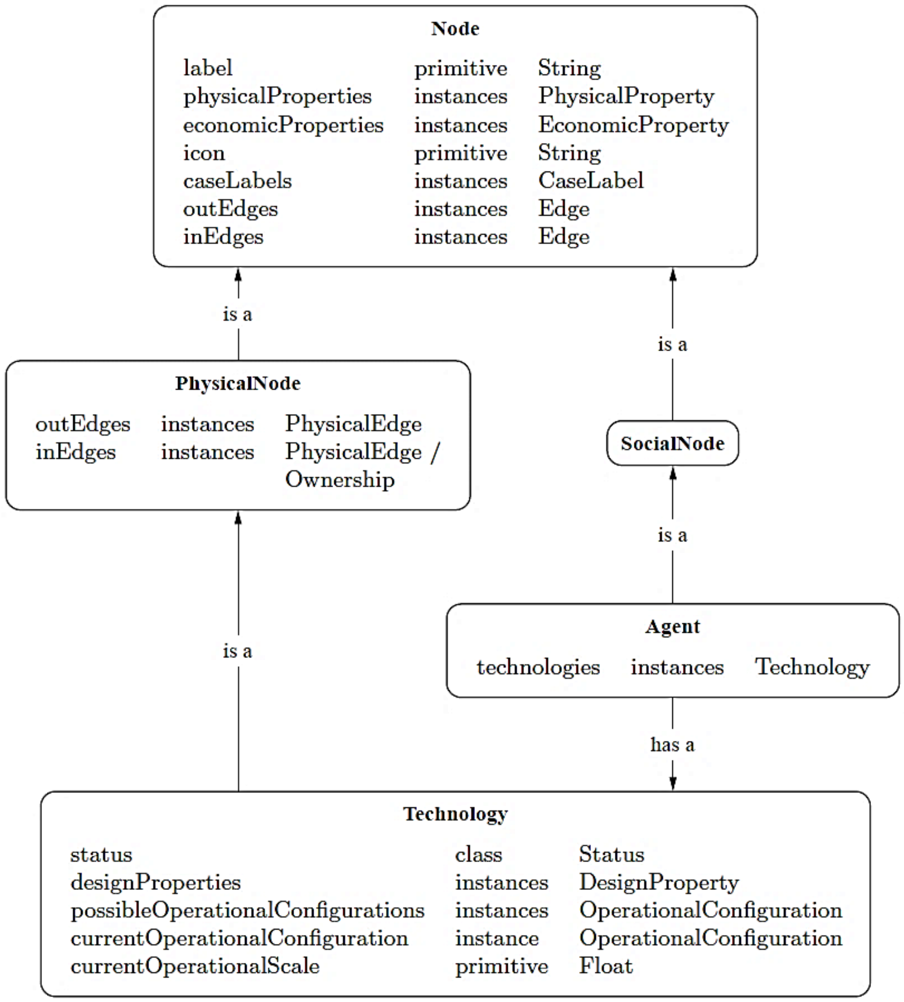


Figure 4.6. Small fraction of socio-technical system ontology (Source: van Dam 2009)

To create the social and physical network two types of edges were used, *social edges* and *physical edges*. Physical edges connected physical nodes and social nodes to their primary class, and did not have their own properties. For example, consider the "*is a*" edges in Figure 4.6 those connect the *PhysicalNode* and *SocialNode* to the *Node*. On the other hand, social edges were used to establish the social network, and the relationship between physical and social nodes. For example, consider the *"has a"* edge in Figure 4.6 that specifies the *Agent* to be the owner of *Technology* (a physical node).

The modeling framework developed by van Dam (2009) can help set up new models of socio-technical systems by following a number of modeling steps and reusing building blocks from available applications. When new elements are created for a specific case, they can be fed back into the shared framework to allow reuse. The development of the framework is an iterative process of applying the framework and the ontology to case studies, and simultaneously making changes to the shared building blocks. van Dam analyzed 21 different projects that shared the developed ontology definition and concluded that the framework itself may never be complete. However, the framework can be considered stable and suitable for a large variety of cases because of its successful implementation in industrial networks.

Before starting the model development process, it is important to familiarize oneself with the ontology structure and to experience it application in a domain. The framework developed by van Dam has been implemented only within one research group and its ontology cannot be used as an off-the-shelf solution. Parts of the framework source code are available through a public license. However, the contents of the knowledgebase are not open because it contains propriety data. Nevertheless, the framework is helpful for modelers without an extensive agent-based modeling background. In developing a new model, definitions of entities in the physical network such as *ontology*, *nodes*, and *edges* can be used. Reusing agent definitions from available applications is impractical since the actors often have a particular behavior that needs to be specified. After understanding the process of the model development, a modeler can begin mapping the elements of a system onto the ontology. The approach can be implemented in other domains, wherein the individuals exchange or share the tasks/activities.

Summary

A literature review of available complex system modeling techniques is performed to identify a suitable technique and the associated concepts for developing an ABC decision-making model. From the literature review it is identified that several industries, such as manufacturing, business, technology, logistics, economics, and the social sciences implement agent-based modeling and simulation packages to effectively manage a complex system and predict system performance. Also, numerical computer-based simulation is identified as a suitable technique for imitating the behavior of a complex system and estimating its performance. Specific findings from the review are summarized as the following:

- The model for the social influence uses random number generation, random selection, and genetic algorithm mutation concepts to simulate the cultural interactions and evolution within a society/population. This model provides information of utilizing the random number generation and mutation concepts to develop interactions in a complex system.
- The model for exploring evolutional patterns establishes processes within the simulation model by means of mathematical functions. This model provides information for relating a mathematical function to a particular process in a complex system.
- The model for the behavior of civil infrastructure systems is developed using Microsoft® Excel to demonstrate the behavior of the pavement network as a complex system. This model provides information for developing an agent-based simulation model using arrays to group respective agents and attributes. The model also provides details of correlating predefined thresholds to quantitative measures for allowing interactions of agents during the simulation. The results from the model show that the complex system behavior and the system performance can be understood by implementing widely available tools, such as Microsoft® Excel. However, the research highlights that explicit explanation of the results is required, which can be achieved by comparing the results to a base case.
- The methodology of modeling complex systems using the discrete-event systems approach provides the fundamental concepts and methodologies underlying a discrete-event simulation package. These methodologies/concepts can provide vital input in developing a simulation model of a complex system. In addition, the approach provides details that can be readily implemented in Microsoft® Excel for modeling and simulating a complex system.
- The swarm intelligent systems approach provides the concept of utilizing probabilities and basic mathematical formulations to develop interactions in a

complex system simulation model. In addition, it provides details of using probabilities to alter the system configuration to explore optimal solutions.

- The review of agent-based modeling approach as well as the available agent-based models provides a perspective of developing an agent-based model without demanding an extensive modeling background. The review recognizes that before starting the model development process, it is important to familiarize oneself with the ontology structure and to experience its application in a domain. The approach is considered to be more widely applicable in other domains, wherein agents exchange or share the activities.

In delivering a project using an ABC method, several internal stakeholders collaborate through the owner agency. This resembles a complex system, wherein the risks/uncertainties associated with the activities and the stakeholder collaboration affect project performance in terms of constructability and durability. Considering the previously discussed conclusions and findings, implementing agent-based complex system modeling methodology is considered suitable for addressing the ABC decision-making need. By using agent-based modeling and simulation, uncertainty associated with the activities of ABC methods, the internal stakeholder interactions, and the constructability and durability of superstructure systems can be evaluated.

CHAPTER V

FRAMEWORK DEVELOPMENT BACKGROUND

Overview

The mathematical modeling of decision-making processes has a guaranteed future, as long as it facilitates the administrators in making optimal judgments. As concluded from the literature review, implementing agent-based complex system modeling methodology is considered suitable for selecting Accelerated Bridge Construction (ABC) methods and the associated superstructure systems for bridge replacement projects. Developing agent-based models for ABC methods facilitates evaluating the associated uncertainty and the interactions of internal stakeholders. For this purpose, the complex system characteristics considered are the following:

- The system consists of a large number of interacting agents acting in parallel with dispersed control.
- The agents in the system are associated with attributes that govern respective actions.
- Each agent performs an action and produces an outcome that affects the system outcome.
- The agents interact with each other and respond to their surrounding environment based on their respective purpose in the system.
- The agents have the ability to change their behavior based on past experiences (knowledgebase).

The ABC methods considered in the scope of this research are Prefabricated Bridge Elements and Systems (PBES), Self-Propelled Modular Transporter (SPMT) move, and Slide-In Bridge Construction (SIBC). This chapter describes the concepts utilized to model and simulate the processes involved in implementing the ABC methods, which are based on the agent-based modeling methodology.

Even though the concepts described in this chapter provide the ability to include the entire list of internal stakeholders and the activities associated with the ABC methods of a desired state/region, only major activities and the associated internal stakeholders are considered in this study. The internal stakeholders involved with the activities of ABC methods are considered as agents. In agent-based complex system modeling, the attributes of agents are modeled using a set of procedures and the experience is modeled using a knowledgebase.

Ontology and process modeling

Modeling a system using the agent-based modeling approach requires a standard interface and a shared model for the agents. An ontology is one of the representations used to define the interface and the shared model for the agents. Ontologies are formal descriptions of agents and their attributes, relationships, predefined thresholds, and responses that are machine-readable and machine-understandable (van Dam 2009). An ontology consists of *nodes* and *edges*. The nodes represent agents and include agents' associated attributes and the edges connect the nodes together, representing the communication network among the agents. Each agent can have several classes of nodes based on the processes. For example, if an agent has two actions to perform, there will be two node classes for that agent, and each node class will be associated with the attributes required for the respective action. These characteristics of an ontology are used to develop the agent-based models for ABC methods that include internal stakeholders (agents) and their associated activities (communication network). Implementing ontologies for the agent-based models offers the flexibility of extending the agent-based models by incorporating additional agents.

For modeling an ABC method, a design-bid-build contract procurement process is considered, wherein the owner agency, such as the Department of Transportation (DOT), transfers detailed engineering design and construction activities, as well as their associated risks to design and construction contractors (FTA 2009). Specifically, the

DOT contracts out the design to the designer and the construction to the general contractor who then subcontracts to consultants/subcontractors. Further, the DOT consists of sub-divisions termed as *DOT groups*, which are responsible for keeping track of certain tasks such as design control, contract management, project implementation, budget control, etc., while delivering a project.

The above-discussed process is used to specify the communication network among the internal stakeholders in the ontologies of ABC methods. Based on the review of past ABC projects archived in the FHWA database (FHWA 2015), the internal stakeholders of an ABC method include the DOT, the designer, the contractor (general contractor), the consultants, the subcontractors, and the public. The consultants and subcontractors vary based on the specific ABC method. Moreover, the communication network depends on the activities included in an ABC method. As an example, the ontology of an ABC method implementation is shown in Figure 5.1. In Figure 5.1, the *Agent* and *DOT Group* blocks represent the nodes and the *Communication Network* arrows represent the edges. The labels (numbers) of activities are shown beside the edges in Figure 5.1 to represent the particular activity associated with an edge. The DOT agent is accompanied by DOT groups (e.g., G-1 to G-5 in Figure 5.1), which are secondary agents and continuously communicate with the DOT agent to keep track of project performance.

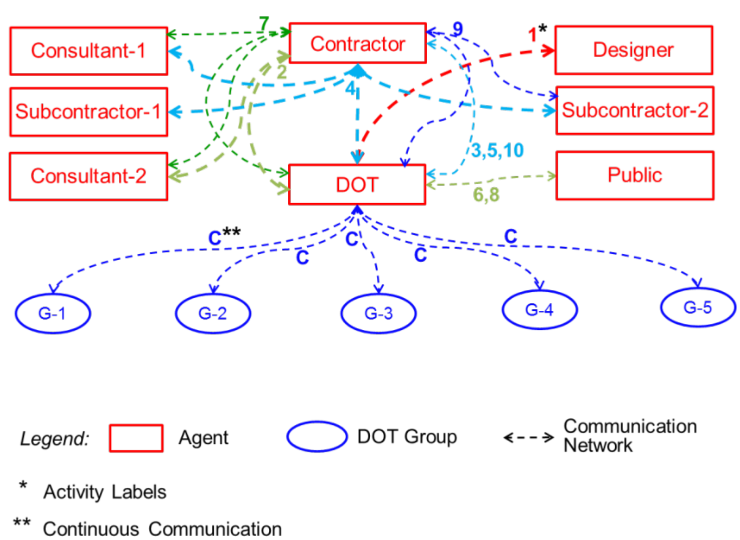


Figure 5.1. Ontology of an ABC method implementation

The *Continuous Communication* shown in Figure 5.1 between the DOT groups and the DOT agent is not emphasized in this study because a DOT group eventually represents the DOT agent when an activity is assigned to another agent during the implementation of an ABC method. Therefore, in this study the DOT agent and the DOT groups are considered one agent.

In order to include the communication network in the ontology of an ABC method, the relationship among the agents needs to be defined with respect to the activities. This can be achieved using a *Task-Actor-Relation Table*, which is discussed in the following section. In order to define the various actions that an agent is responsible for, node classes can be utilized. The node class of an agent includes attributes and a set of procedures, which enable the agent to perform an action and produce a result. Specifically, the node class allows the agent to execute a process during the agent-based model simulation. The node classes are represented using a set of arrays that are discussed in a later section (*Arrays for Processing*).

Task-actor-relation table

A Task-Actor-Relation Table (TART) enables defining the relationship among the agents for the activities in order to reflect the activity assignment for each agent in a system (Du and El-Gafy 2012). Using TART to define the activities of an ABC method and the associated relationship among agents provides several benefits including the following: (1) enables a parallel evaluation environment (Yu et al. 2007) wherein multiple activities can be evaluated simultaneously, (2) reveals the dependency of activities on corresponding agents (Park and Pena-Mora 2003), (3) builds layouts of the process flow (Cheng et al. 2006). During the delivery of a project using an ABC method, each agent is responsible for certain activities and interacts with other agents to produce an outcome. TART can be implemented to define the activities and interaction among the agents, which defines the communication network in an ontology.

Figure 5.2 shows an example TART for the ontology presented in Figure 5.1. As shown in Figure 5.2, TART includes the list of activities in the left column and the list of the agents in the top row. In Figure 5.2, the agents involved with a certain activity are marked using an ‘x’ and the relationship among the agents for an activity is shown using arrows that depict the communication network among the agents. For example, consider the Activity-4 in Figure 5.2, where the DOT communicates with Contractor and the Contractor subsequently communicates with Consultant-1, Subcontractor-1, and Subcontractor-2 to perform the activity. During this activity, Consultant-1, Subcontractor-1, and Subcontractor-2 report to Contractor and then the Contractor reports to the DOT.

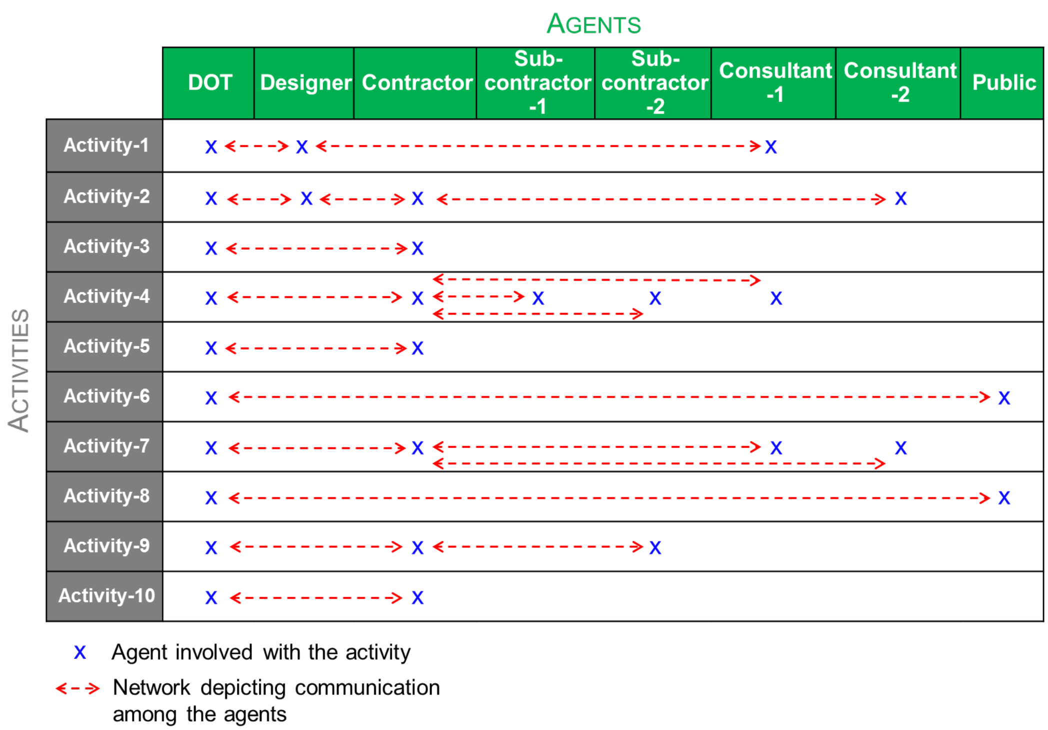


Figure 5.2. Arrangement of activities and agents in a task-actor-relation table

Based on the review of past ABC projects archived in the FHWA database (FHWA 2015), a list of activities (major work assignments) can be developed for an ABC method. In this study, each activity is considered to impact the project performance independently. Further, the interactions among the agents for an ABC method can be identified by reviewing the process followed during the delivery of projects using the ABC method.

Arrays for processing

As mentioned previously, a node class is required for an agent to execute a process during the simulation. Mathematically the procedure of executing a process can be modeled using a set of arrays (Moore et al. 2007; Du and El-Gafy 2012). To understand the array representation and application in the agent-based modeling, consider the scope of this dissertation discussed in Chapter 2. The goal of the decision-making framework is to identify the impact of the uncertainty associated with ABC methods on the project cost and construction duration. Thus, in the agent-based model of an ABC method, it is assumed that the DOT agent evaluates the impact on project cost and construction duration based on the response from other agents. This is a process that the DOT agent needs to execute during the agent-based model simulation. For this specific process, an array can be defined as shown in Figure 5.3. In Figure 5.3, the array includes attributes that enable the DOT agent (MnAgent) to obtain data from another agent for an activity (Act) and calculate the impact on project cost and construction duration with respect to the activity. The data from another agent is obtained in terms of percentage change in cost (ChC%) and percentage change in duration (ChD%) due to the uncertainty of the activity. The updated project cost (UpC) and construction duration (UpD) are calculated by prorating the *base estimates* based on ChC% and ChD%. The UpC and UpD shown in Figure 5.3 are the outputs with respect to the activity for a particular simulation run.

$$\begin{bmatrix} \text{Act} \\ \text{MnAgent} \\ \text{ChC\%} \\ \text{ChD\%} \\ \text{UpC} \\ \text{UpD} \end{bmatrix}$$

Figure 5.3. Array of an agent to obtain the impact on project performance

On the other hand, the array of an agent (ResAgent) who is responsible for the activity (Act) and who provides the percentage change in cost (ChC%) and percentage change in duration (ChD%) to the DOT agent can be defined as shown in Figure 5.4. A set of parameters and a knowledgebase are associated with the activity, which enable ResAgent to obtain the uncertainty of the activity (ActUn) for the site-specific conditions of a given project. The ChC% and ChD% shown in Figure 5.4 are calculated based on ActUn and will be provided as an input to the DOT agent array.

$$\begin{bmatrix} \text{Act} \\ \text{ResAgent} \\ \text{ActUn} \\ \text{ChC\%} \\ \text{ChD\%} \end{bmatrix}$$

Figure 5.4. Array of an agent to obtain the effect due to uncertainty of an activity

From the above it is clear that if an agent is responsible for multiple processes, a separate node class need to be defined for each process. The information transfer among the arrays is referred to as the *Array Mapping* procedure in a computer programming language. The Array Mapping procedure enables a predefined set of procedures in order to calculate required outputs. An example interaction among the agents of PBES implementation using Array Mapping is illustrated in Figure 5.5.

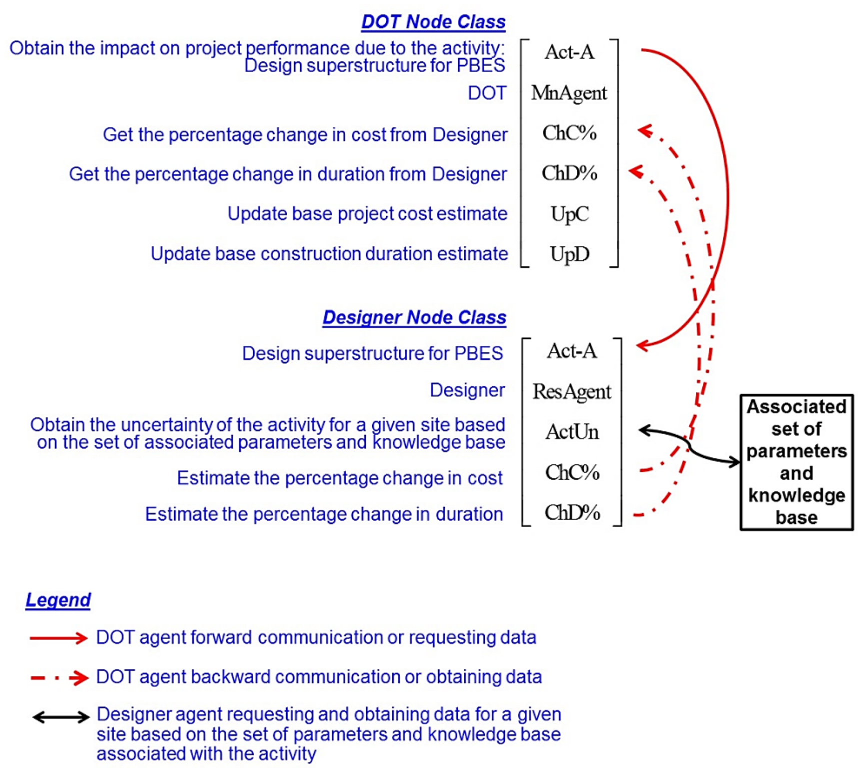


Figure 5.5 Example array mapping between the agents

As shown in Figure 5.5, the DOT (MnAgent) interacts with the designer (ResAgent) using a respective node class in order to obtain the impact on project performance due to the uncertainty of the activity of 'Design superstructure for PBES.' In the interaction, the MnAgent requests data from the ResAgent in the form of percentage change in cost and duration. The ResAgent obtains the uncertainty for the given site based on the associated set of parameters and knowledgebase. Then, the ResAgent estimates the percentage change in cost and duration based on the obtained uncertainty and provides the data to the MnAgent. The MnAgent then calculates the updated project cost and construction duration by prorating the base project cost and base construction duration estimates using the data obtained from the ResAgent. The updated values signify the impact of the activity on the project performance.

As mentioned in the previous example, each activity needs to be associated with a set of parameters and a knowledgebase. The sets of parameters need to be developed so that they contribute to the uncertainty of the activities of ABC methods. The parameters can be correlated to site-specific data in order to develop a knowledgebase that enables obtaining results with respect to the site-specific conditions of a given site. The sets of parameters and parameter correlations with site-specific data for ABC methods will be described in Chapter 6.

Uncertainty of activity and probability of failure concept

Predefined sets of procedures are needed for the agents to perform actions during the simulation. For example, consider the organizational model developed by Du and El-Gafy (2012) based on agent-based modeling methodology in order to analyze the impact of managerial strategies on a project. The model uses flowcharts and equations to define the actions. Working mistakes made by the agents based on the managerial strategy are considered to assess the impact on a project. The impact is measured in terms of project quality and is calculated using Eq. 5-1. If the agents do not make mistakes during the project, the project quality will be 100%.

$$\text{project.quality}\ (\%) = 100 - \frac{\sum \left(\text{task}_i.\text{amount} \times \text{task}_i.\text{mistake} \right)}{\text{project.size}} \tag{5-1}$$

where project.quality is the project quality measured as a percentage, $task_i$.amount is the duration of the task i in hours, $task_i$.mistake is the percentage of task i which is considered a mistake made by the agents while completing task i, and project.size is the total duration of the project in hours.

In this example, each action includes counting the mistakes made by the involved agents during a particular task and storing the results. Eq. 5-2 is used for each action of a task.

$$\text{task.mistake}\left(\mathrm{t}_{\mathrm{n+1}}\right) = \text{task.mistake}\left(\mathrm{t}_{\mathrm{n}}\right) + \text{agent}(k)\text{.mistake}\left(\mathrm{t}_{\mathrm{n}}\right) \tag{5-2}$$

where t_n is the n^{th} time step during the task, and k is the agent number among several agents performing the task.

The initial task.mistake count in Eq. 5-2 is set to 0; if an agent at t_n makes a mistake, the task's mistake count at t_{n+1} is incremented by 1. A similar process is followed during the entire duration (T) of a task. Agents make mistakes based on their attributes that are dependent on the managerial strategy. At the end of the task, the total task.mistake is converted to a percentage using Eq. 5-3 and is used in calculating the project.quality.

$$\text{task.mistake (\%)} = \frac{\text{task.mistake}}{T} \times 100 \tag{5-3}$$

Similar process modeling can be implemented in developing the agent-based models for the ABC methods. Considering the aforementioned goal of the decision-making framework, the predefined set of procedures must allow the calculation of the uncertainties of the activities in the ABC methods. As mentioned earlier, an activity needs to be associated with parameters that contribute to the uncertainty of the activity. The uncertainty of an activity can be calculated based on the parameter probability of affecting project performance (i.e., uncertainty values of the parameters). An activity of the ABC methods is related to the associated parameters such that if at least one parameter has high probability of affecting the project performance, the activity will have a high impact on project performance. The parameters affect the project performance due to specific constructability and durability of a bridge. This relationship between an activity and the associated parameters is analogous to the relationship between a component and its failure modes in reliability engineering. The reliability engineering concept that deals with determining the component reliability based on the failure modes is known as the *Competing Risk Case* of determining component reliability.

In reliability engineering of determining a system reliability, the probability of a system working (i.e., reliability) at a time is considered as the probability that all the associated components are working at that time (Tobias and Trinidade 2012). The components of a system can be connected either with a parallel connection or a series connection. Parallel system consists of a number of components, and it can operate until the last of its components fails. The probability that a parallel system fails (i.e., probability of failure) at a time is the probability that all components fail by that time. On the other hand, a series system is a system with a number of components and all components must function for the system to function properly. The system fails when one component fails, i.e., the first failure causes the failure of the system. The Competing Risk Case analyzes a single component with several failure modes instead of a system with several components (Tobias and Trinidade 2012). The Competing Risk Case uses the series system equations to calculate the probability of failure of a component. The uncertainty is equal to the probability of failure $P(\overline{E})$, and is related to the probability of success or reliability $P(E)$, as $P(\overline{E}) = 1 - P(E)$. As mentioned earlier, the uncertainty of an activity of ABC methods can be calculated using the Competing Risk Case, wherein the activity is analogous to a component, and the associated parameters are analogous to failure modes. The schematic of an activity and the associated parameters as a series system is shown in Figure 5.6.

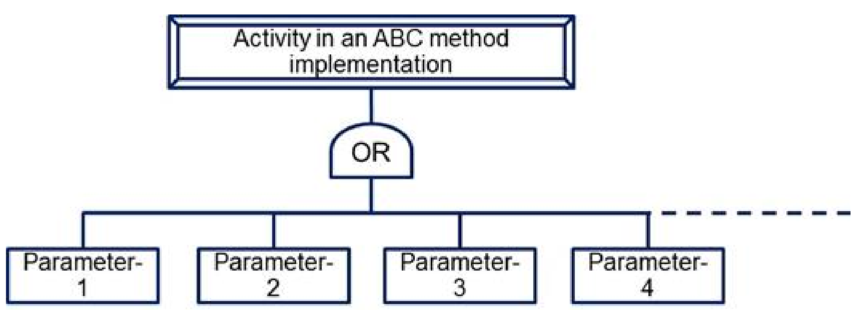


Figure 5.6. Schematic of an activity and the associated parameters as a series system

Thus, the uncertainty (probability of failure, P_f) of an activity that is associated with a number of "independent" parameters can be calculated using Eq. 5-4 as shown below. However, if the associated parameters of an activity are "dependent," then Eq. 5-4 cannot be used.

$$\left(P_f\right)_{\text{activity}} = \left(1 - \prod_{i=1}^{n}\left(1 - P_{fi}\right)\right) \quad \in \{0,1\} \tag{5-4}$$

where $(P_f)_{activity}$ is the uncertainty of an activity, P_{fi} is the i^{th} parameter probability of affecting the project performance, and n is the number of "independent" parameters associated with the activity.

To deal with the dependent component failures of a system in calculating the probability of failure of the system, Fleming (1974) introduced the basic Beta-Factor model. The Beta-Factor model describes the correlation between the independent component failures and dependent component failures of a system, and is one of the most widely used models for calculating dependent failure (Borcsok and Holub 2008; Lees 2012). In the Beta-Factor model, the factor β is calculated as the ratio of the dependent *failure rate* to the total failure rate as shown in Eq. 5-5. In Eq. 5-5, the total failure rate is expressed as the sum of independent failure rate (h_i) and dependent failure rate (h_d).

$$\beta = \frac{h_d}{h_i + h_d} \tag{5-5}$$

In the reliability engineering, the failure rate of a system at a given time (t) is estimated using Eq. 5-6 (Tobias and Trinidade 2012).

$$\widehat{h}(t) = \frac{1}{\Delta t}\left(\frac{\text{Number of component failures in the interval } \Delta t}{\text{Number of working components at the time } t}\right) \tag{5-6}$$

Incorporating Eq. 5-6 in Eq. 5-5 and assuming the same interval (Δt) and time (t) for estimating dependent and independent component failure rates, Eq. 5-5 is reduced to Eq. 5-7 as shown below.

$$\beta = \frac{\frac{1}{\Delta t}\left(\frac{F_d}{S}\right)}{\frac{1}{\Delta t}\left(\frac{F_i}{S}\right) + \frac{1}{\Delta t}\left(\frac{F_d}{S}\right)} = \frac{F_d}{F_i + F_d} \tag{5-7}$$

where F_d is the number of dependent component failures in the interval Δt, F_i is the number of independent component failures in the interval Δt, and S is the total number of working components (survivors) at time t.

The factor β is utilized in calculating the probability of failure of a series system that is associated with a number of dependent and independent components, as shown in Eq. 5-8 (Billinton and Allan 1983; Borcsok and Holub 2008; Lees 2012). Eq. 5-8 is applicable when the system is associated with at least one independent component along with dependent components.

$$\left(P_f\right)_{\text{system}} = 1 - \left(1 - \beta\right) \prod_{i=1}^{n} \left(1 - P_{fi}\right) \tag{5-8}$$

where $(P_f)_{system}$ is the probability of failure of the series system, P_{fi} is the probability of failure of component i in the system, and n is the total number of dependent and independent components in the system.

Therefore, the uncertainty of an activity of ABC methods that is associated with a number of dependent and independent parameters can be calculated using Eq. 5-9. Eq. 5-9 incorporates the Beta-Factor model, wherein a factor β is used to quantify the contribution of dependent parameters to the uncertainty of an activity [$(P_f)_{activity}$] that is associated with a number of dependent parameters (N_D) and a number of independent parameters (N_I). The β is calculated as a ratio of the number of dependent parameters (N_D) to the total number of parameters ($n = N_D + N_I$) associated with an activity. Here, the parameter probability of affecting the project performance of each parameter (P_{fi}) is taken into account and prorated using the factor $1-\beta$.

$$\left(P_f\right)_{\text{activity}} = \left(1-\left(1-\beta\right)\prod_{i=1}^{n}\left(1-P_{fi}\right)\right) \quad \in \{0,1\}$$

$$where: \;\; \beta = \frac{N_D}{n} = \frac{N_D}{N_D+N_I}; \qquad N_I > 0 \tag{5-9}$$

For example, consider the activity "Design superstructure for PBES" that is associated with the parameters *Span Length, Beam Spacing, Skew, Underclearance, Aesthetic Requirements, and Geometric Complexity* as shown in Figure 5.7. The activity and the associated parameters in Figure 5.7 are considered a series system of reliability engineering theory. This is because if one of the parameters such as Span Length has a high probability of affecting the project performance (e.g., project cost) based on the site-specific conditions and characteristics of a proposed superstructure system, the activity will have a high impact on the project performance. This is analogous to the aforementioned Competing Risk Case that implements the series system principles for calculating component reliability.

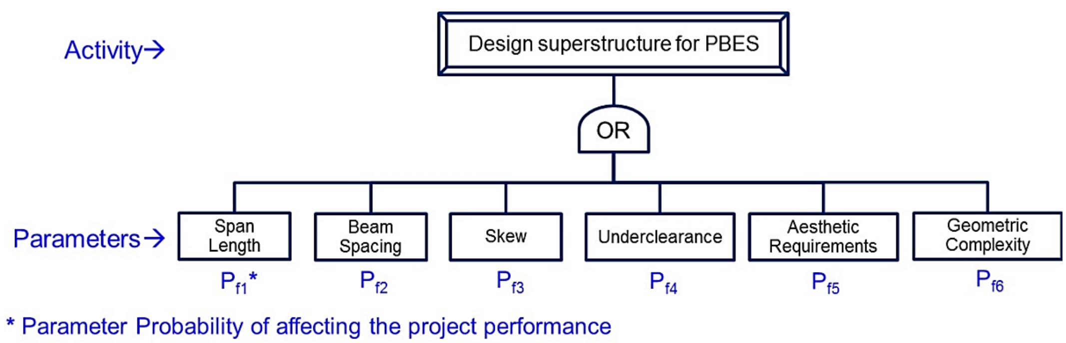


Figure 5.7. Example activity and associated factors as a series system

In Figure 5.7, the parameters Beam Spacing and Underclearance are dependent of the Span Length, whereas the other parameters are independent. As the Span Length of a superstructure increases, the Beam Spacing and Underclearance decreases (PCI 2011). Assume the six parameters shown in Figure 5.7 were assigned the following probabilities of affecting the project performance: $P_{f1} = 0.40$, $P_{f2} = 0.05$, $P_{f3} = 0.20$, $P_{f4} = 0.05$, $P_{f5} = 0.01$, and $P_{f6} = 0.20$. In this case, the uncertainty of the activity [$(P_f)_{activity}$] is calculated as shown below using Eq. 5-9.

$$\beta = \frac{N_D}{N_D + N_I} = \frac{3}{3+3} = 0.5$$

$$\begin{aligned}\left(P_f\right)_{\text{activity}} &= 1-(1-\beta)\left[\left(1-P_{f1}\right)\left(1-P_{f2}\right)\left(1-P_{f3}\right)\left(1-P_{f4}\right)\left(1-P_{f5}\right)\left(1-P_{f6}\right)\right] \\ &= 1-(1-0.5)\left[(1-0.4)(1-0.05)(1-0.2)(1-0.05)(1-0.01)(1-0.2)\right] \\ &= 0.83\end{aligned}$$

Alternatively, if all the parameters associated with an activity are independent, then Eq. 5-4 can be used, wherein the factor β is not used for calculating the uncertainty of the activity.

Uncertainty correlation with measures of project performance

The parameter probability of affecting the project performance (termed as uncertainty rating) depends on site-specific conditions and the ABC method and its associated superstructure system. Thus, the uncertainty of an activity depends on the respective alternative (ABC method and its associated superstructure system). Upon calculating the uncertainty of the activities, the impact on the project performance due to the alternative can be identified. This requires defining a relationship between the uncertainty of an activity and the measures of project performance. Qualitative uncertainty ratings for the parameters can be obtained for each alternative based on the possible site-specific conditions and potential superstructure systems. The details of potential superstructure systems for ABC methods are provided in the next section. Nevertheless, quantitative values are needed to calculate the uncertainty of activities. In order to define the relationship between the uncertainty of an activity and the measures of project performance and to quantify the uncertainty ratings of the parameters, conducting risk assessment of the ABC projects is essential. However, risk assessment of ABC projects is not the focus of this dissertation. Therefore, the available uncertainty/risk estimates for ABC projects developed by Golder Associates Inc. (2014) are utilized. The correlations presented in Table 5.1 help in identifying the impact of the uncertainty of an activity on project cost and construction duration.

Table 5.1. Effect of Risk on Measures of Project Performance (Source: Golder Associates Inc. 2014)

Uncertainty Rating	Range of Uncertainty Value	Range of Cost or Duration Change (%)
Very High	0.7 to 1.0	10 to 25
High	0.4 to 0.7	6 to 10
Medium	0.2 to 0.4	3 to 6
Low	0.05 to 0.2	1 to 3
Very Low	0.0 to 0.05	0 to 1

Considering the above correlations for ABC projects, the impact on project performance can be estimated in terms of percentage change in cost and duration, which can be used to compare the alternatives. The use of correlations can be explained by considering the previous example of the activity of 'Design superstructure for PBES.' In the example, the uncertainty of the activity was calculated as 83%. From Table 5.1, the 0.83 uncertainty value corresponds to a very high uncertainty rating (Table 5.1 row-1). Thus, the respective range of cost and duration change (i.e., 10% to 25%) can be used to obtain statistical inferences of the impact of the activity on project cost and construction duration.

The correlations presented in Table 5.1 can also be used to quantify the qualitative uncertainty ratings of the parameters associated with the activities of ABC methods. The qualitative uncertainty ratings of the parameters and their quantification are described in Chapter 6, which assists in calculating the uncertainty of activities.

Superstructure systems for ABC methods

As described in Chapter 1, superstructure systems need to be evaluated along with ABC methods. Thus, potential superstructure systems need to be specified for each ABC method in order to perform the evaluation. For this purpose, recommendations for elements in superstructure systems are developed in this section.

In April 2004, Ralls et al. (2005) conducted a scanning tour covering five countries under the sponsorship of the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). The purpose was to study prefabricated elements that can be utilized in ABC projects. After the study, several research projects were initiated to develop and standardize new prefabricated superstructure elements for use in ABC projects (Graybeal 2009). The prefabricated superstructure elements identified from literature, which are used in ABC projects, are shown in Figure 5.8.

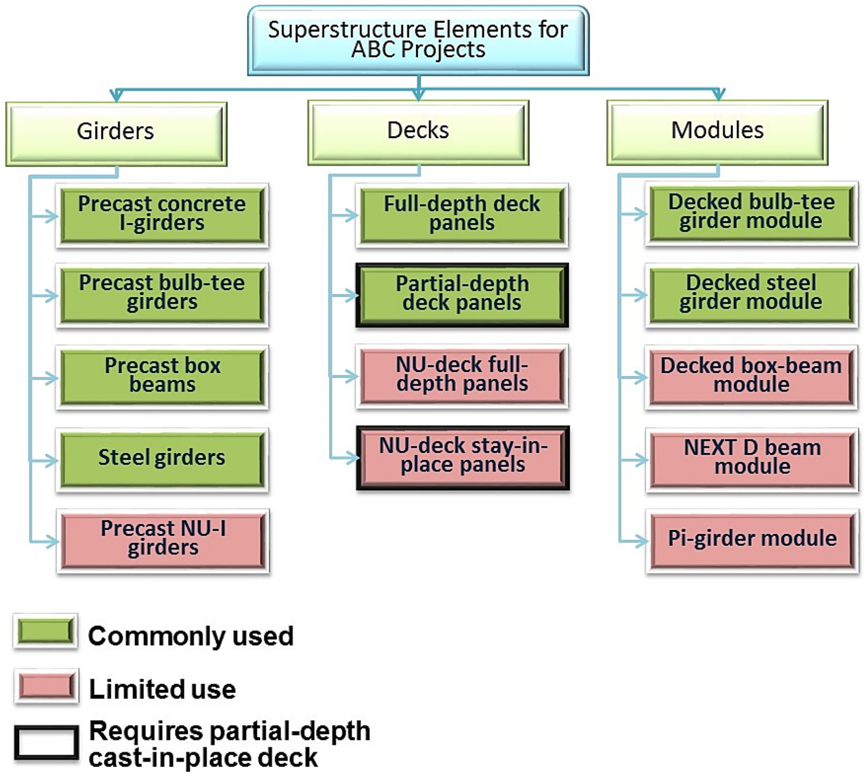


Figure 5.8. Superstructure elements to use with ABC methods

The girders and full-depth deck panels shown in Figure 5.8 represent a superstructure system after assemblage at the site. However, the girders and partial-depth deck panels require cast-in-place concrete to complete the deck after assemblage at the site. The modules shown in Figure 5.8 are the prefabricated girder and deck integrated elements that are assembled at the site to represent the superstructure system. Mostly, the modules used in ABC projects require minimal connection details to complete the superstructure system. The elements are connected through field cast joints using high performance materials. The prefabricated elements for superstructure systems presented in Figure 5.8 are further categorized based on their use in ABC projects. The use categories are color coded as *commonly used* and *limited use*. The elements listed under the limited use category have either been implemented no more than twice or are still under development.

The maximum span length of the standard prefabricated girder sections is given in the PCI Bridge Design Manual (PCI 2011) and the DOT documents (MDOT 2014; UDOT 2014). The suitable standard sections for the required span can be identified from these manuals. However, in addition to the span limitations, the weight of prefabricated elements for transport and placement is a consideration. The FHWA (2012) lists the transport weight and size limitations as one of the major concerns raised by the DOTs during regional peer-to-peer exchanges. The weight issue is addressed in the MDOT Bridge Design Manual (MDOT 2014) Section 7.01.19, which recommends limiting the weight of prefabricated elements to 80 kips (40 tons) for safe handling using conventional equipment. Alternatively, the ABC toolkit developed under the SHRP2 R04 project (SHRP2 2012) recommends limiting weights to 160 kips (80 tons). Where site conditions allow, SHRP2 (2012) suggests using a prefabricated bridge element up to 250 kips (125 tons). Increased weight limits allow building longer spans and wider bridges to further reduce construction duration. However, weight limits need to be reviewed after selecting the girder types because the girder weights may exceed the limits due to the span length.

In order to develop the recommendations of elements for superstructure systems, typical cross-sections and span lengths of superstructure elements used in ABC projects were compiled from reviews of bridge plans, recent demonstration projects, and input from project engineers directly involved in ABC projects (See Appendix A). Reviewing the continuity details, durability performance, familiarity of stakeholders, constructability challenges, and other limitations based on site-specific conditions, the recommended superstructure elements for use with ABC methods are the following:

- Precast concrete (PC) I-girders: These girders are recommended for use with ABC methods because their formwork is widely available at precast plants. The depth of AASHTO PC I-girders ranges from 28 in. to 54 in., and their span ranges up to 114 ft. In addition to AASHTO standard sections, the state-specific PC I-girder sections are available to accommodate longer spans. For example, the Michigan 1800 girder could span up to 145 ft. Moreover, the designers, fabricators, and contractors are familiar with these girders, and past performance data is available that could be utilized in various assessment procedures.

- Precast bulb-tee girders: These girders are recommended for use with ABC methods because there is a significant amount of research data available from the FHWA and various state DOTs. The sections are structurally efficient and cost effective. For example, after evaluating available precast bulb-tee girders in the U.S., the Utah DOT produced standardized girders with a depth ranging from 42 in. to 98 in. and spans ranging up to 186 ft. These girders can also be spliced with the use of post-tensioning to extend up to a span of 220 ft. The formwork of these girders can also be utilized for the decked bulb-tee girder.

- Precast box beams: Box beams are classic elements and are recommended for use with ABC methods because of several inherent advantages. The box beams are used for spread box-beam systems or adjacent box-beam systems. Many state DOTs, prefabricators, and contractors are familiar with the superstructure systems. Because of the large inventory, the past performance data is available going back to the 1950s. Although the adjacent box-beam system has reflective deck cracking potential, the system is widely specified because of a lack of choices for sites with underclearance limitations. Both spread box-beam systems and adjacent box-beam systems require cast-in-place decks.

- Steel girders: A superstructure system with steel girders is recommended because of the stiffness of the section, simple fabrication, and prefabricators and contractors familiarity with the girders. The system is more suitable for bridges in non-corrosive environments. Steel girders with cast-in-place deck or full-depth deck panels have been typically used in past ABC projects (FHWA 2015).

- Full-depth deck panels: A full-depth deck panel system with transverse pre-stressing and longitudinal post-tensioning is recommended for use with ABC methods. This recommendation is based on the superior durability performance of the deck. Transverse pre-stressing provides crack control and allows the use of thinner deck panels and wider spacing of supporting girders. Longitudinal post-tensioning can be designed so that the deck remains under compression under all service load conditions, resulting in a durable system. Moreover, full-depth deck panels have been implemented in several ABC projects, from which lessons-learned reports are available. Additionally, designers and precast plants have experience with the system.

- Decked bulb-tee girder module: The superstructure system with these modules has been implemented in several projects in Florida, New York, Utah, and a few states in the New England region. UDOT (2014) standardized this module for spans up to 180 ft. The superstructure is formed by placing the units next to each other and providing a connection for moment and shear transfer. The superstructure can be designed with or without an overlay. However, an overlay is recommended for durability. The precast forms for the precast bulb-tee girders could also be utilized to cast the decked bulb-tee girder elements.

- Decked steel girder module: The superstructure system with these modules is recommended because it is non-proprietary, fabrication is simple, and prefabricators and contractors are familiar with steel girders. The system is more suitable for bridges in non-corrosive environments. This system requires a wearing surface to enhance durability after assemblage at the site.

- Decked box-beam module: The superstructure system with these modules is recommended based on recent positive experiences from contractors in Michigan (Aktan et al. 2014a). The superstructure can be used with or without an overlay. Again, an overlay is recommended for durability. The precast forms for casting the adjacent box-beams could be utilized to cast the decked box-beam elements. Precast plants and contractors often have experience with the precast box-beams and therefore prefabrication of the decked configuration will not be challenging.

The above recommendations and information from past ABC projects can be used to specify potential superstructure systems for ABC methods to represent the alternatives for evaluation. Potential superstructure systems for PBES, SPMT move, and SIBC can be specified for a particular region, which will be discussed in Chapter 6.

Simulation methodology

After establishing a mathematical model such as an agent-based model for ABC method implementation using the concepts discussed earlier in this chapter, simulation of the processes in the model is required in order to generate an output. The agent actions and interactions can be executed using a procedural programming script for computer simulation, such as VBA for Excel®. However, a methodology is required for generating output that quantifies the impact of the uncertainty of activities on the project performance (in terms of project cost and construction duration).

The key to deliver an ABC project effectively is to identify the ABC method and the associated superstructure system that introduces minimal risk on the project. The two best techniques widely used to quantify the impact of uncertainties/risks on a project are the Programe Evaluation and Review Technique and Monte Carlo Simulation (Wyrozebski and Wyrozebska 2013). Both techniques introduce the aspect of probability to the project planning. Programe Evaluation and Review Technique originally uses beta distribution to estimate the duration of a process (t_e) based on optimistic duration (o), most probable duration (m), and pessimistic duration (p) as shown in Eq. 5-10. The respective standard deviation (σ_{te}) is calculated using Eq. 5-11.

$$t_e = \frac{o + 4m + p}{6} \tag{5-10}$$

$$\sigma_{t_e} = \frac{p - o}{6} \tag{5-11}$$

Based on the estimated times of individual processes, the expected duration of the project (T_e) is calculated. Then, the Z-value statistic is calculated based on T_e and specified duration (T_s) using Eq. 5-12.

$$Z = \frac{T_s - T_e}{\sqrt{\sum \sigma_{t_e}{}^2}} \tag{5-12}$$

Using the Z-value statistic, the probability of completing the project by the specified duration is computed using standard statistical tables. Nevertheless, this technique limits the options of the project to a single case based on the expected value and associated probability of achievement (Wyrozebski and Wyrozebska 2013).

On the other hand, the Monte Carlo Simulation is based on a probabilistic approach rather than a deterministic approach that provides discrete values and less flexibility in the decision-making process. Some commonly used probability distributions for analyzing uncertainties with Monte Carlo Simulation are normal, uniform, triangular, and discrete distributions (Walls and Smith 1998). The normal, uniform, and triangular distributions are smooth distributions and establish the probability symmetrically within the defined range with varying concentration towards the center. In this case, a process can be assigned a specific distribution based on the statistical analysis of historical data and identifying a best-fit distribution type or judgment from experts. Monte Carlo Simulation is considered a more sophisticated and accurate method of assessment to incorporate uncertainty as it is based on numeric data gathered by running multiple simulations using computers. The Project Management Body of Knowledge (PMBOK®) (PMI 2013) advocates the use of Monte Carlo Simulation to quantify the impact of uncertainties on a project. Monte Carlo Simulation helps in removing any kind of project bias regarding the selection of alternatives while planning for uncertainties. The technique helps to forecast the likely outcome of a project due to the associated uncertainties and thereby assists in informed decision-making (Marom 2010). Monte Carlo Simulation includes determining the impact of the uncertainties by running simulations to identify the range of possible outcomes for a number of scenarios. Random sampling is performed by varying uncertainty inputs to generate the range of outcomes and respective confidence measures. Sampling is typically performed by establishing a mathematical model and running simulations using that model.

The Monte Carlo Simulation can be understood using a simple example of a project involving the development of an eLearning module presented by Marom (2010). The example project consists of three processes: (1) writing content, (2) creating graphics, and (3) integrating multimedia elements. The duration estimates for the processes can be inserted either as a probability distribution or as a range of values. Marom determined the best case, most-likely, and worst-case duration estimates for each of the processes as shown in Table 5.2. When three point estimates are available, the triangular distribution is considered more appropriate for specifying the input.

Table 5.2. Estimates for Duration of Processes (Source: Marom 2010)

Process	Best-case duration	Most likely duration	Worst-case duration
Writing content	4 days	6 days	8 days
Creating graphics	5 days	7 days	9 days
Integrating multimedia elements	2 days	4 days	6 days
Total duration	**11 days**	**17 days**	**23 days**

Monte Carlo Simulation for this example includes randomly selecting input values for the processes to calculate the total duration in each run. Here, the summation of all the process durations represents the mathematical model for project evaluation. From Table 5.2, it can be observed that the project can be completed in anywhere between 11 to 23 days. Marom performed 500 simulations using the Monte Carlo Simulation. Table 5.3 summarizes the sample outcome from the simulations.

Table 5.3. Monte Carlo Simulation Example Outcome (Source: Marom 2010)

Total duration (days)	Number of times the simulation result was less than or equal to the respective total duration	Percentage of simulation runs with the result less than or equal to the respective total duration
11	5	1%
12	20	4%
13	75	15%
14	90	18%
15	125	25%
16	140	28%
17	165	33%
18	275	55%
19	440	88%
20	475	95%
21	490	98%
22	495	99%
23	500	100%

The results in Table 5.3 show the likelihood (percentage confidence) of completing the project in a particular duration. For example, the likelihood of completing the project in 19 days or less is 88% (Table 5.3 row-9). From the above analysis, it is clear that the project requires a total duration between 19 to 20 days with 90% confidence.

A Monte Carlo Simulation can be implemented if the parameters associated with the activities of ABC methods have probabilistic values. Particularly, the parameter probability of affecting the project performance has a range of values (distributed values) rather than a deterministic value. In such case, by implementing Monte Carlo Simulation the uncertainty of an activity [$(P_f)_{activity}$] can be calculated in terms of a distribution. This can be understood by considering the example of the activity "Superstructure design for PBES" shown in Figure 5.7. Suppose the probabilities of affecting the project performance for the six parameters in Figure 5.7 are obtained as normally distributed values with respective mean (μ) and variance (σ^2); e.g., $P_{f1}\sim N(\mu_1, \sigma_1^2)$, $P_{f2}\sim N(\mu_2, \sigma_2^2)$, $P_{f3}\sim N(\mu_3, \sigma_3^2)$, $P_{f4}\sim N(\mu_4, \sigma_4^2)$, $P_{f5}\sim N(\mu_5, \sigma_5^2)$, $P_{f6}\sim N(\mu_6, \sigma_6^2)$. Then, by implementing a Monte Carlo Simulation, the uncertainty of the activity can be calculated as a distribution using Eq. 5-9 and *Random Variates*. The calculation of Random Variates depends on the distribution type (Banks et al. 2010). In each run of the Monte Carlo Simulation, random numbers (R_a *and* R_b) will be generated to calculate the variate (X_i) for i^{th} parameter; thus, the variate $X_{activity}$ for the uncertainty of the activity can be calculated using Eq. 5-9 as shown below. The variates $X_{activity}$ are accumulated from several simulations and curve fitting is used to obtain the $(P_f)_{activity}$ as a distribution.

$$X_{\text{activity}} = 1-(1-\beta)\left[(1-X_1)(1-X_2)(1-X_3)(1-X_4)(1-X_5)(1-X_6)\right]$$

where: $X_i = \mu_i + \sigma_i Z_i$;

$$Z_i = \left(-\frac{\ln R_a}{2}\right)^{1/2}\left[\cos(2\pi R_b)+\sin(2\pi R_b)\right] \quad \to for\ N(\mu,\sigma^2)$$

$$R_a, R_b \to \text{independent random numbers}$$

A Monte Carlo Simulation can also be implemented to compare results from the evaluation of the alternatives (ABC methods and the associated superstructure systems). In the evaluation process using the decision-making framework, the agent-based model of each alternative can be subjected to simulation in order to allow agent interactions. From each simulation run, the range of change in the project cost and construction duration can be extracted as model outputs. The obtained outputs can be analyzed using a Monte Carlo Simulation to observe the variability in project cost and construction duration with respect to the base estimates of the alternatives. Monte Carlo Simulation can be performed using available simulation software or can be programmed using VBA for Excel®. Implementing a Monte Carlo Simulation for evaluating the alternatives includes the following:

- Obtain the ranges of change in project cost and change in construction duration for each activity by executing the agent interactions included in an alternative.
- Establish a probability distribution for project cost and construction duration based on the uncertainty of the activities in order to specify the variability.
- Select random values from the obtained ranges of percentage change in cost and duration for all the activities in the alternative. The random values are selected based on respective probability distribution in each run of the simulation.
- Update the base estimates of project cost and construction duration using the selected values in each run.
- Plot the cumulative probability charts of project cost and construction duration for the alternative using output from simulations.
- Follow a similar process for other alternatives.
- Combine charts from all the alternatives in order to assess and compare the respective impact on the project cost and construction duration.

Sample output of cost variability from a Monte Carlo Simulation is shown in Figure 5.9; the alternatives compared in this case include SIBC with steel girder system, SIBC with precast box beam system, SPMT move with steel girder system, and SPMT move with precast box beam system. The chart shown in Figure 5.9 includes the cumulative probability percentage on y-axis and project cost on x-axis. A point on a curve in the chart represents a cost and its corresponding probability of occurrence for the respective alternative. The confidence interval statistics for each alternative can be calculated from the chart, which includes lower limit, upper limit, mean, and standard deviation. The lower limit and upper limit values are inferred based on the cost variability between 0% to 100% probabilities. This provides the decision maker with a vast arena of possible inferences during his/her judgment process.

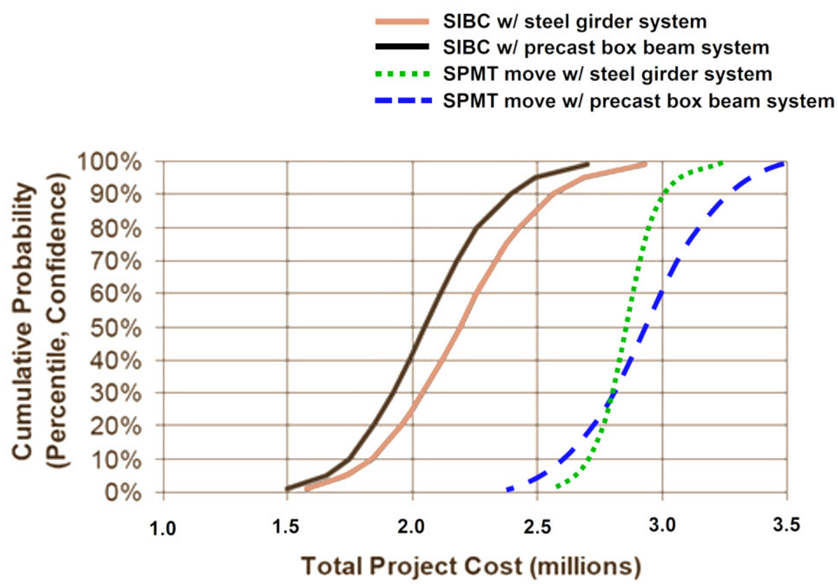


Figure 5.9 Sample result of cost variability from Monte Carlo Simulation

Summary

In this chapter, concepts are described to develop agent-based models for ABC methods and to simulate the processes within the models. Agent-based complex system characteristics considered for modeling an ABC method implementation process are also discussed. The concepts described in this chapter provide the ability to include the internal stakeholders and the activities for evaluating the ABC methods and the associated superstructure systems for a specific state/region. The ABC methods and the associated superstructure systems are termed as the alternatives.

The internal stakeholders considered for implementing an ABC method include the Department of Transportation (DOT), the designer, the contractor (general contractor), the consultants, the subcontractors, and the public. The internal stakeholders are termed as agents, and the involved operations/tasks are termed as activities. Ontology is used to represent the model of an ABC method implementation, which is one of the representations used to define an interface and a shared model for the agents. A Task-Actor-Relation Table (TART) is described in this chapter, which can be used to define the activities of an ABC method and the associated relationship among agents. TART includes the list of activities, the list of agents, and the relationship among the agents for their respective activities.

An agent needs to be associated with several node classes that enable the agent to execute processes during the agent-based model simulation. The process execution is mathematically modeled using a set of arrays. An array includes attributes that enable an agent to obtain data from another agent for an activity and calculate the impact on project cost and construction duration with respect to the activity. The information transfer among the arrays is referred to as the Array Mapping. The array representation and interaction among the agents is described using an example. From the example, it is demonstrated that each activity in an alternative needs to be associated with a set of parameters such that they contribute to the uncertainty of the activity.

Further, a predefined set of procedures is needed for the agents to perform actions (execute processes) during the agent-based model simulation. In the agent-based model of an ABC method implementation, the predefined set of procedures will allow calculating the uncertainty associated with an activity. The uncertainty of an activity is calculated by implementing the reliability engineering concept of the Competing Risk Case of determining system reliability, which considers the probability of affecting the project performance of the associated parameters. An equation to calculate the uncertainty of an activity that is associated with a number of "independent" parameters is described. If an activity is associated with a number of "dependent" and "independent" parameters, the Beta-Factor model is implemented and the corresponding equation to calculate the uncertainty is described including an example.

The available uncertainty/risk correlations for ABC projects are described in this chapter that assist in drawing statistical inferences of the impact of the uncertainty of the activities on project cost and construction duration, and comparing the results of the alternatives. The correlations also assist in quantifying the parameter probability of affecting the project performance.

Superstructure systems need to be evaluated along with ABC methods. Therefore, recommendations of elements for superstructure systems are developed and presented in this chapter. The recommendations assist in specifying potential superstructure systems for ABC methods in order to perform the evaluation. In order to develop the recommendations, typical cross-sections and span lengths of superstructure elements used in ABC projects were compiled from reviews of bridge plans, recent demonstration projects, and input from project engineers directly involved in ABC projects. The recommendations are based on a careful analysis of the continuity details, durability performance, familiarity of stakeholders, constructability challenges, and other limitations due to site-specific conditions.

Although the agent actions and interactions in the simulation of an agent-based model can be executed using a procedural programming script for computer simulation, such as VBA for Excel®, a methodology is required for generating an output that quantifies the impact of the uncertainty associated with the alternatives. The Monte Carlo Simulation technique has been selected for this purpose, as it provides results using a probabilistic approach. The significance of the Monte Carlo Simulation is described in this chapter using an example. A process is described to implement a Monte Carlo Simulation for obtaining the uncertainty of an activity that is associated with parameters having a range of values (distributed values) of respective parameter probability. Further, a process is described to implement a Monte Carlo Simulation for analyzing the impact of uncertainty associated with the alternatives on project cost and construction duration. A sample output is provided from a Monte Carlo Simulation implementation. The output illustrates the possible inferences a decision maker can make during the decision-making process.

CHAPTER VI

ABC DECISION-MAKING FRAMEWORK

Overview

The framework for evaluating Accelerated Bridge Construction (ABC) methods and the associated superstructure systems for a given site will be described in this chapter. The ABC methods considered in this research include the following: (1) Prefabricated Bridge Elements and Systems (PBES), (2) Self-Propelled Modular Transporter (SPMT) move, and (3) Slide-In Bridge Construction (SIBC). Each ABC method can be implemented for a given site using various superstructure systems (Figure 6.1). The framework will enable selecting an ABC method and an associated superstructure system that is suitable for a given site (e.g., PBES with SS-1 (Figure 6.1)). The superstructure systems constructed using the following are considered in this research: (1) prefabricated girders and deck panels, (2) prefabricated girders and cast-in-place (CIP) deck, and (3) prefabricated modules (described in Chapter 5).

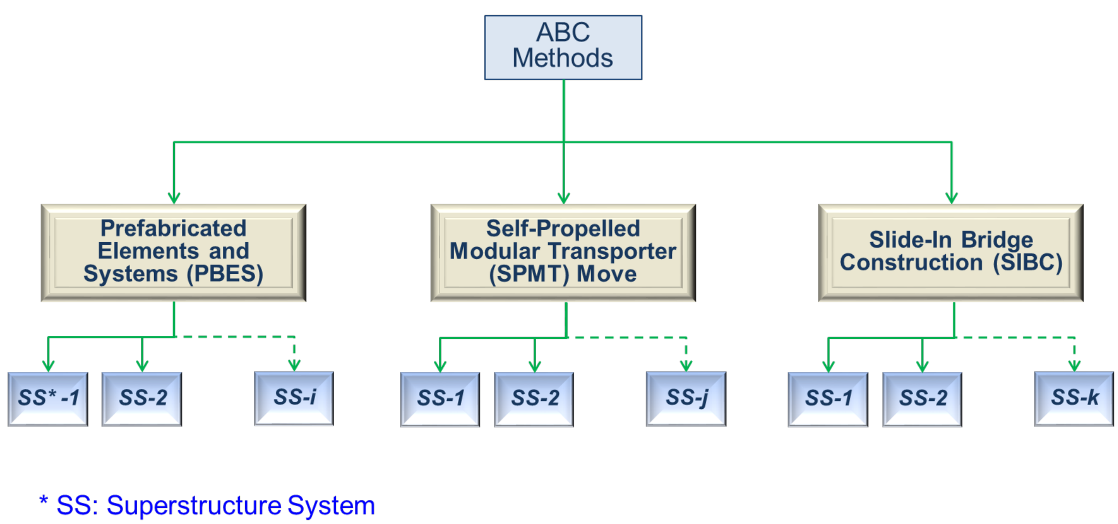


Figure 6.1. Schematic of ABC methods and associated superstructure systems

The *internal stakeholders* that work together to deliver a project using an ABC method are considered as agents. Major activities of the ABC methods will be described in this chapter. Each ABC method will be represented in terms of an ontology that provides a simulation model for the agents to interact while delivering a project using the ABC method. As described in Chapter 5, a design-bid-build procurement method is assumed for the agent interactions, wherein the owner such as the Department of Transportation (DOT) transfers the activities to the internal stakeholders such as the designer, contractors, consultants, etc. In this case, while delivering a project the internal stakeholders interact with each other particularly through the DOT's agreement. Hence, the DOT agent is considered in this framework such that it is involved with each activity wherein it assigns the activity to other agent and assesses the activity impact on project performance.

Parameters associated with activities of the ABC methods will be described in this chapter. The parameters allow assessing the impact of an activity on the project performance. The impact is measured in terms of uncertainty of an activity, i.e., the probability of an activity affecting the project performance. In order to assess a parameter effect on project performance, parameter correlations with site-specific data will be developed for a specific region. A procedure will be described in this chapter to calculate uncertainty of an activity based on the associated parameters and interactions among the agents. Finally, a statistical simulation technique will be implemented for generating the evaluation results.

The framework development methodology

As described in Chapter 5, an agent-based complex system modeling methodology is selected for addressing the ABC decision-making needs. To implement an agent-based modeling concept for formulating the decision-making framework, a series of modeling and simulation steps need to be defined. Figure 6.2 depicts the framework development methodology and the associated modeling and simulation steps.

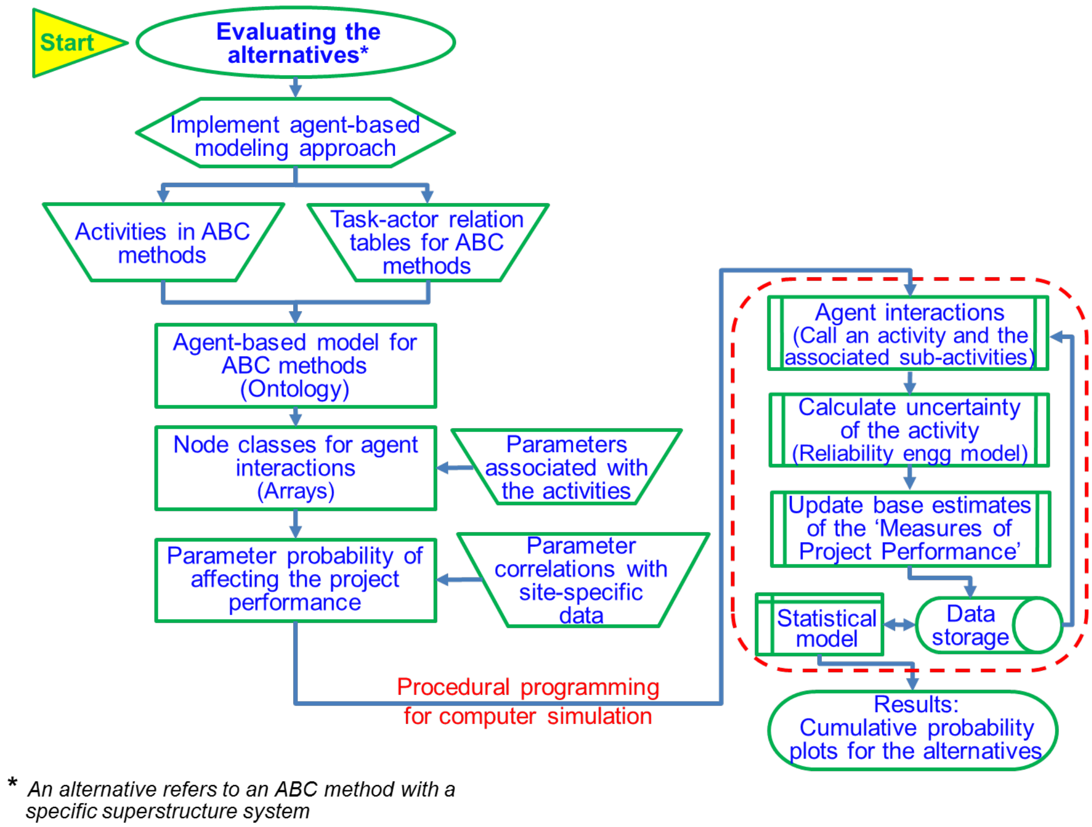


Figure 6.2. ABC decision-making framework development methodology

As illustrated in Figure 6.2, for evaluating ABC methods and the associated superstructure systems using agent-based modeling approach, activities (major-work assignments) included in the ABC methods need to be identified. Also, specific to an ABC method, stakeholder communication/coordination for the activities need to be identified and represented in terms of task-actor-relation table. The above steps enable modeling an agent-based model for the ABC methods that facilitates performing simulations.

In order to mathematically allow the agents to request and obtain data based on respective activities, node classes are needed. A node class is represented in the form of an array, and is associated with a set of parameters based on the activity. Thus, as illustrated in Figure 6.2, parameters associated with the activities need to be defined along with the node classes. The parameters contribute to uncertainty of an activity based on respective parameter effect on the project performance. A few of these parameters include sub-parameters that are associated with a set of a sub-activities. The sub-parameters contribute to uncertainty of a sub-activity that is also used in calculation of uncertainty of the activity.

Next, the parameter probability of affecting the project performance is considered in order to quantify a parameter or sub-parameter effect on project performance. As illustrated in Figure 6.2, parameter correlations with potential site-specific conditions are developed for obtaining the parameter probability values. In order to develop the correlations, potential superstructure systems for each ABC method need to be considered based on the recommended superstructure elements listed in Chapter 5. Also, the viewpoint of internal stakeholders involved with ABC projects of a region need to be understood for developing the correlations. The parameter correlations provide a knowledgebase for the framework, and allow evaluating the alternatives with respect to the site-specific conditions. In this study, the correlations are developed using information presented in past ABC project documentation obtained from FHWA (2015a), and in the ABC workshop report by Aktan et al. (2014a).

After the modeling steps, simulation steps are performed as illustrated in Figure 6.2. In each step, an agent interaction is executed for an alternative based on the ontology of respective ABC method. Mathematically, an activity and the associated sub-activities are called. The agents use respective node classes (that include sets of parameters) in order to calculate uncertainty of the activity. Array Mapping is utilized in the process. Uncertainty of the activity is calculated using the reliability engineering equations that are described in Chapter 5. Based on the uncertainty value, the base estimates of the *measures of project performance* (such as project cost and construction duration) are updated and stored with respect to the activity of the alternative. A similar process is followed for all the agent interactions associated with the alternative. The stored values are analyzed using a statistical model in order to develop cumulative probability charts of the measures of project performance. The simulation steps are followed for all the alternatives and cumulative probability charts are developed. The charts provide the variability in the measures of project performance with respect to the base estimates. The variability will be because of the uncertainty of respective ABC method and the associated superstructure system based on the site-specific conditions.

Agent-based model for ABC methods

ABC methods will be represented using ontologies in order to obtain a standard interface for the internal stakeholders (agents) to interact during a project. The standard interface depicts an agent-based model that facilitates performing simulations. This section presents the development of ontologies for the ABC methods. In order to develop the ontologies, ABC activities and networks that depict the communication among the agents will be defined in this section.

ABC methods and related activities

The ABC methods considered are PBES, SPMT move, and SIBC. The activities included in each of these methods are documented after reviewing past ABC projects listed in the FHWA (2015b) database, and are presented in Appendix B. Major activities of the ABC methods are selected (from Appendix B) for the framework considering their significance in the ABC decision-making. Major activities of PBES selected for the framework are listed in Table 6.1. PBES also includes the activities of demolition of existing structure, construction of approaches, and finishing of punch list items; however, these particular activities are not considered because they are common for the ABC methods, and hence, they are insignificant in the evaluation. Using a similar thought process, major activities of other ABC methods are selected for the framework.

Table 6.1. Major Activities of PBES Implementation

Label	Activity
1	Design superstructure
2	Transport the elements
3	Close the facility carried for traffic
4	Repair/Construct permanent substructure on existing alignment
5	Erect the elements
6	Connect the elements (Connection details)

The major activities of SPMT move are listed in Table 6.2. From the past ABC projects, it is identified that while implementing SPMT move the substructure is preferably repaired/constructed before demolishing the old bridge. In such case, the bridge demolition is performed soon after closing the facility carried and feature intersected for traffic during the ABC window (typically a weekend duration).

Table 6.2. Major Activities of SPMT Move Implementation

Label	Activity
1	Design superstructure
2	Prepare staging area
3	Construct superstructure at staging area
4	Repair/Construct permanent substructure on existing alignment
5	Close the facility carried and feature intersected for traffic
6	Prepare travel path (Excavation/placing level pad)
7	Jack and move the superstructure to permanent substructure in accordance with special provisions

The SIBC can be implemented using one of the following cases:

1) Case-1: SIBC with diverting traffic on new superstructure while old bridge is demolished and new substructure constructed. In this case, full-width or part-width of the new superstructure can be used for traffic diversion and is termed *temporary run-around*. This case is generally implemented when the existing substructure cannot be reused and the facility carried cannot be closed to traffic for a long duration.
2) Case-2: SIBC without traffic diversion on new superstructure. In this case, the facility carried is completely closed to traffic while the old superstructure is demolished and the existing substructure is repaired. This case is implemented only if the existing substructure can be reused with minor repairs or improvements.
3) Case-3: SIBC with sliding of both old and new superstructures. This case is implemented only if the existing substructure can be reused with minor repairs or improvements, and demolishing the old superstructure on existing alignment is a concern.

The major activities of SIBC with case-1, case-2, and case-3 are listed in Table 6.3, Table 6.4, and Table 6.5, respectively. In SIBC case-1 and case-3, apart from the listed activities, the facility carried is completely closed to traffic for a limited duration while moving the superstructure. This is considered a minor activity and therefore, it is accounted by including relevant parameters for the major activities (parameters associated with the major activities are presented in the next section under *Parameters Associated with Activities*).

Table 6.3. Major Activities of SIBC with Diverting Traffic on New Superstructure (Case-1)

Label	Activity
1	Design superstructure
2	Construct temporary substructure
3	Construct superstructure on temporary substructure
4	Construct approaches for temporary run-around
5	Route traffic onto temporary run-around
6	Construct permanent substructure on existing alignment
7	Jack and move the superstructure to permanent substructure in accordance with special provisions

Table 6.4. Major Activities of SIBC without Traffic Diversion on New Superstructure (Case-2)

Label	Activity
1	Design superstructure
2	Construct temporary substructure
3	Construct superstructure on temporary substructure
4	Close the facility carried for traffic
5	Repair permanent substructure
6	Jack and move the superstructure to permanent substructure in accordance with special provisions

Table 6.5. Major Activities of SIBC with Sliding of both Old and New Superstructures (Case-3)

Label	Activity
1	Design superstructure
2	Construct temporary substructure on both sides of existing alignment
3	Construct superstructure on temporary substructure
4	Jack and move the old superstructure to temporary substructure
5	Repair permanent substructure
6	Jack and move the new superstructure to permanent substructure in accordance with special provisions

Defining agents for ABC methods

Internal stakeholders involved with delivering a project using an ABC method are selected based on the activities and review of past ABC projects from FHWA (2015b) database. A task-actor-relation table (TART) enables defining the relation among the stakeholders (agents) for the activities. As mentioned earlier, the DOT agent (i.e., the owner) directs the activities to other agents.

Considering the activities listed in Table 6.1, the agents selected for PBES implementation include (1) DOT, (2) Designer, (3) Contractor, (4) Prefabricator, (5) Geotechnical Consultant, and (6) Public. The TART for PBES is developed and shown in Figure 6.3. Figure 6.3 shows the list of the PBES activities in the left column and the list of the agents in the top row. The agents involved with a certain activity are marked using an 'x' and the communication network among the agents for the activity is shown using arrows in Figure 6.3.

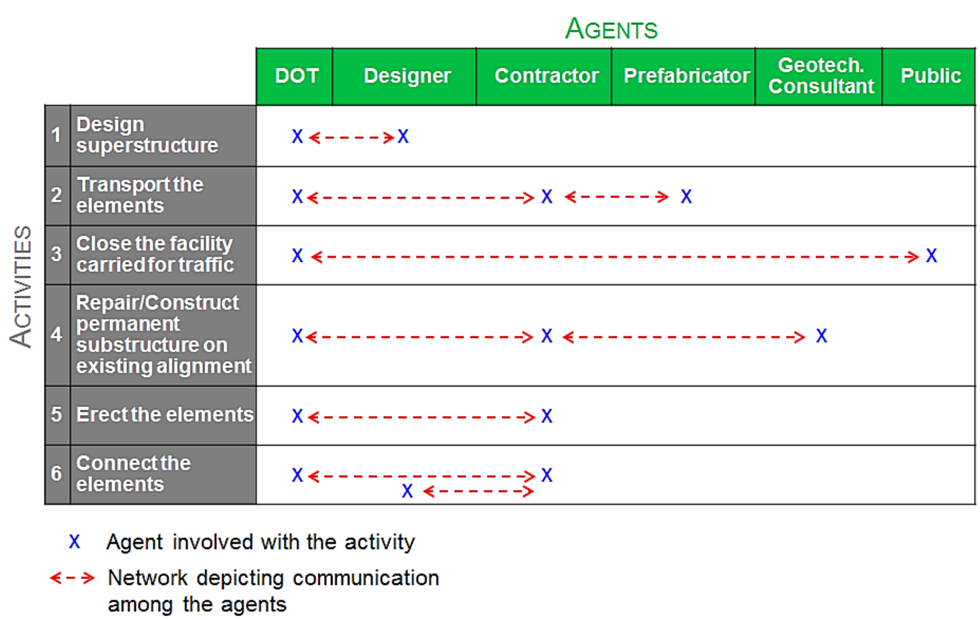


Figure 6.3. Task-actor-relation table for PBES implementation

Considering the activities listed in Table 6.2, the agents selected for SPMT move include (1) DOT, (2) Designer, (3) Contractor, (4) Prefabricator, (5) SPMT Subcontractor, (6) Geotechnical Consultant, (7) Utility Relocation Consultant, and (8) Public. Similarly, considering the activities listed in Table 6.3, Table 6.4, and Table 6.5, the agents selected for SIBC include (1) DOT, (2) Designer, (3) Contractor, (4) Prefabricator, (5) Slide Subcontractor, (6) Geotechnical Consultant, (7) Utility Relocation Consultant, and (8) Public. The TARTs for SPMT move and SIBC are provided in Appendix C.

Ontologies of ABC methods

Ontologies provide a standard interface for the agents to interact and generate results during a simulation. The ontology of an ABC method describes the agents and the associated interactions required for the activities in the ABC method. The ontology of PBES is developed using the activity labels shown in Table 6.1 and the communication network shown in Figure 6.3. The ontology of PBES is shown in Figure 6.4. In Figure 6.4, the DOT agent is accompanied by secondary agents (DOT groups) who continuously communicate with the DOT agent for keeping track of project performance. The DOT groups involved with an ABC method depend on the activities. However, as described in Chapter 5, the DOT agent and the DOT groups are considered one agent for the framework. For the simulation of PBES implementation, an activity is selected and the respective agents interact following the network shown in Figure 6.4. As shown in Figure 6.4, for the activity-1 (refer to activity label) the DOT agent interacts with Designer agent and obtains results. Similarly, it interacts with Public agent for activity-3 and obtains results. For the activities 2, 4, 5, and 6, the DOT agent interacts with Contractor agent who consequently interacts with other agents to obtain required data in order to provide results to the DOT agent. Using a similar format, the ontologies of SPMT move and SIBC are developed and provided in Appendix C.

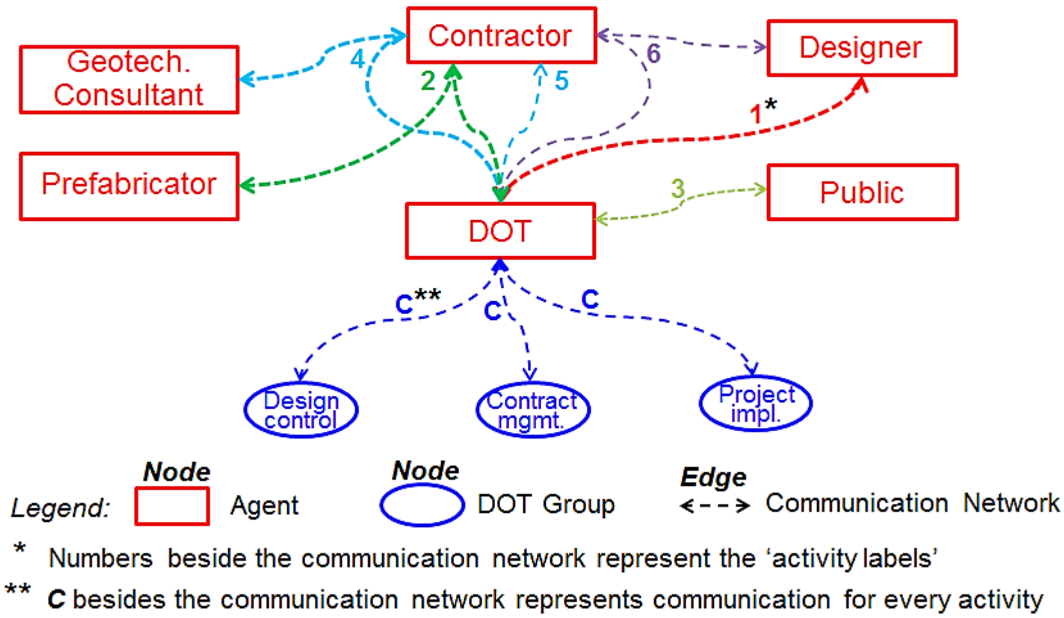


Figure 6.4. Ontology of PBES implementation

Node class for agent interactions

In order to mathematically execute the processes included in the agent-based model of an ABC method, the agents are assigned node classes in the form of arrays as described in Chapter 5. Multiple node classes are needed for the agents based on the processes. A node class of an agent includes attributes and a set of procedures, which enable the agent to execute a process and generate results during the model simulation.

In this study, the goal is to identify the impact of the uncertainty associated with the activities of an ABC method on the project cost and construction duration. An activity is considered to be dependent on a set of parameters and sub-activities that contribute to uncertainty of the activity. Further, the agents in the model are considered to perform the following three processes: (1) an agent evaluates the impact on project cost and construction duration due to an activity by obtaining data from other agent who will be responsible for that particular activity, (2) an agent who will be responsible for an activity evaluates the set of parameters and sub-activities associated with the activity and calculates the uncertainty of the activity, and (3) an agent who will be responsible for a sub-activity evaluates the set of parameters associated with the sub-activity and calculates the uncertainty of the sub-activity which will be used in calculating the uncertainty of the corresponding activity. Therefore, based on the array representation described in Chapter 5, the node class of the agent who performs the process-1 is represented as shown in Figure 5.3. In Figure 5.3, the node class includes the following attributes:

a) Act: Label or name of the activity for which the impact on project cost and construction duration will be evaluated
b) MnAgent: Label or name of the agent who evaluates the impact on project cost and construction duration
c) ChC%: Percentage change in cost that is obtained from other agent for the activity
d) ChD%: Percentage change in duration that is obtained from other agent for the activity
e) UpC: Updated project cost based on the percentage change in cost
f) UpD: Updated construction duration based on the percentage change in duration.

$$\begin{bmatrix} \text{Act} \\ \text{MnAgent} \\ \text{ChC\%} \\ \text{ChD\%} \\ \text{UpC} \\ \text{UpD} \end{bmatrix}$$

Figure 6.5. Node class of an agent to obtain the impact on project performance

The node class of the agent who performs the process-2 is represented as shown in Figure 6.6. In Figure 6.6, the node class includes the following attributes:

a) Act: Label or name of the activity for which the agent is responsible or is affected
b) ResAgent: Label or name of the agent who is responsible for or is affected by the activity
c) ActUn: Uncertainty of the activity which is calculated based on the set of parameters and sub-activities that are associated with the activity
d) ChC%: Percentage change in cost which is calculated based on the uncertainty of the activity

e) ChD%: Percentage change in duration which is calculated based on the uncertainty of the activity.

$$\begin{bmatrix} \text{Act} \\ \text{ResAgent} \\ \text{ActUn} \\ \text{ChC\%} \\ \text{ChD\%} \end{bmatrix}$$

Figure 6.6. Node class of an agent to obtain the uncertainty of an activity and its effect

The node class of the agent who performs the process-3 is represented as shown in Figure 6.7. In Figure 6.7, the node class includes the following attributes:

a) SubAct: Label or name of the sub-activity for which the agent is responsible or is affected

b) AffAgent: Label or name of the agent who is responsible for or is affected by the sub-activity

c) SubUn: Uncertainty of the sub-activity which is calculated based on the set of sub-parameters that are associated with the sub-activity.

$$\begin{bmatrix} \text{SubAct} \\ \text{AffAgent} \\ \text{SubUn} \end{bmatrix}$$

Figure 6.7. Node class of an agent to obtain the uncertainty estimate of a sub-activity

As described above, each activity in the ABC methods needs to be associated with a set of parameters and sub-activities that contribute to uncertainty of the activity. Further, the sub-activities need to be associated with a set of sub-parameters. The parameters and sub-parameters associated with the activities will be described in the following section.

Parameters associated with activities

The activities or sub-activities need to be associated with parameters that contribute to respective uncertainties. The uncertainty of an activity or a sub-activity refers to the ambiguity in obtaining successful results from the activity or the sub-activity in terms of constructability and durability of a bridge. Sets of parameters that affect the constructability and durability of a bridge are developed for PBES, SPMT move, and SIBC by extensive analysis of the completed ABC projects (FHWA 2015b; ABC center 2014), ABC policies of DOTs (MassDOT 2009; JLARC 2010; IowaDOT 2012; VDOT 2012; WisDOT 2013; MDOT 2013a; MDOT 2014a), related literature (FHWA 2007; UDOT 2009; PCI 2011; MDOT 2013b; UDOT 2013; Shutt 2013a, b, c; FHWA 2013; Aktan et al. 2014a; FHWA 2014; MDOT 2014b), and personnel communication with prefabricators and third-party quality assurance inspectors (Stress-Con Industries, personal communications, 2015). The parameters were scrutinized and associated with the activities of ABC methods such that that the uncertainty of an activity can be obtained based on the respective parameters. The uncertainty of an activity of an ABC method for a particular project will be calculated using the parameter probability of affecting the project performance. In order to obtain the probability values of the parameters, a knowledgebase consisting of parameter correlations with site-specific data and uncertainty ratings based on the characteristics (in terms of constructability and durability) of the ABC methods and their associated superstructure systems, will be developed specific to a region (described in the next section).

The sets of parameters developed for PBES activities are shown in Table 6.6. Few of the parameters are associated with sub-activities, thus, included with sub-parameters. The respective sub-parameters for PBES activities are shown in Table 6.7. The sub-parameters contribute to uncertainty of the sub-activities. The sets of parameters developed for SPMT move activities are shown in Table 6.8, and the respective sub-parameters are shown in Table 6.9 and Table 6.10. Similarly, the sets of parameters developed for SIBC activities are shown in Table 6.11, and the respective sub-parameters are shown in Table 6.12 and Table 6.13.

Table 6.6. Parameters Associated with PBES Activities

	Activities					
	Design superstructure	**Transport the elements**	**Close the facility carried for traffic**	**Repair/Construct permanent substructure on existing alignment**	**Erect the elements**	**Connect the elements**
Parameters	Span length	Transportation limitations	Average daily traffic (ADT) on facility carried (FC)	Right-of-way (ROW) on feature intersected (FI) for equipment staging	Lane closure/ traffic shift restrictions on FI	Material availability
	Beam spacing	Safety requirement	Financial and political risks	Lane closure/ traffic shift restrictions on FI	ROW on FI for equipment staging	Contractor experience
	Skew	Equipment malfunction possibility	Site condition complexities	Vertical grade/slope of superstructure	Crane set-up difficulty	Equipment malfunction possibility
	Underclearance	Fabricating elements*	Impact on public*	Quality assurance of repair		Interagency agreements*
	Aesthetic requirements			Environmental protection near and within site		
	Geometric complexity (curved bridge, etc.)			Subsurface considerations*		

* Parameter that includes sub-parameters associated with a sub-activity

Table 6.7. Sub-Parameters of PBES Activity Parameters

	Activities			
	Transport the elements	**Close the facility carried for traffic**	**Repair/Construct permanent substructure on existing alignment**	**Connect the elements**
	Parameters			
	Fabricating elements	***Impact on public***	***Subsurface considerations***	***Interagency agreements***
Sub-Parameters	Prefabricator experience	Stakeholder (nearby property owners') limitations	Scour or hydraulic issues	Constructability of design
	Material availability	Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	Complexity of constructing new foundation when bridge is not in service	Non-conformances in element fabrication/ tolerances
		Detour availability/ Length of detour		
		Impact on local communities		

Table 6.8. Parameters Associated with SPMT Move Activities

	Activities						
	Design superstructure	**Prepare staging area**	**Construct superstructure at staging area**	**Repair/Construct permanent substructure on existing alignment**	**Close the facility carried and feature intersected for traffic**	**Prepare travel path**	**Jack and move the superstructure**
Parameters	Span length	Availability of staging area	Material procurement*	Right-of-way (ROW) on feature intersected (FI) for equipment staging	Average daily traffic (ADT) on facility carried (FC)	Travel path complexity	Project special provisions
	Beam spacing	Number of spans for SPMT move	Contractor experience	Lane closure/ traffic shift restrictions on FI	ADT on FI	Number of spans for SPMT move	Equipment malfunction possibility
	Skew	Environmental sensitivity of staging area	Constructability of design	Vertical grade/slope of superstructure	Financial and political risks	Underclearance at final alignment	Vertical grade/ slope of superstructure
	Underclearance	Subsurface considerations*	Equipment malfunction possibility	Quality assurance of repair	Impact on public*	Vertical grade/slope of superstructure	SPMT stroke availability
	Aesthetic requirements	Utility relocation considerations*	Move specific details*	Environmental protection near and within site		Subsurface considerations*	Limitations for SPMT move operation (e.g., weather)
	Geometric complexity (curved bridge, etc.)	SPMT subcontractor coordination*		Subsurface considerations*		Utility relocation considerations*	Contractor coordination*
						SPMT subcontractor coordination*	

* Parameter that includes sub-parameters associated with a sub-activity

Table 6.9. Sub-Parameters of SPMT Move Activity Parameters (Part-I)

	Activities						
	Prepare staging area			**Construct superstructure at staging area**		**Repair/Construct permanent substructure**	**Close the facility carried and feature intersected for traffic**
	Parameters						
	Subsurface considerations	***Utility relocation considerations***	***SPMT subcontractor coordination***	***Material procurement***	***Move specific details***	***Subsurface considerations***	***Impact on public***
Sub-Parameters	Complexity of constructing temporary substructure (piles, etc.)	Impact on overhead & underground utilities	DOT/Contractor coordination	Material availability	Project special provisions	Scour or hydraulic issues	Impact on nearby major intersection/highway-rail grade crossing with full closure of facility carried
	Base preparation requirement based on allowable ground bearing pressure	Complexity of relocating utilities	SPMT subcontractor experience	Prefabricator experience	Complexity of lifting and moving the superstructure	Complexity of constructing new foundation when bridge is in service	Impact on nearby major intersection/highway-rail grade crossing due to closure of feature intersected
					SPMT subcontractor experience		Detour availability/ Length of detour
							Stakeholder (nearby property owners') limitations
							Impact on local communities

Table 6.10. Sub-Parameters of SPMT Move Activity Parameters (Part-II)

	Activities			
	Prepare travel path			**Jack and move the superstructure**
	Parameters			
	Subsurface considerations	***Utility relocation considerations***	***SPMT subcontractor coordination***	***Contractor coordination***
Sub-Parameters	Base preparation requirement based on allowable ground bearing pressure	Impact on overhead & underground utilities	DOT/Contractor coordination	DOT coordination
		Complexity of relocating utilities	SPMT subcontractor experience	Safety assurance

Table 6.11. Parameters Associated with SIBC Activities

	Activities								
	Design superstructure	**Construct temporary substructure**	**Construct superstructure on temporary substructure**	**Construct approaches for temporary run-around**	**Route traffic onto temporary run-around**	**Construct permanent substructure**	**Close the facility carried for traffic**	**Repair permanent substructure**	**Jack and move the superstructure**
Parameters	Span length	Average daily traffic (ADT) on feature intersected (FI)	Material procurement*	Complexity of constructing temporary run-around	ADT on FC	ROW on FI for equipment staging	ADT on FC	ROW on FI for equipment staging	Project special provisions
	Beam spacing	Right-of-way (ROW) on FI for equipment staging	Contractor experience	ADT on facility carried (FC)	Financial and political risks	Lane closure/ traffic shift restrictions on FI	Financial and political risks	Lane closure/ traffic shift restrictions on FI	Equipment malfunction possibility
	Skew	Lane closure/ traffic shift restrictions on FI	Constructability of design	Restriction on closure of curb-lanes on FC	Impact on public*	Vertical grade/slope of superstructure	Impact on public*	Vertical grade/slope of superstructure	Vertical grade/ slope of superstructure
	Underclearance	Vertical grade/slope of superstructure	ROW on FI for equipment staging	ROW on FC for equipment staging		Environmental protection near and within site		Quality assurance of repair	Contractor coordination*
	Aesthetic requirements	Environmental protection near and within site	Lane closure/ traffic shift restrictions on FI	Vertical grade/ slope of superstructure		Subsurface considerations*		Environmental protection near and within site	Limitations of operation (e.g., weather limitations, geometric complexity, and superstructure getting stuck in skid tracks.)
	Geometric complexity	Design considerations*	Equipment malfunction possibility					Subsurface considerations*	
		Subsurface considerations*	Move specific details*					Impact on public*	
		Utility relocation considerations*							

* Parameter that includes sub-parameters associated with a sub-activity

Table 6.12. Sub-Parameters of SIBC Activity Parameters (Part-I)

	Activities						
	Construct temporary substructure			**Construct superstructure on temporary substructure**		**Route traffic onto temporary run-around**	**Construct permanent substructure**
	Parameters						
	Design considerations	***Subsurface considerations***	***Utility relocation considerations***	***Material procurement***	***Move specific details***	***Impact on public***	***Subsurface considerations***
Sub-Parameters	Loads on superstructure at temporary location	Scour or hydraulic issues	Impact on overhead & underground utilities	Material availability	Project special provisions	Stakeholder (nearby property owners') limitations	Scour or hydraulic issues
	Site constraints for parallel replacement structure construction	Complexity of constructing new foundation	Complexity of relocating utilities	Prefabricator experience	Complexity in sliding the superstructure	Risk of traffic within work zone	Complexity of constructing new foundation
	Available ROW for SIBC				SIBC subcontractor experience	Detour availability/ Length of detour	

Table 6.13. Sub-Parameters of SIBC Activity Parameters (Part-II)

	Activities			
	Close the facility carried for traffic	**Repair permanent substructure**		**Jack and move the superstructure**
	Parameters			
	Impact on public	***Subsurface considerations***	***Impact on public***	***Contractor coordination***
Sub-Parameters	Stakeholder (nearby property owners) limitations	Scour or hydraulic issues	Stakeholder (nearby property owners) limitations	Safety assurance
	Impact on nearby major intersection/highway-rail grade crossing with full closure of FC		Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	Impact of sliding forces on the structure
	Detour availability/ Length of detour		Detour availability/ Length of detour	
	Impact on local communities		Impact on local communities	

Parameter probability of affecting the project performance

When implementing an ABC method, the site-specific conditions and superstructure details play a major role in the constructability and durability of the bridge. Thus, the parameters associated with the activities of ABC methods are presumed to affect the project performance based on site-specific conditions and characteristics (in terms of constructability and durability) of ABC method and its associated superstructure system. In order to quantify a parameter impact on project performance, parameter probability of affecting the project performance is considered. The probability values of the parameters will be utilized in calculating the uncertainty of an activity. A parameter may affect project performance in terms of either project cost or construction duration, or both. In this section, the parameters will be correlated with site-specific data and respective qualitative ratings will be established. Then, available uncertainty/risk estimates for ABC projects will be utilized to quantify the qualitative ratings (i.e., to obtain the probability values for the parameters).

Parameter correlations with site-specific data

The parameters are dependent on site-specific data and characteristics of ABC method and its associated superstructure system. The site-specific data is further dependent on a region or state. Therefore, for presenting the correlations and establishing respective qualitative ratings, the state of Michigan is considered. A qualitative rating for a parameter represents the significance of respective parameter probability of affecting the project performance. The ratings are termed as *uncertainty ratings*. The following rating scale is used for establishing the uncertainty ratings for the parameters:

- VL: Very low probability of affecting the project performance
- L: Low probability of affecting the project performance
- M: Moderate probability of affecting the project performance
- H: High probability of affecting the project performance
- VH: Very high probability of affecting the project performance.

Also, potential superstructure systems for each ABC method are selected for Michigan based on the recommendations provided in Chapter 5 as well as considering past ABC projects, regional requirements of superstructure systems, and preferences of contractors/prefabricators as discussed in Aktan et al. (2014a). The ABC methods and the associated superstructure systems are termed as alternatives in the decision-making. Potential superstructure systems selected for PBES include the following:

a) Decked bulb tee (DBT) girder system
b) Precast concrete (PC) I-girder and full-depth (FD) deck panel system
c) Steel girder and FD deck panel system.

Potential superstructure systems selected for SPMT move include the following:

a) PC I-girder and cast-in-place (CIP) deck system
b) Steel girder and CIP deck system.

Potential superstructure systems selected for SIBC include the following:

a) PC I-girder and CIP deck system
b) Steel girder and CIP deck system
c) Precast spread box beam and CIP deck system.

The parameter correlations developed for PBES are shown in Table 6.14 to Table 6.19. The site-specific data includes qualitative judgments as well as project specific quantitative data. The qualitative judgments can be obtained from the project manager; whereas, the quantitative data can be obtained from bridge management database and preliminary project planning data such as data from corridor and traffic analyses. Possible site-specific data (options) that are used in the parameter correlations are based on the site-specific data inputs developed by the author as a part of Michigan Department of Transportation (MDOT) research project MDOT RC-1618A (Aktan and Attanayake 2015). The uncertainty ratings are established by considering the impact of an alternative on the project performance for a particular site-specific condition. The ratings are based on documentation of past ABC projects and information gathered by conducting an ABC workshop (Aktan et al. 2014a). Using a similar format, the parameter correlations for SPMT move and SIBC are developed and presented in Appendix C. Uncertainty ratings may change if innovative details and materials are implemented in a region.

Table 6.14. Parameter Correlations for the PBES Activity: Design Superstructure

Parameters for 'Design Superstructure'	Site-Specific Data (Options)	Uncertainty Rating (Parameter Probability of Affecting the Project Performance)			Reasoning for Ratings
		DBT girder system	PC I-girder & FD deck panel system	Steel girder & FD deck panel system	
Span length[1] (L)	L < 60 ft	VL	VL	VH	Use of DBT girders system is preferred up to spans of 120 ft for effectiveness of the system while accommodating the weight limitations (UDOT 2010; PCI 2011). On the other hand, the PC I-girders such as the most popular AASHTO I-girders are typically used for spans up to 140 ft, and the steel girders are typically used for spans up to 170 ft (PCI 2011; FHWA 2015b). For short spans steel girders system is not preferred because of cost of steel.
	60 ft ≤ L < 80 ft	L	VL	VL	
	80 ft ≤ L < 140 ft	M	VL	VL	
	L ≥ 140 ft	VH	L	VL	
Beam spacing[1] (S)	S < 6 ft	VH	VL	VL	For a wide bridge, large beam spacing is preferred for economy (WSDOT 2008a; UDOT 2010). However, the beam spacing is decided based on the span length as it is inversely proportional to the span length. A DBT girder has a standard flange width of 6 ft, thus, predetermined beam spacing for the DBT girders system (PCI 2011). Therefore, high uncertainty of DBT system for beam spacing other than 6 ft. Further, low uncertainty of PC I-girder system with large beam spacing compared to steel girder system because of the need of additional intermediate diaphragms for steel girder system in order to resist torsion (Hughes et al. 2011).
	6 ft ≤ S < 10 ft	VL	VL	VL	
	10 ft ≤ S < 12 ft	VH	L	M	
	S ≥ 12 ft	VH	L	M	
Skew (θ)	θ = 0° (no skew)	VL	VL	VL	A DBT girder system is best implemented with skew less than 30° (MnDOT 2015). A FD deck panel system has been successfully implemented with skew more than 45° (Chung et al. 2008; FHWA 2015b).
	θ ≤ 30°	VL	VL	VL	
	30° < θ ≤ 45°	VH	VL	VL	
	θ > 45°	VH	VL	VL	
Underclearance[1] (UC) (existing)	UC < 14.25 ft	H	VH	VH	The underclearance is inversely proportional to the span length. If the span length increases the girder depth increases, thus, the underclearance is reduced. If the existing underclearance is low, the system requiring deep girders for a particular span is less preferred. A considerable depth of PC I-, and steel girders is required compared to box beams and DBT girders for a given span (UDOT 2010; Graybeal 2010; Abudayyeh 2010; Grace et al. 2015). Box beams system and DBT girders system are more preferred with low underclearance (MDOT 2014a; Grace et al. 2015).
	14.25 ft ≤ UC < 15 ft	M	H	H	
	15 ft ≤ UC < 16.25 ft	VL	M	M	
	UC ≥ 16.25 ft	VL	L	L	

Table 6.14. — Continued

Parameters for 'Design Superstructure'	Site-Specific Data (Options)	Uncertainty Rating (Parameter Probability of Affecting the Project Performance)			Reasoning for Ratings
		DBT girder system	PC I-girder & FD deck panel system	Steel girder & FD deck panel system	
Aesthetic requirements	None/ Low	VL	VL	VL	The DBT and PC I- girder systems cannot incorporate significant aesthetic requirements such as different architectural concepts that steel girder system can accommodate (Culmo 2011b).
	Moderate	M	M	VL	
	High	H	H	VL	
Geometric complexity (curved bridge)	Low	L	L	VL	A DBT girder system is not appropriate for flared or curved structures. This is based on MnDOT recommendations for bridge type selection (MnDOT 2015). Short length PC I- girders can be used for curved bridges; however, difficulty increases with increase in geometric complexity of a bridge. On the other hand, a steel girder system can be curved or built to accommodate the complex geometry of a bridge (Chung et al. 2008; FHWA 2015b).
	Moderate	H	H	VL	
	High	VH	VH	VL	

[1] Dependent parameters

Table 6.15. Parameter Correlations for the PBES Activity: Transport the Elements

Parameters/Sub-Parameters for 'Transport the Elements'	Site-Specific Data (Options)	Uncertainty Rating (Parameter Probability of Affecting the Project Performance)			Reasoning for Ratings
		DBT girder system	PC I-girder & FD deck panel system	Steel girder & FD deck panel system	
Transportation limitations	None	VL	VL	VL	SHRP2 (2013) recommends limiting the weight of a prefabricated element to 160 kips. However, MDOT (2014a) recommends limiting the weight of a prefabricated element to 80 kips in Michigan. For a span length of more than 60 ft, the DBT girders typically exceed the 80 kip weight limit in Michigan; thus, requiring additional permits for transportation (Aktan and Attanayake 2013). Thus, high uncertainty rating for DBT girder system compared to others.
	Moderate	H	M	M	
	High	VH	M	M	
Safety requirement	Moderate	M	M	L	Camber is considered as an inherent side effect of prestressed girder construction (Culmo 2011b). Further, the prestressed concrete girders are heavier compared to steel girders for a given span [Based on girders used in past ABC projects, average weight of PC I-girders is 0.71 kip/ft and of DBT girders is 1.52 kip/ft; whereas, average weight of steel girders is 0.60 kip/ft (Aktan and Attanayake 2013; FHWA 2015b)]. Thus, prestressed concrete girders require special safety devices for securing on truck and require additional care while making truck turns.
	High	H	H	M	
Prefabricator experience	Low	VH	VH	VH	The prefabricator experience significantly affects the manufacturing and transporting of precast prestressed elements. Additional work is required to achieve element tolerances (Attanayake et al. 2014). Thus, the uncertainty rating is high with DBT girders system and systems including FD deck panels.
	Moderate	H	H	H	
	High	M	M	M	
	Very High	VL	VL	VL	
Equipment (trucks) malfunction possibility	Low	L	VL	VL	Highly reliable trucks are required for transporting prefabricated modules that are typically heavier than prefabricated girders (Schoenborn 2012). Thus, high uncertainty with systems including prefabricated modules such as DBT girders system.
	Moderate	H	M	M	
	High	VH	H	H	
Material availability	Low	M	M	VH	Concrete is more readily available compared to steel (Aktan et al. 2014b). Thus, steel girder system is assigned high uncertainty rating. If innovative materials are used in a system, the uncertainty ratings may change.
	High	VL	VL	L	

Table 6.16. Parameter Correlations for the PBES Activity: Close the Facility Carried for Traffic

Parameters/Sub-Parameters for 'Close the Facility Carried for Traffic'	Site-Specific Data (Options)	Uncertainty Rating	Reasoning for Ratings
Average daily traffic (ADT) on facility carried (FC)	1 ≤ ADT < 5,000	VL	If the ADT on FC is very high, the significance of FC traffic is very high. With high significance of FC traffic, the activity of closing the FC traffic will highly affect the project performance in terms of cost (FHWA 2015b).
	5,001 ≤ ADT < 20,000	L	
	20,001 ≤ ADT < 50,000	M	
	50,001 ≤ ADT < 100,000	H	
	100,001 ≤ ADT	VH	
Financial and political risks	Low	VL	If a project is highly politically sensitive, complete closure of FC for the duration of PBES construction (typically 2 weeks to 3 months) may be a concern (Aktan and Attanayake 2015). Thus, high uncertainty rating.
	Moderate	M	
	High	H	
	Very High	VH	
Site condition complexities	None/Low	VL	If the site has complex conditions such as viaduct, etc., complete closure of FC for the duration of PBES construction (two weeks to a month) may be a concern (Aktan and Attanayake 2015). Thus, high uncertainty rating.
	Moderate	M	
	High	H	
	Very High	VH	
Stakeholder limitations	None	VL	If the stakeholder limitations are very high, closing FC traffic for the duration of PBES construction (two weeks to a month) will be a concern (Aktan and Attanayake 2015). Thus, high uncertainty rating.
	Low	L	
	Moderate	M	
	High	H	
	Very High	VH	
Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	None	VL	If the impact on nearby major intersection/highway-rail grade crossing is very high with closure of FC, closing the FC traffic will highly affect the project performance in terms of cost (Aktan and Attanayake 2015). Thus, high uncertainty rating.
	Low	L	
	Moderate	M	
	High	H	
	Very High	VH	
Detour availability/ Length of detour	Short	VL	If the detour is very long or unavailable, the travelling public is impacted significantly with closure of FC (Aktan and Attanayake 2015). Thus, high uncertainty rating.
	Moderate	M	
	Very Long or Unavailable	VH	
Impact on local communities	None	VL	If the FC is closure has very high impact on the local communities, closing FC traffic will be a concern (Aktan and Attanayake 2015). Thus, high uncertainty rating.
	Low	L	
	Moderate	M	
	High	H	
	Very High	VH	

Table 6.17. Parameter Correlations for the PBES Activity: Repair/Construct Permanent Substructure on Existing Alignment

Parameters/Sub-Parameters for 'Repair/Construct Permanent Substructure on Existing Alignment'	Site-Specific Data (Options)	Uncertainty Rating	Reasoning for Ratings
Right-of-way on feature intersected (FI) for equipment staging	Limited	VH	With limited right-of-way on FI, temporary easement or lane rental may be required for placing equipment and for obtaining safe work space for the construction crew while the FI is open to traffic. This will have high impact on the project performance in terms of cost while implementing PBES method (FHWA 2015b).
	Moderate	H	
	Unrestricted	VL	
Lane closure/ traffic shift restrictions on feature intersected (FI)	None	VL	With high restrictions on FI, lane rental will be difficult for the contractor during substructure construction (Aktan et al. 2014a). Thus, high uncertainty rating.
	Low	L	
	Moderate	M	
	High	H	
	Very High	VH	
Vertical grade/slope of superstructure at final alignment	4% or less	VL	If the superstructure has extreme grade, the accessibility to the existing substructure may be limited for repair because to the revetment (FHWA 2015b). Thus, the difficulty in repairing the substructure is considered to increase with the grade of superstructure.
	4-6%	M	
	Up to 8%	H	
	More than 8%	VH	
Quality assurance of repair (Outcome depends on contractor experience; hence, contractor experience level is used here)	Moderate	M	The quality assurance of the substructure repair depends on the contractor experience (FHWA 2015b). If highly experienced contractor is performing repair, there will be least impact on project performance (very low uncertainty rating).
	High	L	
	Very High	VL	
Environmental protection near and within site	None/Low	VL	If high environmental protection is required near and within the site, the activity of constructing permanent substructure for PBES method is highly affected (FHWA 2015b). Thus, affecting the project performance in terms of construction duration (high uncertainty rating).
	Moderate	M	
	High	VH	
Scour or hydraulic issues	None	VL	If high scour or hydraulic issues are encountered at a site, the activity of constructing permanent substructure on existing alignment is highly affected. Thus, affecting the project performance in terms of construction duration (high uncertainty rating) (Aktan and Attanayake 2015).
	High	VH	
Complexity of constructing new foundation when bridge is not in service	None/Low	VL	If there is high complexity of constructing new foundation at the site, the activity of constructing permanent substructure is highly affected (Aktan and Attanayake 2015). Thus, high uncertainty rating.
	Moderate	M	
	High	H	
	Very High	VH	

Table 6.18. Parameter Correlations for the PBES Activity: Erect the Elements

Parameters for 'Erect the Elements'	Site-Specific Data (Options)	Uncertainty Rating (Parameter Probability of Affecting the Project Performance)	Reasoning for Ratings
Lane closure/ traffic shift restrictions on feature intersected (FI)	None	VL	With high restrictions on FI, the work space for the construction crew is restricted and thus, limiting the constructability during erecting the elements (Aktan et al. 2014a). This will have high impact on the project performance in terms of construction duration while implementing PBES method. Thus, high uncertainty ratings with high restrictions on FI.
	Low	L	
	Moderate	M	
	High	H	
	Very High	VH	
Right-of-way on FI for equipment staging	Limited	VH	With limited right-of-way on FI, temporary easement or lane rental may be required for placing equipment for erecting the elements (Aktan et al. 2014a). This will have high impact on the project performance in terms of cost while implementing PBES method. Thus, high uncertainty rating with limited right-of-way on FI.
	Moderate	H	
	Unrestricted	VL	
Crane set-up difficulty	None/Low	VL	For erecting the elements in PBES implementation, prior investigation needs to be performed in order to set-up the crane so that the elements can be erected in a safe manner. Crane set-up includes identifying the crane location and boom length requirements based on the lift points of elements and final alignment of the bridge (Culmo 2011b; Aktan et al. 2014a). Thus, very high uncertainty is considered if extreme difficulty is expected for setting-up the crane at a particular site.
	Moderate	M	
	Extreme	VH	

Table 6.19. Parameter Correlations for the PBES Activity: Connect the Elements

Parameters/Sub-Parameters for 'Connect the Elements'	Site-Specific Data (Options)	Uncertainty Rating			Reasoning for Ratings
		DBT girder system	PC I-girder & FD deck panel system	Steel girder & FD deck panel system	
Material availability	Low	H	VH	VH	Specialized materials are typically used for grouting connections and haunches in FD deck panel systems (Hieber et al. 2005; Graybeal 2010). If specialized material availability is low for a specific project, it will affect the project performance in terms of cost. Thus, moderate to high uncertainty with FD deck panel systems.
	Moderate	M	H	H	
	High	VL	M	M	
Contractor experience (for each superstructure system)	Low	H	VH	VH	Experienced contractor is required for superstructure systems with several connection details and tolerances, such as FD deck panel systems (Attanayake et al. 2014). Thus, the uncertainty is moderate to high with FD deck panel systems.
	Moderate	M	H	H	
	High	L	M	M	
Equipment malfunction possibility (based on available equipment and spares)	Low	L	M	M	Reliable equipment is required to assemble elements at site (SHRP2 2013). FD deck panel systems require more assembling than prefabricated module systems, such as DBT girders system. Thus, moderate to very high uncertainty rating for FD deck panel systems.
	Moderate	M	H	H	
	High	H	VH	VH	
Constructability of design (for each superstructure system)	Not difficult	VL	VL	VL	Superstructure systems that require less connection details are easy to construct (Culmo 2009). FD deck panel system has more connections compared to prefabricated modules system such as DBT girders system. Also, FD deck panels require post-tensioning. Thus, DBT girders system is assigned low to moderate uncertainty rating.
	Moderate	L	H	H	
	Difficult	M	VH	VH	
Non-conformances in element fabrication/ tolerances	Low	VL	M	L	The non-conformances in element tolerances become more important when a system has more connections. FD deck panel system has more connections compared to prefabricated modules system such as DBT girders system. Also, non-conformances of camber and other time dependent properties in prestressed concrete elements are critical. Thus, DBT is rated considering camber tolerance. PC I-girders and FD deck panels system is rated considering more connections as well as camber tolerance. Steel girders and FD deck panels system is rated considering more connections.
	Moderate	L	H	M	
	High	M	VH	H	

Quantification of qualitative ratings

The uncertainty rating of a parameter for a specific project is based on the site-specific conditions and the regional considerations with respect to the ABC method and the associated superstructure systems. The uncertainty ratings of the parameters can be quantified by converting them to probability values. Deterministic estimates neglect the uncertainty by treating the input as discrete fixed variables. Thus, using deterministic estimates for uncertainty ratings is not justifiable. Alternatively, probabilistic distributions can be used for input variables in order to obtain statistical inferences of the results (Attanayake et al. 2012). As described in Chapter 5, available uncertainty/risk estimates for ABC projects can be utilized in the framework in order to quantify the uncertainty ratings. Therefore, the qualitative uncertainty ratings described in the previous section are quantified using the ranges of uncertainty values provided in Golder Associates Inc. (2014), as shown in Table 5.1. The ranges of values with corresponding lower and upper bounds for respective uncertainty rating shown in Table 5.1 are used as the range of probability values for the parameters. The uncertainty of an activity will be calculated based on the range of probability values of the associated parameters as described in the next section.

Table 6.20. Probability Range Based on Uncertainty Rating (Source: Golder Associates Inc. 2014)

Uncertainty Rating	Range of Uncertainty Value
Very High	0.7 to 1.0
High	0.4 to 0.7
Medium	0.2 to 0.4
Low	0.05 to 0.2
Very Low	0.0 to 0.05

Results calculation

In order to evaluate the alternatives for a given project using the framework, first, applicable site-specific options for the parameters/sub-parameters associated with an activity need to be selected from the knowledgebase. The applicable site-specific options can be derived using (1) feedback from region scoping engineer and project manager, (2) data from preliminary project planning such as corridor and traffic analyses, (3) feedback from adjacent property owners and local community, and (4) data from early investigations of the site such as geotechnical, utility relocation, and staging area investigations. Also, base estimates of the measures of project performance need to be specified for each alternative, such as base project cost and base construction duration. At the onset of the evaluation, agent interactions for each alternative will be performed based on respective ontology. Output from each agent interaction will be the uncertainty of an activity which will be used to update the base estimates. Outputs from all the interactions will be stored, and later a simulation technique will be implemented to generate the results. The process of agent interactions, calculating the uncertainty of an activity, updating measures of project performance, and generating results will be described in this section.

Agent interactions

The interaction network shown in the ontology of an ABC method defines the mapping among respective node classes (arrays), and it enables employing typical Array Mapping procedures for calculating required outputs. During the evaluation, the interactions among the agents for each activity associated with the alternatives are processed by mapping respective node classes as illustrated by the example shown in Figure 6.8. In Figure 6.8, Agent-X is the agent who assigns an activity (Activity-A) to another agent and evaluates the impact on project performance, and is represented by the node class described in Figure 5.3. Agent-Y is the agent who is responsible for the activity, and is represented by the node class described in Figure 6.6. Agent-Z is the agent who is responsible for a sub-activity (SubAct-1), and is represented by the node class described in Figure 6.7. As shown in Figure 6.8, agent interactions for Activity-A are performed as the following:

1) First, the node class of Agent-X is mapped to the node class of Agent-Y.
2) Agent-Y evaluates the parameters associated with Activity-A based on the selected site-specific options in order to calculate the uncertainty of Activity-A.
3) During the parameter evaluation, assume Agent-Y encounters a parameter that includes sub-parameters associated with a sub-activity (SubAct-1). Thus, Agent-Y interacts with Agent-Z; this maps the node class of Agent-Y to the node class

of Agent-Z. Note that, if multiple sub-activities exist for an activity, Agent-Y interacts with multiple agents that are similar to Agent-Z.

4) Agent-Z evaluates the sub-parameters based on the selected site-specific options, and calculates the uncertainty of SubAct-1.
5) Agent-Z reports the calculated uncertainty to Agent-Y who uses that value in calculating the uncertainty of Activity-A.
6) Agent-Y then calculates the percentage change in cost and duration based on the uncertainty of Activity-A, and reports the percentage change values to Agent-X.
7) Agent-X uses the percentage change values to update the base estimates of project cost and construction duration, and stores the data with respect to Activity-A.
8) Next, another activity is considered, and a similar process is performed.

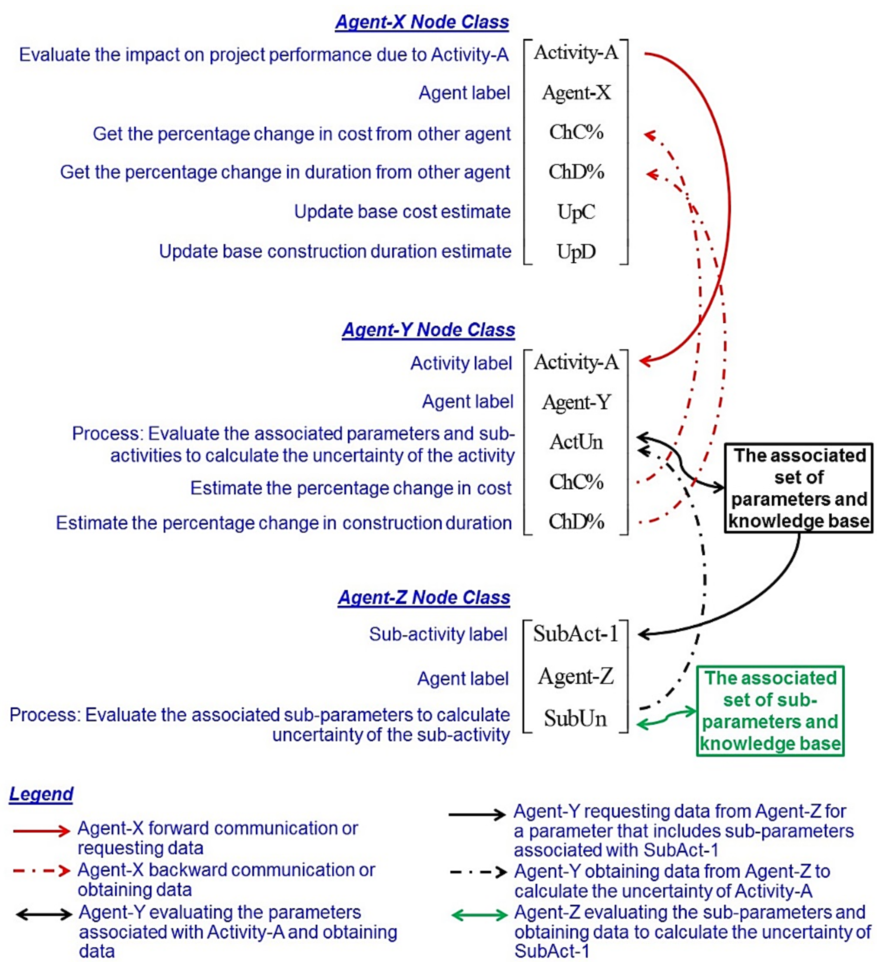


Figure 6.8. Example interaction for an activity

Calculate uncertainty of an activity

An activity/sub-activity is dependent on several parameters/sub-parameters. If at least one parameter/sub-parameter highly affects the project performance and leads to undesirable results, the activity/sub-activity is expected to yield undesirable results in terms of constructability and durability of the project. This particular relationship between the activity/sub-activity and the associated parameters/sub-parameters can be evaluated by implementing the reliability engineering concept of the *Competing Risk Case* as described in Chapter 5. Therefore, the uncertainty of an activity/sub-activity is calculated using the equations derived in Chapter 5 (i.e., Eq. 5-4 and Eq. 5-9).

The uncertainty ratings of the parameters/sub-parameters for the selected site-specific options are converted to the probability values using Table 5.1. As shown in Table 5.1, an uncertainty rating is correlated to a range of probability values with corresponding lower and upper bounds. A uniform distribution can be assumed for an input having a range of values with lower and upper bounds (Walls and Smith 1998). According to Johnson (1994), "*a uniform distribution is a family of probability distributions such that for each member of family, all intervals of same length on the distribution's support are equally probable*." Considering the above, for a particular uncertainty rating a uniformly distributed probability values are used as an input to Eq. 5-4 and Eq. 5-9. Note that Eq. 5-4 is used when an activity/sub-activity is associated with "independent" parameters/sub-parameters; whereas, Eq. 5-9 is used when an activity/sub-activity is associated with "dependent" and "independent" parameters.

As described in Chapter 5, Monte Carlo Simulation can be implemented for an equation that contains variables in the form of distributions. Thus, Monte Carlo Simulation is implemented for Eq. 5-4 and Eq. 5-9 with inputs as uniformly distributed probability values. In each run of Monte Carlo Simulation while using Eq. 5-4, a *variate* of the uncertainty of the activity ($X_{activity}$) is calculated using Eq. 6-1. Eq. 6-1 uses variates of the inputs that are probability values of n number of independent parameters and m number of sub-activities. The equation of variate (X_i) for parameter i depends on the distribution type. X_i is represented by Eq. 6-2 for parameter i with a uniformly distributed probability value.

$$X_{\text{activity}} = 1 - \left(\prod_{i=1}^{n} \left[1 - X_i \right] \right) \left(\prod_{j=1}^{m} \left[1 - X_j \right] \right) \tag{6-1}$$

$$\begin{aligned} &X_i = a_i + (b_i - a_i)R \quad \textit{such that} \quad R \in \{0,1\} \\ &\textit{where}: X_i \sim U(a_i, b_i) \end{aligned} \tag{6-2}$$

The variate (X_j) of sub-activity j is calculated using Eq. 6-3 based on the variates (X_k) of k number of the associated independent sub-parameters. X_k for sub-parameter k with uniformly distributed parameter probability is also represented by Eq. 6-2.

$$X_j = 1 - \prod_{k} \left[1 - X_k \right] \tag{6-3}$$

Alternatively, while using Eq. 5-9, in each run of Monte Carlo Simulation the variate $X_{activity}$ is calculated using Eq. 6-4. Eq. 6-4 uses variates of P_D number of dependent parameters, P_I number of independent parameters, and m number of sub-activities. The variate X_j of sub-activity j is calculated using Eq. 6-5 based on the variates of S_D number of dependent sub-parameters and S_I number of independent sub-parameters. Again, the variate X_i for parameter i and the variate X_k for sub-parameter k with uniformly distributed parameter probability are represented by Eq. 6-2.

$$\begin{aligned} &X_{\text{activity}} = 1 - (1-\beta) \left(\prod_{i=1}^{P_D + P_I} \left[1 - X_i \right] \right) \left(\prod_{j=1}^{m} \left[1 - X_j \right] \right) \\ &\textit{where}: \beta = \frac{P_D}{P_D + P_I + m} \end{aligned} \tag{6-4}$$

$$\begin{aligned} &X_j = 1 - (1-\beta) \left(\prod_{k=1}^{S_D + S_I} \left[1 - X_k \right] \right) \\ &\textit{where}: \beta = \frac{S_D}{S_D + S_I} \end{aligned} \tag{6-5}$$

In each simulation run, a random number R is generated and the variates are calculated using respective equations. The variates X_j are accumulated from a large number of simulations and curve fitting is used to obtain the uncertainty of a sub-activity as a distribution. Again, a large number of simulations are performed and the variates $X_{activity}$ are accumulated. A similar curve fitting process is used to obtain the uncertainty of the activity $(P_f)_{activity}$ as a distribution.

Update measures of project performance

In the previous section, the uncertainty of an activity is obtained as a range of variates that are represented as a distribution. For a particular variate, the correlations with project cost and construction duration help in identifying the impact on project performance. Thus, correlations of uncertainty of activity with change in project cost and construction duration as shown in Table 6.21 are utilized in the framework. The correlations are based on the risk/uncertainty correlations developed by Golder Associates Inc. (2014) for risk management in ABC projects.

Table 6.21. Correlations of Uncertainty of Activity with Change in Cost and Duration

Variate of Uncertainty of Activity ($X_{activity}$)	**Percentage Change in Project Cost (C%)**	**Percentage Change in Construction Duration (D%)**
$0.7<X_{activity}\leq 1.0$	$10<C\%\leq 25$	$10<D\%\leq 25$
$0.4<X_{activity}\leq 0.7$	$6<C\%\leq 10$	$6<D\%\leq 10$
$0.2<X_{activity}\leq 0.4$	$3<C\%\leq 6$	$3<D\%\leq 6$
$0.05<X_{activity}\leq 0.2$	$1<C\%\leq 3$	$1<D\%\leq 3$
$0<X_{activity}\leq 0.05$	$0<C\%\leq 1$	$0<D\%\leq 1$

An activity may affect project cost or construction duration, or both based on its associated parameters. For the range of the variates obtained in previous section, respective percentage change in cost or duration can be calculated using Table 6.21. Linear interpolation is used to obtain percentage change in cost or duration for a particular variate. In the agent interactions, the above process is performed by the agent who is responsible for the activity (Agent-Y in Figure 6.8 example). Thus, based on the activity, the agent estimates cost change percentage or duration change percentage or both.

Next, the agent who assigns the activity to other agent (Agent-X in Figure 6.8 example) obtains the percentage change values, and updates the base estimates of project cost and construction duration. The updated values are stored with respect to the particular activity of an alternative. A similar process is followed during the interactions of all the activities included in the alternative, and the updated project cost and construction duration are stored as a range of values with respect to each activity.

Generate results

A range of updated project cost and construction duration values are extracted as model outputs for each activity, as described in previous section. The outputs can be used to deduce statistical inferences of the impact on project cost and construction duration for the associated alternative. This enables comparing the results of alternatives for the decision-making.

The key to deliver an ABC project effectively is to identify the alternative that introduces minimal risk/uncertainty on the project performance. Thus, considering the benefits of Monte Carlo Simulation in quantifying the impact of risks/uncertainties on the project performance (described in Chapter 5), it is employed to generate results. Specifically, Monte Carlo Simulation is implemented to plot cumulative probability charts for project cost and construction duration for each alternative. The simulation utilizes the range of updated project cost and construction duration values obtained in the previous section. The charts of project cost for all the alternatives are combined to observe respective variability in the project cost as described in Chapter 5. The obtained variability is due to the uncertainty associated with the particular alternative. Similarly, charts of construction duration for all the alternatives are combined to observe respective variability in construction duration. An example implementation of the decision-making framework and the evaluation results will be described in Chapter 7.

Summary

The Accelerated Bridge Construction (ABC) decision-making framework for evaluating alternatives is described in this chapter. An alternative refers to an ABC method with an associated superstructure system. Framework methodology is presented that includes the modeling and simulation steps of the framework.

Ontologies for the ABC methods are developed that provide models for the stakeholders to interact. During the process of developing the ontologies, major activities and internal stakeholders included in the ABC methods are described. The stakeholders are considered as agents, and the activities are considered to be dependent on several parameters. Node classes for the agents are described in this chapter. A node class includes variables, and is associated with a set of parameters based on the activity. Parameters associated with activities of the ABC methods are described, which allow assessing the impact of an activity on the project performance. The impact is measured in terms of uncertainty of an activity.

Parameter probability of affecting the project performance is considered to quantify a parameter impact on project performance. In order to obtain parameter probabilities, parameter correlations with possible site-specific conditions are developed. In developing the parameter correlations, qualitative ratings are established based on characteristics of ABC methods and the associated superstructure systems, and the regional requirements. A qualitative rating for a parameter represents the significance of respective parameter probability of affecting the project performance. In this chapter, potential superstructure systems for each ABC method and the correlations are presented for Michigan based on documentation of past ABC projects and information obtained from an ABC workshop. The qualitative uncertainty ratings are converted to probability values using the available uncertainty/risk estimates for ABC projects.

An example is provided that illustrates the mathematical processing of an interaction by mapping node classes of agents. The calculation of uncertainty of an activity is described by implementing the reliability engineering concept of the *Competing Risk Case*. A process to update the base estimates of measures of project performance based on the uncertainty of an activity is described. A procedure is presented to generate the evaluation results for the alternatives using Monte Carlo Simulation. Cumulative probability charts are described as the format for presenting the results to the decision makers. The charts allow observing the variability in the measures of project performance due to uncertainty associated with the ABC method, respective superstructure system, and respective stakeholder interactions.

CHAPTER VII

DECISION-MAKING FRAMEWORK IMPLEMENTATION

Overview

This chapter presents an implementation of the decision-making framework described in Chapter 6. The M-50 over I-96 bridge project is used as an example for demonstrating the data input, workings, and results of the framework. The author was one of the team members to monitor the construction process of M-50 over I-96 bridge project during the Michigan Department of Transportation (MDOT) research project conducted by Aktan and Attanayake (2015). Thus, the author had access to all the relevant project information for the framework implementation.

M-50 over I-96 bridge project

Site characteristics

The M-50 (Alden Nash Highway) over I-96 project site is located 10 miles East of Grand Rapids in Lowell, Kent County, Michigan (Figure 7.1). Traffic data from 2012 shows that I-96 carries an average daily traffic (ADT) of 44,600 with an average daily truck traffic (ADTT) of 11%. Also, ADT on M-50 is given as 11,100 with an ADTT of 6%. An insufficient number of lanes caused severe backups on the ramps to M-50 spilling onto I-96 EB, during peak traffic hours. In addition, the bridge was aging and was classified as functionally obsolete. Thus, the bridge needed replacement. However, a minimum disruption during the bridge replacement was required because the M-50 interchange is the main access route to the nearby MDOT carpool parking lot, and I-96 is a heavily travelled interstate. Therefore, Accelerated Bridge Construction (ABC) was selected following the evaluation of the site for conventional construction or ABC. The project consisted of full structure replacement and improvements to the ramps at the intersection.

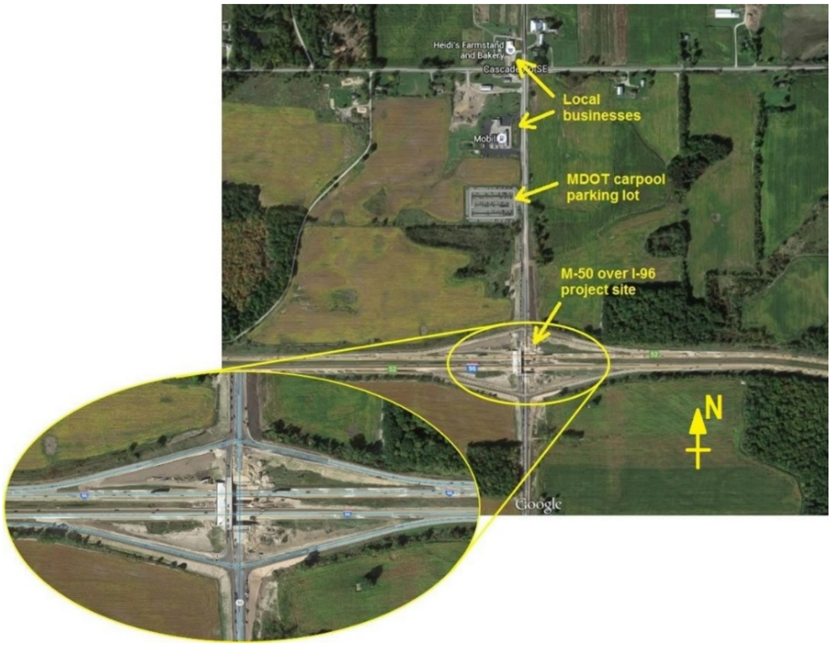


Figure 7.1. Bridge location (Source: Google map)

The old 4-span bridge was 227 ft long and 37 ft 5 in. wide. The proposed bridge is a 2-span structure, 198 ft long and 71 ft 3 in. wide, and includes wide shoulders and two left turn lanes (Figure 7.2).

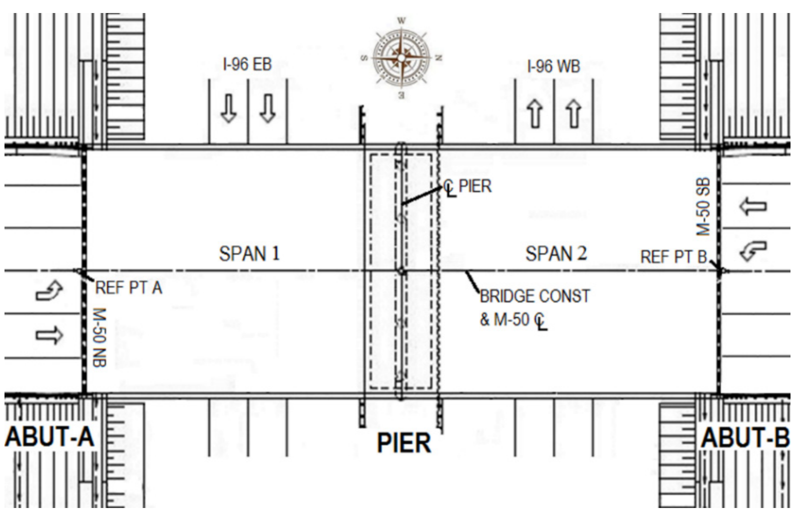


Figure 7.2. Proposed bridge plan

As shown in Figure 7.1, the carpool lot is located just north of the project site. It is essential to maintain access to the carpool lot and businesses located north of the bridge for the entire duration of the project. Also, traffic on I-96 must be maintained at all times. Abundant right-of-way (ROW) is available; however, consideration have to be given to avoiding ROW conflicts with the property located east of the project site. The property is currently protected under the Farmland and Open Space Preservation Program (PA116), due to the presence of the northern long-eared bat. Hence, tree cutting in the area may only occur from November through April. Moreover, a bridge closure at this location for an extended duration would cause a significant impact on the local economy and the commuters who need to follow a very long detour. The use of ABC for this project results in a large social and economic significance. Further benefits of ABC include better quality of the bridges, improved safety for construction workers, and ease of constructability. However, a particular ABC method and an associated superstructure system need to be selected for this project.

Alternatives for the evaluation

Deliberating the regional requirements and preference of contractors/prefabricators in Michigan, the following alternatives are considered for the M-50 over I-96 project in order to identify their feasibility given the respective cost, duration, constructability, and durability:

1) **PBES-X**: Prefabricated Bridge Elements Systems (PBES) with decked bulb tee (DBT) girder system
2) **PBES-Y**: PBES with precast concrete (PC) I-girder and full-depth (FD) deck panel system
3) **PBES-Z**: PBES with steel girder and FD deck panel system
4) **SPMT Move-X**: Self-Propelled Modular Transporter (SPMT) move with PC I-girder and cast-in-place (CIP) deck system
5) **SPMT Move-Y**: SPMT move with steel girder and CIP deck system
6) **SIBC-X**: Slide-In Bridge Construction (SIBC) with PC I-girder and CIP deck system
7) **SIBC-Y**: SIBC with steel girder and CIP deck system
8) **SIBC-Z**: SIBC with precast spread box beam and CIP deck system.

Among SIBC case-1, case-2, and case-3 methods that are described in Chapter 6, the SIBC case-1 is assumed for the above SIBC alternatives based on the site characteristics of the project. As described in Chapter 6, the SIBC case-1 method includes routing the traffic onto new superstructure (temporary run-around) while old bridge is demolished and new substructure constructed.

Prerequisite requirements

The following are the requirements that were considered for implementation of the decision-making framework on M-50 over I-96 bridge project:

1) The decision-making team should familiarize themselves with benefits of each of the ABC methods being evaluated. Also, the decision-making team should be familiar with superstructure systems and their applicability to the project.
2) The decision-making team should have an understanding of the locally available prefabricators/manufacturers and contractors including their capabilities, limitations, and available resources for all the alternatives in consideration.
3) The law and code requirements for accelerated construction of bridge in the project region should be clearly understood and be considered while providing the qualitative judgements.
4) In order to specify project related data and preference ratings for the implementation, the decision making team should have gathered a complete layout of the project site, its accessibility (including nearby emergency facilities), relevant characteristics of the project, traffic impact, environmental concerns, material/component procurement, weather, agency and political limitations.
5) The analyses that should be performed to gather the input data are the following:
    a) Corridor analysis that includes identifying the significance of the corridor and its impact on the surrounding businesses and communities, and identifying the existing condition of substructure and superstructure of the bridge.
    b) Project cost estimation based on the cost estimates developed by the author (Mohammed et al. 2016) that includes cost of material and labor, cost of maintenance of traffic, cost of utility relocation, cost of specialty equipment/ contractor for SPMT move and SIBC, cost of mobilization for SPMT move, cost

of preparing travel path for SPMT move, cost of preparing staging area for SPMT move, cost of equipment and accessories for SIBC, cost of preparing and operating SIBC, and cost of temporary structures for SPMT move and SIBC.

c) Construction duration estimation for the alternatives, which is the period of time from when a contractor enters the project site location (including staging area) until all construction-related activities are removed. This includes, but is not limited to, the removal of traffic control markings, signage, devices, equipment, and personnel.

d) Preliminary analysis of the site taking into account the alternatives in order to identify relocation and disbursement requirements.

e) Early investigation of the site in order to identify any utility constraints or archeological constraints.

Specifying project specific data and preferences

Comprehending the prerequisite requirements mentioned in previous section helps in obtaining data for the decision-making framework. The framework comprises of two types of input data: project specific data and qualitative preferences. The input data for the M-50 over I-96 bridge project and respective sources of input are presented in Table 7.1 to Table 7.8. The project specific data was obtained based on the data available from the corridor planning process and a bridge management database (Pontis database). The Web Soil Survey (USDA 2013) and Michigan wetland inventory maps (DTMB 2016) were reviewed to supplement some of the project specific input data. The resources provide the soil properties and terrain of an area-of-interest, and the locations in the region that are environmentally sensitive. The qualitative preferences were obtained based on the review of the project documents, and communication with the project personnel as well as engineering and planning experts who were familiar with the alternatives. While providing the qualitative preferences for the parameters, the corresponding activities were deliberated. The input data is scrutinized based on the parameter correlations developed in Chapter 6, and incorporated in a simulation platform for executing the interactions and performing simulations in order to generate the results. The simulation platform is described in the following section.

Table 7.1. Data for Parameters and Sub-Parameters Associated with PBES Activities (Part-I)

	Activities					
	Design superstructure		Transport the elements		Close the facility carried for traffic	
	Parameter	***Data (Source)***	***Parameter***	***Data (Source)***	***Parameter***	***Data (Source)***
Parameters/Sub-Parameters Data	Span length (L)	99 ft (proposed bridge plans) [i.e., 80 ft ≤ L < 140 ft, (see the correlations in Chapter 6)]	Transportation limitations	Moderate (location of the bridge and truck route to the bridge from prefabrication plants)	Average daily traffic (ADT) on facility carried (FC)	11,100 (Pontis dBase)
	Beam spacing (S)	6 ft ≤ S < 10 ft (expected based on the proposed width and span length of the bridge (see the correlations in Chapter 6))	Safety requirement	Moderate (truck route to the bridge from prefabrication plants)	Financial and political risks	High (based on significance of PBES implementation for the project)
	Skew (θ)	θ = 0° (proposed bridge plans)	Equipment malfunction possibility	Moderate (past projects in the region)	Site condition complexities	None (existing bridge plans and site layout)
	Underclearance (UC)	UC = 16.07 ft (existing) (Pontis dBase)	Prefabricator experience (for fabricating and transporting elements)	Moderate (available prefabricators in the region)	Stakeholder (nearby property owners') limitations	Very High (corridor analysis, MDOT carpool parking lot is highly affected)
	Aesthetic requirements	Low (significance of the bridge location)	Material availability (for fabricating elements)	High (availability of materials required for PBES in the region)	Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	None (traffic analysis and site layout)
	Geometric complexity (curved bridge, etc.)	Low (layout of proposed structure)			Detour availability/ Length of detour	Unavailable (Pontis dBase; Note: The dBase gives a value of 0 miles, i.e., detour is not feasible)
					Impact on local communities	High (corridor analysis, site layout, and project influence area)

Table 7.2. Data for Parameters or Sub-Parameters Associated with PBES Activities (Part-II)

	Activities					
	Repair/Construct permanent substructure on existing alignment		**Erect the elements**		**Connect the elements**	
	Parameter	***Data (Source)***	***Parameter***	***Data (Source)***	***Parameter***	***Data (Source)***
Parameters/Sub-Parameters Data	Right-of-way (ROW) on feature intersected (FI) for equipment staging	Unrestricted (existing bridge plans and site layout)	Lane closure/ traffic shift restrictions on FI	Very High (corridor analysis)	Material availability	Low (availability of specialized materials in the region for PBES connections)
	Lane closure/ traffic shift restrictions on FI	Very High (corridor analysis)	ROW on FI for equipment staging	Unrestricted (existing bridge plans and site layout)	Contractor experience (specific to superstructure system)	High (for DBT girder system requiring few connections); Moderate (for a FD deck panel system) (based on available contractors for the project)
	Vertical grade/slope of superstructure	3.04% (existing bridge plans)	Crane set-up difficulty	Moderate (early investigation of the site and ground condition information from Web Soil Survey (USDA 2013))	Equipment malfunction possibility	Low (availability of equipment and spares required for connecting the elements)
	Quality assurance of repair	Very High (based on experience of available contractors)			Constructability of design (specific to superstructure system)	Not difficult (for DBT girder system); Moderate (for a FD deck panel system) (based on proposed bridge plans)
	Environmental protection near and within site	None (based on information from the Michigan wetland inventory maps (DTMB 2016) and site layout)			Non-conformances in element fabrication/ tolerances	Moderate (available prefabricators in the region and their past performance)
	Scour or hydraulic issues	None (existing bridge plans & Pontis dBase)				
	Complexity of constructing new foundation when bridge is not in service	Low (site layout and existing bridge plans)				

Table 7.3. Data for Parameters or Sub-Parameters Associated with SPMT Move Activities (Part-I)

	Activities					
	Design superstructure		Prepare staging area		Construct superstructure at staging area	
Parameters/Sub-Parameters Data	***Parameter***	***Data (Source)***	***Parameter***	***Data (Source)***	***Parameter***	***Data (Source)***
	Span length (L)	99 ft (proposed bridge plans) [i.e., 80 ft ≤ L < 140 ft]	Availability of staging area	Limited and additional area purchase required (site layout and early investigation of the site)	Material availability (for prefabricating girders)	High (availability of materials in the region taking into account the superstructure systems)
	Beam spacing (S)	6 ft ≤ S < 10 ft (expected based on the proposed width and span length of the bridge)	Number of spans for SPMT move	2 (proposed bridge plans)	Prefabricator experience (for delivering girders to staging area on-time)	Very High (available prefabricators in the region)
	Skew (θ)	θ = 0° (proposed bridge plans)	Environmental sensitivity of staging area	High (based on information from the Michigan wetland inventory maps (DTMB 2016) and site layout)	Contractor experience	Low (available contractors of SPMT move for the project)
	Underclearance (UC)	UC = 16.07 ft (existing) (Pontis dBase)	Complexity of constructing temporary substructure	High (site layout and early investigation of the site)	Constructability of design	Not difficult (proposed superstructure systems for SPMT move)
	Aesthetic requirements	Low (significance of the bridge location)	Base preparation requirement based on allowable ground bearing pressure	High (based on information from Web Soil Survey (USDA 2013))	Equipment malfunction possibility	Low (availability of equipment required for constructing the superstructure at staging area)
	Geometric complexity	Low (layout of proposed structure)	Impact on overhead & underground utilities	High (site layout and early investigation of the site)	Project special provisions	Limited (specifications for SPMT move in the region are yet to be developed)
			Complexity of relocating utilities	Very High (early investigation of the site)	Complexity of lifting and moving the superstructure	Moderate (taking into account the superstructure systems and site layout)
			DOT/Contractor coordination	Moderate (past ABC projects in the region)	SPMT subcontractor experience	Low (available SPMT subcontractors)
			SPMT subcontractor experience	Low (available SPMT subcontractors in the region)		

Table 7.4. Data for Parameters or Sub-Parameters Associated with SPMT Move Activities (Part-II)

	Activities			
	Repair/Construct permanent substructure on existing alignment		Close the facility carried and feature intersected for traffic	
	Parameter	***Data (Source)***	***Parameter***	***Data (Source)***
Parameters/Sub-Parameters Data	Right-of-way (ROW) on feature intersected (FI) for equipment staging	Unrestricted (existing bridge plans and site layout)	Average daily traffic (ADT) on facility carried (FC)	11,100 (Pontis dBase)
	Lane closure/ traffic shift restrictions on FI	Very High (corridor analysis)	ADT on FI	44,600 (Pontis dBase)
	Vertical grade/slope of superstructure	3.04% (existing bridge plans)	Financial and political risks	Moderate (based on significance of SPMT move implementation for the project)
	Quality assurance of repair	Very High (based on experience of available contractors for the project)	Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	None (traffic analysis and site layout)
	Environmental protection near and within site	None (based on information from the Michigan wetland inventory maps (DTMB 2016) and site layout)	Impact on nearby major intersection/highway-rail grade crossing due to closure of FI	None (traffic analysis and site layout)
	Scour or hydraulic issues	None (existing bridge plans and Pontis dBase)	Detour availability/ Length of detour	Unavailable (Pontis dBase)
	Complexity of constructing new foundation when bridge is in service	Very High (site layout and existing bridge plans)	Stakeholder (nearby property owners') limitations	Very High (corridor analysis, MDOT carpool parking lot is highly affected)
			Impact on local communities	High (corridor analysis, site layout, and project influence area)

Table 7.5. Data for Parameters or Sub-Parameters Associated with SPMT Move Activities (Part-III)

	Activities			
	Prepare travel path		Jack and move the superstructure	
	Parameter	***Data (Source)***	***Parameter***	***Data (Source)***
Parameters/Sub-Parameters Data	Travel path complexity	High (site layout and early investigation of the site)	Project special provisions	Limited (specifications for SPMT move in the region are yet to be developed)
	Number of spans for SPMT move	2 (proposed bridge plans)	Equipment malfunction possibility	High (no experience of SPMT move in the region)
	Underclearance (UC) at final alignment	UC = 16.07 ft (existing) (Pontis dBase)	Vertical grade/ slope of superstructure	3.04% (existing bridge plans)
	Vertical grade/slope of superstructure	3.04% (existing bridge plans)	SPMT stroke availability	Limited (based on available SPMT move equipment in the region)
	Base preparation requirement based on allowable ground bearing pressure	High (based on information from Web Soil Survey (USDA 2013))	Limitations for SPMT move operation (e.g., weather)	Low (operations involved in SPMT move and typical weather in the project region)
	Impact on overhead & underground utilities	High (based on SPMT move staging area) (site layout and early investigation of the site)	DOT coordination	Moderate (past ABC projects in the region)
	Complexity of relocating utilities	Very High (based on SPMT move staging area) (early investigation of the site)	Safety assurance	Moderate (available SPMT subcontractor experience with respect to safety)
	DOT/Contractor coordination	Moderate (past projects in the region)		
	SPMT subcontractor experience	Low (available SPMT subcontractors in the region)		

Table 7.6. Data for Parameters or Sub-Parameters Associated with SIBC Activities (Part-I)

	Activities			
	Design superstructure		**Construct temporary substructure**	
	Parameter	***Data (Source)***	***Parameter***	***Data (Source)***
Parameters/Sub-Parameters Data	Span length (L)	99 ft (proposed bridge plans) [i.e., 80 ft ≤ L < 140 ft]	Average daily traffic (ADT) on feature intersected (FI)	44,600 (Pontis dBase)
	Beam spacing (S)	6 ft ≤ S < 10 ft (expected based on the proposed width and span length of the bridge)	Right-of-way (ROW) on FI for equipment staging	Unrestricted (existing bridge plans and site layout)
	Skew (θ)	θ = 0° (proposed bridge plans)	Lane closure/ traffic shift restrictions on FI	Very High (corridor analysis)
	Underclearance (UC)	UC = 16.07 ft (existing) (Pontis dBase)	Vertical grade/slope of superstructure	3.04% (existing bridge plans)
	Aesthetic requirements	Low (significance of the bridge location)	Environmental protection near and within site	None (based on information from the Michigan wetland inventory maps (DTMB 2016) and site layout)
	Geometric complexity	Low (layout of proposed structure)	Loads on superstructure at temporary location	Heavy (assuming SIBC case-1 and considering the truck traffic on the bridge)
			Site constraints for parallel replacement structure construction	Minor (existing bridge plans and site layout)
			Available ROW for SIBC	Unrestricted (existing bridge plans and site layout)
			Scour or hydraulic issues	None (existing bridge plans and Pontis dBase)
			Complexity of constructing new foundation (for temporary substructure construction alongside to the existing bridge)	Low (site layout and existing bridge plans)
			Impact on overhead & underground utilities	Low (based on SIBC temporary substructure construction alongside the existing structure) (site layout and early investigation of the site)
			Complexity of relocating utilities	None (based on SIBC temporary structure construction alongside the existing structure) (early investigation of the site)

Table 7.7. Data for Parameters or Sub-Parameters Associated with SIBC Activities (Part-II)

	Activities			
	Construct superstructure on temporary substructure		**Construct approaches for temporary run-around**	
Parameters/Sub-Parameters Data	***Parameter***	***Data (Source)***	***Parameter***	***Data (Source)***
	Material availability (for prefabricating girders)	High (availability of materials in the region taking into account the superstructure systems)	Complexity of constructing temporary run-around	Moderate (site layout and early investigation of the site)
	Prefabricator experience (for delivering girders to the project site on-time)	Very High (available prefabricators in the region)	ADT on facility carried (FC)	11,100 (Pontis dBase)
	Contractor experience	Moderate (available contractors of SIBC for the project)	Restriction on closure of curb-lanes on FC	Moderate (corridor analysis)
	Constructability of design	Moderate (proposed superstructure systems for SIBC)	ROW on FC for equipment staging	Unrestricted (existing bridge plans and site layout)
	ROW on FI for equipment staging	Unrestricted (existing bridge plans and site layout)	Vertical grade/ slope of superstructure	3.04% (existing bridge plans)
	Lane closure/ traffic shift restrictions on FI	Very High (corridor analysis)		
	Equipment malfunction possibility	Low (availability of equipment and spares required for constructing the superstructure alongside the existing bridge)		
	Project special provisions	Moderate (specifications available and limited experience of SIBC in the region)		
	Complexity in sliding the superstructure	Low (existing bridge plans, site layout, and early investigation of the site)		
	SIBC subcontractor experience	Moderate (available SIBC subcontractors in the region)		

Table 7.8. Data for Parameters or Sub-Parameters Associated with SIBC Activities (Part-III)

	Activities					
	Route traffic onto temporary run-around		Construct permanent substructure		Jack and move the superstructure	
	Parameter	***Data (Source)***	***Parameter***	***Data (Source)***	***Parameter***	***Data (Source)***
Parameters/Sub-Parameters Data	ADT on FC	11,100 (Pontis dBase)	ROW on FI for equipment staging	Unrestricted (existing bridge plans and site layout)	Project special provisions	Moderate (specifications available and limited experience of SIBC in the region)
	Financial and political risks	Low (based on significance of SIBC implementation for the project)	Lane closure/ traffic shift restrictions on FI	Very High (corridor analysis)	Equipment malfunction possibility	Moderate (availability of equipment and spares required for sliding the new superstructure)
	Stakeholder (nearby property owners') limitations	Very High (corridor analysis, MDOT carpool parking lot is highly affected)	Vertical grade/slope of superstructure	3.04% (existing bridge plans)	Vertical grade/ slope of superstructure	3.04% (existing bridge plans)
	Risk of traffic within work zone	Low (traffic analysis and early investigation of the site taking into account SIBC operations)	Environmental protection near and within site	None (based on information from the Michigan wetland inventory maps (DTMB 2016) and site layout)	Safety assurance	High (based on available SIBC subcontractor experience with respect to safety while implementing SIBC case-1)
	Detour availability/ Length of detour	Unavailable (Pontis dBase)	Scour or hydraulic issues	None (existing bridge plans & Pontis dBase)	Impact of sliding forces on the structure	Low (proposed structure layout and proposed sliding plans)
			Complexity of constructing new foundation (after the traffic is routed onto temporary run-around and the old bridge demolished)	Low (site layout and existing bridge plans)	Limitations of operation (e.g., weather limitations, geometric complexity, and superstructure getting stuck in skid tracks.)	Moderate (operations involved in SIBC, typical weather in the project region, proposed bridge plans, and site layout)

Generating the results

In order to execute the agent interactions for the alternatives and generate the evaluation results, a simulation platform was developed using Excel® worksheets and VBA scripts. The input data presented in Table 7.1 to Table 7.8 is converted to the project-specific uncertainty ratings based on the *knowledgebase* of *parameter correlations* developed in Chapter 6. The project-specific uncertainty ratings are incorporated in the simulation platform using a distinct Excel® worksheet for the set of alternatives that implement the same ABC method. The screen shots of the input are presented in Appendix D.

Further, the input to the simulation platform includes specifying the alternatives and the agents that are involved with respective activities; ontologies of the alternatives are utilized for this purpose. The base cost and base duration estimates of the alternatives are also introduced in the simulation platform. For the M-50 over I-96 project, the base cost and base duration of the alternatives were estimated using the cost estimates from Abudayyeh et al. (2010), Attanayake et al. (2012), Aktan and Attanayake (2015), and Mohammed et al. (2016). In addition, the equipment hubs of Sarens and Mammoet in-and-around Michigan were identified from respective websites to assist in the cost calculations for the specialty equipment mobilization and procurement costs. The cost estimates are also shown in Appendix D. The activities of the alternatives may affect project cost, construction duration, or both. Therefore, the decision maker must specify the *measure of project performance* that is affected due to the respective activities.

The simulation platform consists of sets of tables that are associated with VBA scripts. The main set of simulation tables that allow specifying the alternatives and performing the simulations in order to generate the results are shown in Figure 7.3. The simulation table that executes agent interactions when called by the main set of simulation tables is shown in Figure 7.4. After all the input data is incorporated in the simulation platform, the simulation is executed using *Run Simulation and Generate Results* command button (Figure 7.3). In each simulation run, a random interaction is generated for each alternative and respective agents are called. Then, the agents generate random probability values and use respective node classes (typically node class *B* and node class

C shown in Figure 7.4) in order to calculate an activity uncertainty variate for the associated activity. This process represents a step in the Monte Carlo Simulation. Using the activity uncertainty correlations described in Chapter 6, the percentage change in cost and duration are calculated (typically an agent with node class *B* provides the calculated values to the agent with node class *A* shown in Figure 7.4). Based on the activity associated with the selected interaction, the updated project cost, updated construction duration or both are calculated and stored (typically an agent with node class *A* shown in Figure 7.4 calculates the updated values and stores the data).

RUN SIMULATION AND GENERATE RESULTS

Agent Interactions for Alternative:	Activity Row	Activity No.	Base Cost ($)	Base Duration (days)	Updated Cost Estimate ($)	Updated Duration Estimate (days)
PBES X	2	10	$ 1,978,577	58		
PBES Y	4	21	$ 2,909,390	86		
PBES Z	3	20	$ 3,240,352	90		
SPMT Move X	7	30	$ 4,866,546	4		
SPMT Move Y	6	23	$ 5,315,904	3		
SIBC X	11	50	$ 3,895,673	14		
SIBC Y	9	32	$ 4,627,060	8		
SIBC Z	12	51	$ 4,444,000	10		

Random Interaction No.	
PBES	4
PBES	8
PBES	3
SPMT	11
SPMT	16
SIBC	8
SIBC	5
SIBC	8

Main Activity	Sub-activity	Agent w/ 'A'	Agent w/ 'B'	Agent w/ 'C'	Agent w/ 'C' Calc. Un. Est. $\{1-\pi(1-P_f)\}$	Agent w/ 'B' Calc. $\pi(1-P_f)$	Agent w/ 'B' Calc. Activity Un. $\{1-\pi(1-P_f)\}$	Agent w/ 'A' getting % change cost	Agent w/ 'A' getting % change duration
20		Yes	Yes			0.418873398	0.581126602	8.415021362	0
20		Yes	Yes				0.661270411	9.48360548	0
	21		Yes	Yes	0.19133182	0.418873398			
20		Yes	Yes				0.686063742	9.814183225	0
	21		Yes	Yes	0.19133182	0.418873398			
	22		Yes	Yes	0.07319505				
20		Yes	Yes				0.712244032	9.814183225	0
	21		Yes	Yes	0.19133182	0.418873398			
	22		Yes	Yes	0.07319505				
	23		Yes	Yes	0.08339365				

Figure 7.3. Set of simulation tables for generating results

AGENT W/ NODE CLASS A

Act	=	Calc. for PBES_X_20
MnAgent		DOT
ChC%		23.3731
ChD%		23.3731
UpC		2379897.551
UpD		69.76431378

AGENT W/ NODE CLASS B

Act	=	20
ResAgent		Contractor
ActUn		0.9675
ChC%		23.3731
ChD%		23.3731

Activity & ABC System: 20X

Project-Specific Uncertainty Ratings for Respective Activity	Parameter Probability of Affecting the Project Perfromance (P_f)	1-P_f
H	0.6414	0.3586
M	0.3521	0.6479
H	0.5939	0.4061
0		
0		
0		
	Product:	0.0943

AGENT W/ NODE CLASS C

SubAct	=	21
Agent		Prefabricator
SubUn		0.6551

Sub-Activity & ABC System: 21X

Project-Specific Uncertainty Ratings for Respective Sub-Activity	Parameter Probability of Affecting the Project Perfromance (P_f)	1-P_f
H	0.6414	0.3586
VL	0.0380	0.9620
0		
0		
0		
0		
	Product:	0.3449

Significance	**Uncertainty Variate Range**	
VL	0	0.05
L	0.05	0.2
M	0.2	0.4
H	0.4	0.7
VH	0.7	1

Random No.
0.2834
0.1928
0.8677
0.0089
0.0793
0.9318

Figure 7.4. Simulation table to perform agent interactions

A total of 5000 simulation runs are performed and the model output from each simulation run is obtained using the process described above. The sample data obtained from the simulation is analyzed using the statistical analysis software Stat::Fit®. The analysis showed that the sample data for each alternative is a *no fit* to the available probability distributions in Stat::Fit®. In such cases, Stat::Fit® recommends using the empirical function in order to obtain the cumulative probability of the sample data. The empirical function estimates the cumulative distribution function underlying the sample data and converges with the probability 1.0 according to the Glivenko-Cantelli theorem (Geer Mountain Software Corp. 2001). The cumulative probability charts obtained for the alternatives using the empirical function are shown in Figure 7.5 and Figure 7.6. The charts provide the likelihood (percentage confidence) of the measures of project performance for an alternative; this provides the decision makers with a vast arena of possible inferences during their judgment process. Descriptive statistics of the data is calculated in order to draw conclusions, which are presented in the following section.

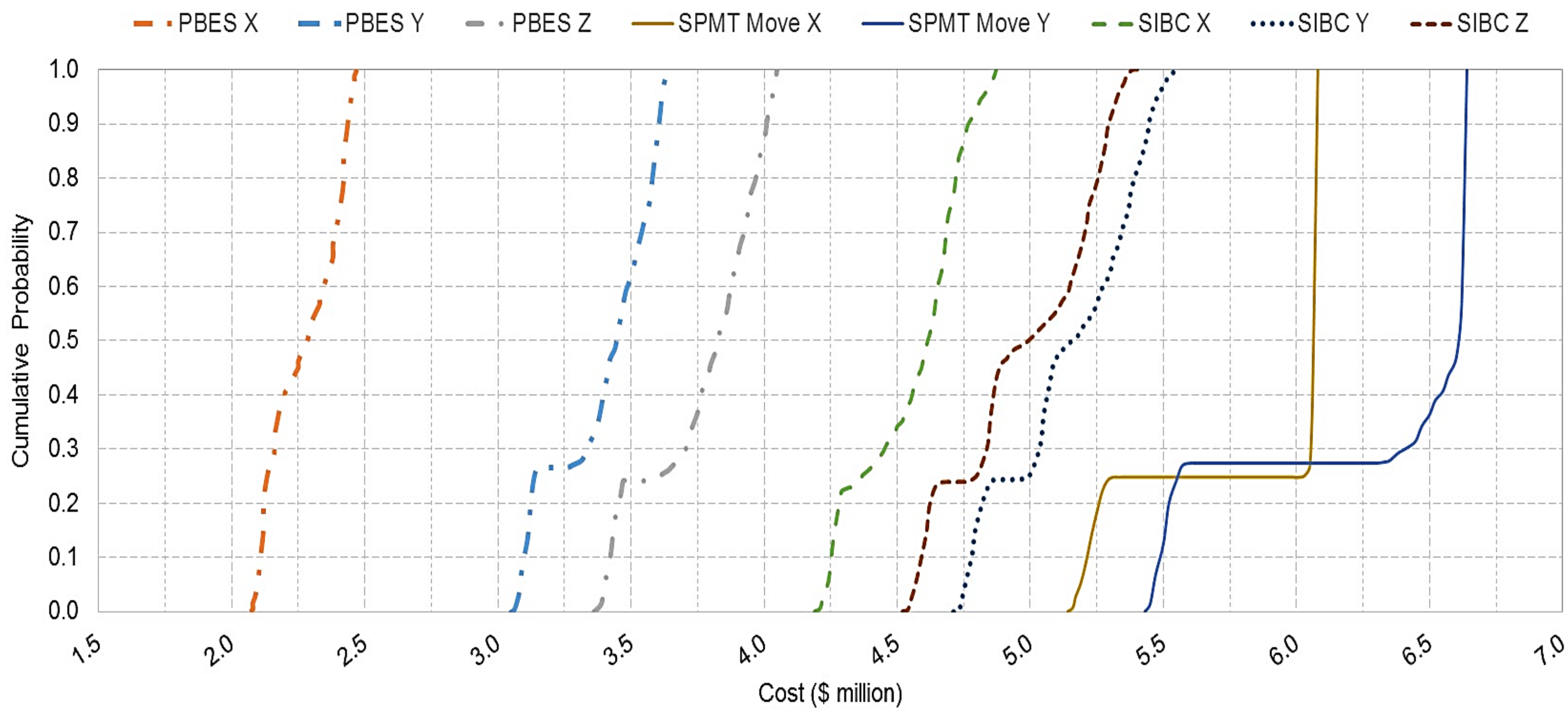
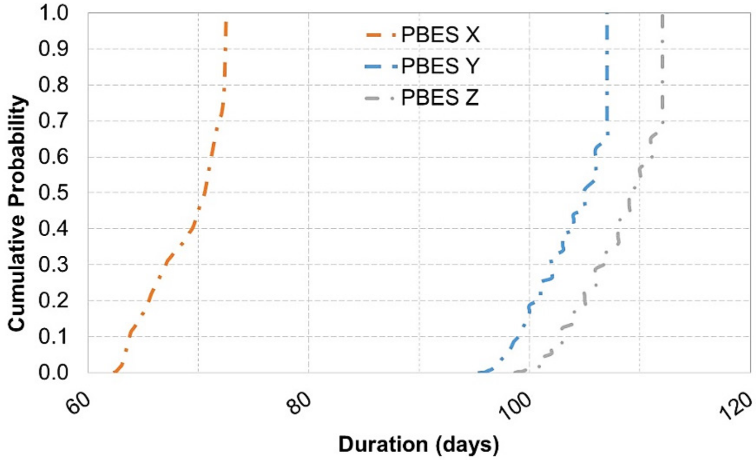
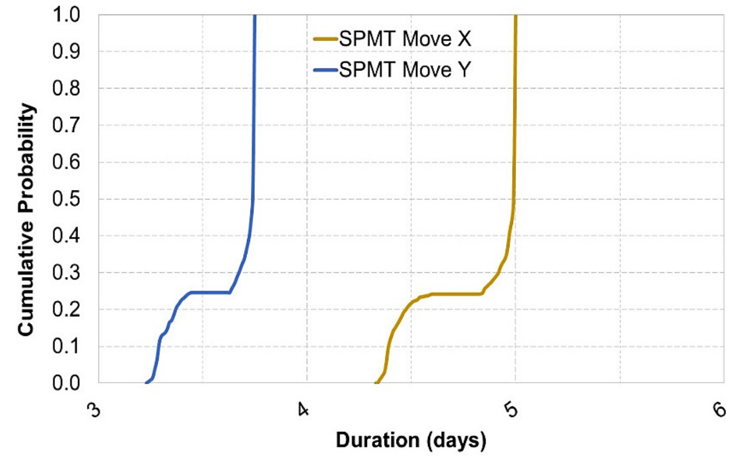


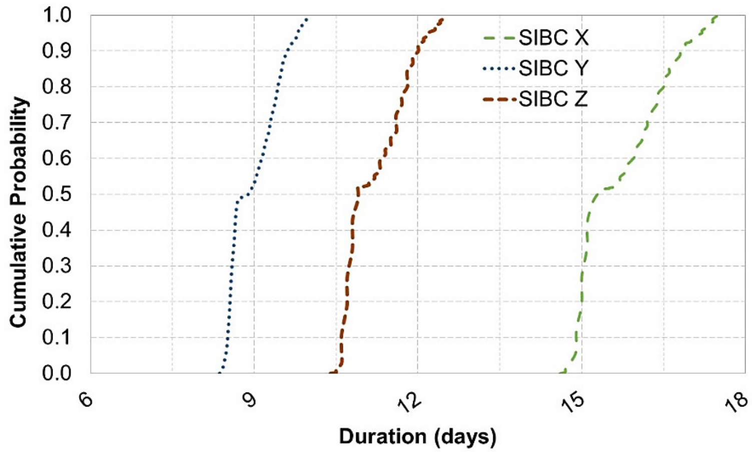
Figure 7.5. Cumulative probability charts for the cost of the alternatives



(a) Alternatives with PBES method



(b) Alternatives with SPMT move method



(c) Alternatives with SIBC method

Figure 7.6. Cumulative probability charts for the duration of the alternatives

Interpretation of the results and conclusions

An alternative (i.e., an ABC method and an associated superstructure system) with the least cost may not be optimal for a project because it may not provide the desired durability and constructability of the bridge. If the durability and constructability associated with an alternative are optimal for a project, there will be less uncertainty and the alternative will be the most appropriate for the project.

The effect of implementing an alternative at a project site can be identified by observing the variability in project cost and construction duration with respect to the base estimates. Here, the variability is defined as the deviation of the calculated cost or duration value from respective base estimate in each simulation run. The variability will be due to the uncertainty that arises based on the activities associated with the ABC method, the characteristics of the superstructure system, and the collaboration of internal stakeholders while implementing the ABC method.

For the implementation example, the descriptive statistics of the data for each alternative is obtained as shown in Table 7.9 and Table 7.10. The standardized statistic called coefficient of variation (COV) is used for observing the variability in project cost and construction duration. The COV measures the dispersion of a probability distribution and shows the extent of variability in a data set (Everitt 1998; Lomax 2007; Mendenhall et al. 2009). The COV is expressed as a percentage and is calculated using Eq. 7-1.

$$COV(\%) = \frac{\text{Dispersion of Data}}{\text{Expected Return}} \times 100 \tag{7-1}$$

The Standard Deviation can provide the deviation from an expected value for each alternative; however, it is unsuitable for comparing the alternatives because the base estimates of the alternatives differ significantly for a project. Alternatively, the COV is useful for comparing the alternatives because it provides a ratio for each alternative in the context of respective expected value such as the base estimate. For comparison between data sets with widely different means, COV is recommended instead of the Standard Deviation (Everitt 1998; Lomax 2007; Mendenhall et al. 2009). The COV is commonly used in engineering and physics while performing comparative studies. The COV is also common in applied probability fields such as renewal theory, queueing theory, and reliability theory. The higher the COV value, the higher is the dispersion of data from the expected value.

In our case, to identify the variation in the obtained data from the base estimate, COV is calculated using Eq. 7-2, wherein the dispersion of data is calculated using the 'Sample Standard Deviation' with respect to the base estimate.

$$COV(\%) = \frac{\text{Dispersion of Data w.r.t. Base Estimate}}{\text{Base Estimate}} \times 100 \qquad (7\text{-}2)$$

For the M-50 over I-96 bridge project, the COV of cost data and duration data can be used to infer the most appropriate ABC method in terms of constructability and durability. However, the COV of duration data can be specifically used to infer the most appropriate superstructure system for the site. The duration data is selected to identify the most appropriate superstructure system because the duration is considered as the chief measure of performance of the project. Identifying the least COV values in Table 7.9 and Table 7.10, it can be concluded that SIBC method is suitable for the M-50 over I-96 bridge project. Further, observing the COV values of the duration data (Table 7.10) it can be concluded that the alternative SIBC-Z (i.e., SIBC with precast spread box beams and CIP deck system) is the most appropriate alternative.

Note that the inferences of the results may vary if the decision makers choose to select other measure of performance of the project in order to identify the most appropriate alternative. The decision-making framework can be extended in order to obtain evaluation results specific to other measures of project performance as a future research (will be discussed in Chapter 8).

Table 7.9. Descriptive Statistics of Cost Data for the Alternatives

	PBES-X	PBES-Y	PBES-Z	SPMT Move-X	SPMT Move-Y	SIBC-X	SIBC-Y	SIBC-Z
Data Points	1974	2015	1963	1159	1144	1424	1460	1400
Mean	2,272,960	3,392,720	3,766,440	5,861,370	6,296,590	4,552,420	5,144,190	4,975,910
Median	2,279,910	3,440,940	3,827,330	6,071,060	6,609,700	4,617,070	5,152,690	4,996,020
Mode	2,119,800	3,114,230	3,432,230	6,083,170	6,644,880	4,266,930	5,047,610	4,863,960
Base estimate	1,978,577	2,909,390	3,240,352	4,866,546	5,315,904	3,895,673	4,627,060	4,444,000
Dispersion of data w.r.t. base estimate	322,062	520,167	569,406	1,060,913	1,097,543	685,205	574,229	595,645
Coefficient of variation w.r.t. base estimate (COV)	**16.28**	**17.88**	**17.57**	**21.80**	**20.65**	**17.59**	**12.41**	**13.40**

Table 7.10. Descriptive Statistics of Duration Data for the Alternatives

	PBES-X	PBES-Y	PBES-Z	SPMT Move-X	SPMT Move-Y	SIBC-X	SIBC-Y	SIBC-Z
Data Points	2047	1936	2035	1188	1173	1424	1435	1446
Mean	69.18	104.04	108.57	4.84	3.63	15.69	8.98	11.19
Median	70.50	105.26	109.42	4.99	3.74	15.25	8.88	10.86
Mode	72.49	107.50	112.48	5.00	3.75	15.07	8.55	10.75
Base estimate	58	86	90	4	3	14	8	10
Dispersion of data w.r.t. base estimate	11.64	18.34	18.93	0.88	0.66	1.86	1.08	1.32
Coefficient of variation w.r.t. base estimate (COV)	**20.07**	**21.33**	**21.03**	**21.97**	**21.88**	**13.30**	**13.49**	**13.17**

Summary

An implementation example of the decision-making framework is presented in this chapter using M-50 over I-96 bridge replacement project in Michigan. The site characteristics of the project are described including the proposed bridge configuration. The aspects that required consideration during the bridge replacement are highlighted. The alternatives for the project are selected for evaluation by deliberating the regional requirements and the preference of contractors/prefabricators in the project region.

Requirements that were considered prior to implementation of the decision-making framework are discussed. Comprehending the requirements helps in obtaining the required input data for the decision-making framework. Two types of input data are required: (1) project specific data and (2) qualitative preferences. The data obtained for the M-50 over I-96 bridge project is presented. The project specific data was obtained based on the data available from the corridor planning process. The qualitative preferences were obtained based on the review of the project documents, and communication with the project personnel as well as engineering and planning experts who were familiar with the alternatives. While providing the qualitative preferences for the parameters, the corresponding activities of alternatives were deliberated.

The input data is converted to the project-specific uncertainty ratings based on the *knowledgebase* of *parameter correlations* developed in Chapter 6, and incorporated in a simulation platform for executing the interactions and performing simulations. The simulation platform consists of sets of tables in Excel® worksheets which are associated with VBA scripts. The input to the simulation platform includes specifying the alternatives and the agents that are involved with respective activities. For the M-50 over I-96 project, the base cost and base duration of the alternatives were estimated based on the author's previous research work, and were incorporated in the simulation platform.

A total of 5000 simulation runs are performed and the model output from each simulation run is obtained. In each simulation run, a random interaction is generated for each alternative and respective agents are called. Then, the agents generate random probability values and use respective node classes in order to calculate an activity uncertainty variate for the associated activity. Later, the updated project cost, updated construction duration or both are calculated and stored with respect to the activity.

The sample data obtained from the simulation is analyzed using the statistical analysis software Stat::Fit®. The cumulative probability charts obtained for the alternatives are presented. The charts provide the likelihood (percentage confidence) of the measures of project performance for an alternative. The standardized statistic called coefficient of variation (COV) is considered to measure the extent of variability in the obtained data with respect to the base estimates. The COV of duration data is used to infer the most appropriate ABC method for the M-50 over I-96 bridge project. It is concluded that 'SIBC with precast spread box beam and CIP deck system' is the most appropriate alternative for the project. It is highlighted that it is possible for the decision makers to have dissimilar inferences of the results provided they select other measure of project performance.

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

Summary

In recent years, several state Departments of Transportation (DOTs) in the U.S. have developed decision-making models to compare broadly Accelerated Bridge Construction (ABC) to conventional bridge construction for a particular site. However, several limitations in the available decision-making models were identified. To overcome the limitations in the available decision-making models, a hybrid decision-making model was developed by the author as a part of Michigan Department of Transportation (MDOT) research project MDOT RC-1602 (Aktan and Attanayake 2013). Yet, the hybrid decision-making model addresses only one of the several challenges that state DOTs encounter during scoping of ABC projects. Thus, further research was required to address the ABC decision-making need of specifying a particular superstructure system to be used with an ABC method, and of evaluating constructability and durability of ABC methods and the superstructure systems with respect to site-specific conditions.

Understanding the current and future needs of the state DOTs, this research study was initiated to develop a decision-making model/tool that addresses the ABC decision-making need by means of evaluating the uncertainty of the alternatives. The uncertainty arises because of the activities associated with ABC methods, and constructability and durability of superstructure systems with respect to site-specific conditions. Moreover, the interactions among the internal stakeholders such as the DOT, Designer, Contractors, Consultants, etc., while delivering a project using an ABC method contribute to the uncertainty.

To gauge the impact of the uncertainty and the interactions on an ABC project performance, two metrics were used: (1) project cost, and (2) construction duration (mobility impact time). These were termed as measures of performance of the project. During the inception of this research, literature was gathered to identify the state-of-the-art decision-making models for bridge projects. Also, literature was gathered to identify mathematical models used in the decision-making and their respective capabilities and limitations. From the literature review, it was concluded that the complex system modeling methodology is appropriate for addressing the ABC decision-making needs. The process of implementing an ABC method was considered a complex system, wherein the risks/uncertainties associated with the activities and the stakeholder collaboration affect project performance in terms of constructability and durability.

Additionally, a need was recognized to identify a suitable complex system modeling technique for formulating the decision-making model. This directed to the review of complex system modeling techniques. From the review it was identified that several industries, such as manufacturing, business, technology, logistics, economics, and the social sciences implement agent-based modeling and simulation packages to effectively manage a complex system and predict system performance. Also, numerical computer-based simulation was identified as a suitable technique for imitating the behavior of a complex system and estimating its performance. Considering the specific findings from the review, implementing agent-based complex system modeling methodology was considered suitable for formulating the decision-making model. The complex system characteristics considered for this purpose were the following:

- The system consists of a large number of interacting agents acting in parallel with dispersed control.
- The agents in the system are associated with attributes that govern respective actions.
- Each agent performs an action and produces an outcome that affects the system outcome.
- The agents interact with each other and respond to their surrounding environment based on their respective purpose in the system.

- The agents have the ability to change their behavior based on past experiences (knowledgebase).

The concepts utilized to model and simulate the processes involved in implementing the ABC methods were discussed. Then the decision-making framework for evaluating ABC methods and the associated superstructure systems (alternatives) for a given site was developed. The framework incorporated specific ABC methods: (1) Prefabricated Bridge Elements and Systems (PBES), (2) Self-Propelled Modular Transporter (SPMT) move, and (3) Slide-In Bridge Construction (SIBC). The superstructure systems constructed using the following were considered in the framework: (1) prefabricated girders and deck panels, (2) prefabricated girders and cast-in-place (CIP) deck, and (3) prefabricated modules. Further, the owner agency such as the DOT was considered to transfer detailed engineering design and construction activities to the design and construction contractors. The internal stakeholders considered for implementing an ABC method included the DOT, the designer, the contractor (general contractor), the consultants, the subcontractors, and the public.

In the framework, for evaluating the alternatives using agent-based modeling approach, activities (major-work assignments) included in the ABC methods were identified. Also, specific to an ABC method, relationship among the agents for respective activities was identified and represented in terms of task-actor-relation table. Ontology was used to represent the agent-based model of an ABC method implementation. The impact was measured in terms of uncertainty of an activity. Agents were associated with several node classes that enable them to execute processes during the simulation. A node class was represented in the form of an array that included attributes which enabled an agent to obtain data from other agents for an activity and calculate the impact on project cost and construction duration.

Recommendations of elements for superstructure systems were developed in order to assist in specifying the superstructure systems for the evaluation. In order to develop the recommendations, typical cross-sections and span lengths of superstructure elements used in ABC projects were compiled from reviews of bridge plans, recent demonstration projects, and input from project engineers directly involved in ABC projects. The recommendations are based on careful analysis of the continuity details, durability performance, familiarity of stakeholders, constructability challenges, and other limitations due to site-specific conditions.

Each activity in an alternative was associated with a set of parameters such that they contribute to the uncertainty of the activity. Parameter probability of affecting the project performance was considered in order to quantify the impact of a parameter on project performance. Parameter correlations with potential site-specific conditions were developed for obtaining the parameter probabilities. In order to develop the correlations, potential superstructure systems for each ABC method were considered based on the recommended superstructure elements. Also, the viewpoint of internal stakeholders involved with ABC projects of a region was considered for developing the correlations. In this study, potential superstructure systems for each ABC method and the correlations were presented for Michigan.

In the agent-based model of an ABC method implementation, a set of procedures were defined that allowed calculating the uncertainty associated with an activity. The uncertainty of an activity was calculated by implementing the reliability engineering concept of the *Competing Risk Case* of determining component reliability. Equation to calculate the uncertainty of an activity that is associated with a number of "independent" parameters was defined. For the activities that were associated with a number of "dependent" and "independent" parameters, Beta-Factor model was implemented and the corresponding equation to calculate the uncertainty was defined. The available uncertainty/risk correlations for ABC projects were utilized in drawing statistical inferences of the impact of the uncertainty of the activities on project cost and construction duration. The correlations were also utilized in quantifying the parameter probability of affecting the project performance. After the modeling steps, simulation steps were defined. A process was defined to implement Monte Carlo Simulation for analyzing the impact of uncertainty associated with the alternatives on project cost and construction duration.

An implementation of the decision-making framework was demonstrated using M-50 over I-96 bridge project. The site characteristics of the project were described including the proposed bridge configuration. The aspects that needed consideration during the bridge replacement were highlighted. The alternatives for the project were selected for evaluation by deliberating the regional requirements and the preference of contractors/prefabricators in Michigan. Prerequisites for implementation of the decision-making framework were discussed. Two types of input were required for the implementation: (1) project specific data and (2) qualitative preferences. The data obtained for the M-50 over I-96 bridge project was presented. The project specific data was obtained based on the data available from the corridor planning process and a bridge management database (Pontis database). The Web Soil Survey under the jurisdiction of United States Department of Agriculture and Michigan wetland inventory maps were also reviewed to supplement some of the project specific data input. In addition, the equipment hubs of Sarens and Mammoet in-and-around Michigan were identified from respective websites to assist in the cost calculations for the specialty equipment mobilization and procurement. On the other hand, the qualitative preferences were obtained based on the review of the project documents, and communication with engineering and planning experts who were familiar with the alternatives. While providing the qualitative preferences for the parameters, the corresponding activities were also deliberated.

The input data was converted to the project-specific uncertainty ratings based on the 'knowledgebase of parameter correlations' developed for Michigan, and was incorporated in a simulation platform for performing simulations. The simulation platform consisted of sets of tables in Excel® worksheets which were associated with VBA scripts. For the M-50 over I-96 project, the base cost and base duration of the ABC alternatives were estimated based on the author's previous research work, and were incorporated in the simulation platform. The sample data obtained from several simulation runs was analyzed using the statistical analysis software Stat::Fit®. Cumulative probability charts obtained for the alternatives provided the percentage confidence of the project cost and construction duration. Standardized statistic called coefficient of variation was used to infer the most appropriate alternative for the project.

Conclusions

A decision-making framework is developed for evaluating the ABC methods and the associated superstructure systems (termed as alternatives in the decision-making) for a given site, which furnishes the primary stage towards developing an automated decision-making model/tool for obtaining optimal constructability and durability of bridges. Specific conclusions that are derived from this research study are the following:

- Agent-based modeling is a valuable technique for the decision-making of bridge construction projects.
- Implementing ontologies for the agent-based models offer the flexibility of modifying/extending the decision-making model for project specific needs.
- Arrays are useful means for mathematically formulating the attributes of agents and allowing data exchange among the agents.
- *Competing Risk Case* of determining component reliability along with *Beta-Factor* model is suitable for mathematically modeling the relationship between an activity and the associated dependent/independent parameters in the decision-making.
- Numerical computer-based simulation techniques are favorable for implementing agent-based modeling and probabilistic approach in the decision-making model.
- Deriving conclusions from the simulation data highly depends on the *goodness of fit* of the data to an available probability distribution. If the obtained data is a *no fit* to the available probability distributions, an empirical function can be used. However, the empirical function should estimate the cumulative distribution function underlying the sample data and converge with probability 1.0.
- Cumulative probability charts are ideal for presenting the results to the decision makers as they illustrate the possible inferences that a decision maker can use during the decision-making.
- Uncertainty associated with the ABC methods and the collaboration of internal stakeholders of ABC projects have significant impact on the constructability and durability of bridges.

- Several metrics in addition to the project cost and construction duration can be used in the decision-making in order to gauge the impact of the uncertainty on a project performance.
- The best alternative for a bridge project exhibits optimal durability and constructability, rather than the least cost. Optimal durability and constructability of an alternative leads to the least uncertainty (variation in the data). The Coefficient of Variation (COV) statistic is appropriate for identifying the optimal alternative rather than the Standard Deviation (SD) statistic, because SD is unsuitable for comparing the alternatives with widely different base estimates for a project. The COV provides ratios for the alternatives in the context of respective base estimate, which offer a uniform measure for comparing the alternatives.
- Standardizing superstructure elements, developing material specifications, and providing construction guidelines for specific ABC methods help in collecting reliable performance data for the decision-making.
- It is imperative to develop a region-specific knowledgebase, which includes performance ratings of the available alternatives with respect to the decision-making parameters, for ABC project scoping.

Recommendations for future research

Deliberating the scope of this research study, the following future research studies can be conducted:

- The decision-making framework developed in the research study can be expanded to include several ABC methods and associated superstructure systems (alternatives) for a particular region. Also, the list of internal stakeholders and the list of activities of ABC methods can be expanded for more detailed evaluation of the alternatives. For this, it requires identifying additional parameters that are associated with the activities and that affect the project performance. Further, the parameter correlations with site-specific data and respective qualitative ratings need to be updated based on the requirements of a particular region and favorable superstructure systems in the region.
- The developed sets of parameters for the activities can be refined by using the available resources such as the Web Soil Survey (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm), Michigan Comprehensive GIS Web (http://mgs.geology.wmich.edu/webmgs/migis.html), the Michigan Department of Technology, Management and Budget (http://www.michigan.gov/cgi/0,4548,7-158-52927_53037_12540_13817-58858--,00.html), and Michigan Department of Environmental Quality (www.mi.gov/wetlands). These resources can assist in identifying additional parameters that encompass site conditions, geology, geographic requirements, environmental investigation requirements, and environmental permit requirements. Such resources can also be used to identify the respective parameter probability of affecting the project performance.
- A comprehensive uncertainty/risk analysis can be conducted as the next stage of this research study in order to identify accurate range of values and/or distributions for the parameter probability of affecting the project performance. The risk analysis need to consider the available ABC methods and the associated superstructure systems. In the risk analysis, the parameter probabilities can be identified by gathering data from various consultants and internal stakeholders using a survey or available risk registers. If historical data is available, the data can be organized in the form of a frequency distribution and curve fitting can be

used to obtain appropriate distribution for the parameter probabilities. However, if historical data is unavailable, estimates from literature and judgment of experts need to be used for obtaining the parameter probabilities. Alternatively, database of the performance data of bridges constructed using ABC methods can be developed. This will help in identifying the statistical behavior of the performance of bridges, which can assist in developing the parameter correlations with site-specific data and associated parameter probabilities. Important parameters and activities that impact the project performance should be contemplated while developing the performance database. Further, the uncertainty/risk analysis and/or the performance database can assist in identifying accurate correlations between the uncertainty of activities and the measures of project performance.

- *Risk mitigation opportunities* can be identified for specific activities of ABC methods. Risk mitigation opportunities are additional activities that need to be considered while implementing an ABC method in order to alleviate the uncertainties/risks. A risk assessment study can help identifying the risk mitigation opportunities for respective ABC methods. It is anticipated that the risk mitigation opportunities will require additional cost/duration for the project; however, if risk mitigation opportunities are included, the reliability of a particular ABC method increases and reduces the variability in cost/duration due to the uncertainty/risk.
- Along with project cost and construction duration, additional metrics can be incorporated in the decision-making framework in order to identify the impact of uncertainty associated with the alternatives on the project performance. Further, along with the coefficient of variation statistic, other statistics can be utilized for inferring the results. This will provide the decision makers with vast arena of evaluation data for making statistical inferences regarding the alternatives.
- In future, a general purpose procedural programming language, such as VBA in Microsoft® Excel can be used to assemble the agent-based modeling methodology presented in this research study and develop the Graphical User Interface for user input, simulating, and reporting results. Alternatively, the existing Michigan

Accelerated Bridge Construction Decision-Making (Mi-ABCD) tool can be upgraded by replacing the hybrid AHP process with the agent-based modeling methodology presented in this research study. Hence, from the above, the research objective of making the tool widely available to the internal stakeholders at a reasonable cost can be achieved.

- In a future research, the resources and databases mentioned in this research study such as Pontis, can be linked to the decision-making tool in order to automate the project specific data input in future. This will help limiting the user input to qualitative preferences that are based on user experience. Obtaining the qualitative preferences from users provides an opportunity to develop a user knowledgebase within the process. The knowledgebase can increase the efficiency of the ABC decision-making process.

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Appendix A

Elements for superstructure systems

Superstructure element details from literature and past ABC projects

Girders

Precast concrete girders are the most commonly specified among all the prefabricated structural elements. Girder types and sections are developed considering span, underclearance, aesthetics, traffic loading, and exposure. Use of these girders in ABC is limited because they can only be combined with partial-depth or full-depth deck panels to qualify for accelerated construction. Though the steel girder is listed in the superstructure elements to use with ABC methods, the discussion is limited because it is possible to design steel girders for most commonly used spans using rolled or built-up sections. On the other hand, prestressed concrete girders require testing and validation when they are different from commonly used sections and spans. Hence, commonly used spans and design strengths are provided with the prestressed girders to help designers specify sections for preliminary design based on site parameters.

Most of the precast girders listed below have been used in vast majority of the projects. A few of them are standardized, and the designers, fabricators, and contractors are familiar with the benefits and limitations. The girder types, the projects where they are utilized, information on cross-section dimensions and span lengths, applicable concrete strengths, and benefits and limitations of using the girders are summarized in this Appendix. The girder types reviewed during this study include the following:

- Precast concrete (PC) I-girders
- Precast bulb-tee girders
- Precast box beams
- Steel girders
- Precast NU I-girders.

The tables given below (Table A.1, Table A.2, and Table A.3) show the design strength and possible span ranges for standard I-girders, box-beams, girders with spliced span, and bulb-tee girders.

Table A.1. Standard PC I-Girders, Spread Box Girders, and Girders with Spliced Details (Source: MDOT 2014a; Castrodale and White 2004)

	Depth (in.)	Spans up to (ft)	28-day concrete strength (psi)
PC - I (type I – IV)	28 – 54	~114	5,000 – 7,000
PC – I (Wisconsin type)	70	~120	5,000 – 7,000
PC – I (MI 1800)	70.9	~145	5,000 – 7,000
Spread box-beam (36 in. wide)	42	~95	5,000 – 7,000
Spread box-beam (48 in. wide)	60	~140	5,000 – 7,000

Table A.2. Depth and Span Range of Utah Bulb-Tee Girders (Source: UDOT 2010b)

	Depth (in.)	Spans up to (ft)		Diameter of prestressing strands (in.)	Number of strands
		28-day concrete strength of 6,500 psi	28-day concrete strength of 8,500 psi		
Utah bulb-tee girders spaced at 8 ft	42	~85	~98	0.6	N/A
	50	~97	~117		
	58	~112	~131		
	66	~124	~146		
	74	~140	~157		
	82	~150	~167		
	90	~164	~177		
	98	~169	~186		

Table A.3. Depth and Span Range of NEBT Girders (Source: PCI 2011)

	Depth (in.)	Spans up to (ft)	Diameter of prestressing strands (in.)	Number of strands	28 day concrete strength (psi)
NEBT girders spaced at 8 ft	39.4	~85	0.6	60	10,000
	47.2	~98			
	55.1	~111			
	63	~121			
	70.9	~131			

The girders are specified considering span, capacity, efficiency, and benefits/limitations. Most girders are suitable for short and short-to-medium span bridges (up to 130 ft). The girder options are limited for medium span bridges (130 ft to 260 ft). Several efforts have been made to develop girders for medium span bridges (Geren and Tadros 1994). Another option for medium span bridges is girder splicing, which could potentially provide sections for spans up to 220 ft with post-tensioning (Castrodale and White 2004; Chung et al. 2008). Specifically, prestressed I- and bulb-tee girders can be redesigned to incorporate post-tensioning and/or spliced details to accommodate longer spans. Russell et al. (1997) performed a comprehensive study on effect of strand size and spacing on capacity and cost for high strength concrete girders. This study showed that 0.7 in. diameter strands at 2 in. spacing in a bulb-tee girder with 10,000 psi strength provide an economical solution for longer spans.

The NU-I girder series includes depths ranging from 30 in. to 95 in. and constant dimensions for top and bottom flanges, and includes depths for spans up to 300 ft with post-tensioning (Beacham and Derrick 1999). However, the girder web thickness needs to be increased when post-tensioning is used. Reinforcement details are standardized so that the amount of post-tensioning, girder span, or girder spacing does not affect the reinforcement pattern except the spacing (details of NU I-girder reinforcement are presented later in this Appendix). Moreover, the large span-to-depth ratio allows for specifying these sections in lieu of steel girders without increasing the superstructure depth (Beacham and Derrick 1999). These girders have been used in many projects and had proven to be durable for continuous spans.

The NU 900 I-girder (35.4 in. deep) is the shallowest section of the series, which has been successfully implemented in several projects (Morcous et al. 2011). In 2009, two non-proprietary Ultra High Performance Concrete (UHPC) mixes were developed by the University of Nebraska-Lincoln and designated as NU-UHPC mix #4 and mix #5. A detailed discussion on these mixes is given in Tadros and Morcous (2009). A new configuration of the NU 900 I-girder was developed with the NU-UHPC mix #5 and 0.7 in. diameter prestressing strands. Research on the NU 900 I-girder verified the implementation with 2 in. strand spacing (Morcous et al. 2011). NU 900 I-girder spans, number of strands, strand size, and compressive strength of concrete are shown in Table A.4. The typical NU I-girder series includes a wide range of depths and spans (Table A.5).

Table A.4. NU 900 I-Girder Specifications (Source: Morcous et al. 2011)

	Spans up to (ft)	Diameter of prestressing strands (in.)	Number of strands	Concrete strength at release (psi)
NU 900 I-girder (depth – 35.4 in.)	~90	0.5	60	6,000
	~110	0.6	60	8,500
	~90		36	
	~130	0.7	60	11,000
	~110		38	
	~90		26	

Table A.5. NU I-Girder Series Specifications (Source: Hanna et al. 2010)

	Depth (in.)	Spans up to (ft)	Diameter of prestressing strands (in.)	Number of strands	28 day concrete strength (psi)
NU I-girder	94.5	~200	0.6	60	12,000
	78.7	~180			8,000 – 12,000
	70.9	~172			8,000 – 12,000
	63.0	~155			8,000 – 12,000
	53.1	~135			8,000 – 12,000
	43.3	~118			8,000 – 12,000
	35.4	~110			8,000 – 12,000

Decks

Precast full-depth and partial-depth deck panels that were reviewed include the following:

- Full-depth deck panels with transverse prestressing and longitudinal post-tensioning
- Full-depth deck panels with only longitudinal post-tensioning
- Full-depth deck panels with only transverse prestressing
- Partial-depth deck panels
- NU-deck full-depth panels
- NU-deck stay-in-place panels.

The full-depth deck panels with transverse prestressing and longitudinal post-tensioning is currently most specified for the superstructure system of ABC projects. The primary limitations are related to grouting connections and repair and rehabilitation complexities of the post-tensioned superstructure system. With regard to limitations on repair and rehabilitation with the post-tensioning, it is best to implement this deck panels at sites where girder damage (e.g., high-load hits) is unlikely. Based on the currently available data, superstructure systems including full-depth deck panels without longitudinal post-tensioning could not fulfill the durability performance expectations.

New partial and full-depth deck panels have been developed. These are NU-deck panels (1^{st} and 2^{nd} generation – full-depth) (Badie et al. 2006; Hanna et al. 2010), the modified NU-deck panel (full-depth) (Wipf et al. 2009), and the NU-deck stay-in-place (SIP) panels (Badie et al. 1998; Versace and Ramirez 2004). These panels use unprotected prestressing and post-tensioning strands, which will not result in a durable deck assemblage. Considering all the benefits and limitations, full-depth deck panels with transverse prestressing and longitudinal post-tensioning are still the best choice for Michigan bridges where substantial winter maintenance is required.

Superstructure modules

Prefabricated elements that are placed side-by-side to form a bridge superstructure and connected by shear and/or flexure-shear transfer details are referred to as superstructure modules. Examples are single-cell rectangular box-beams specified in adjacent box-beam bridges, trapezoidal box girders, single-cell or multi-cell sections for segmental box girder bridges, tee-beams, double-tee girders, and deck integrated sections. The decked single-cell rectangular box-beam was developed in 2010 and fabricated in 2012 for the M-25 bridge over the White River in Michigan (MDOT M-25 bridge plans 2010).

Superstructure modules, such as the INVERSET™ and decked steel girder modules, are developed by combining multiple girders and a precast slab. The decked steel girder module design standards and design examples are provided in the SHRP 2 Project R04 publications (SHRP2 2013). The decked steel girder module has been used in the I-93

Fast 14 project in Medford, MA (MassDOT 2011), and the Keg Creek bridge replacement project in Pottawattamie County, IA (IowaDOT 2011).

Superstructure modules that were reviewed in order to identify respective attributes, benefits, and limitations include the following:

- Double-tee girder
- Decked bulb-tee girder module
- Decked steel girder module
- Decked box-beam module
- NEXT beam module
- Pi-girder module
- Trapezoidal box girder
- Inverted-T precast slab
- Precast modified beam in slab.

The superstructure modules are suitable for short-span bridges (i.e., 20 ft to 60 ft) and up to short-to-medium span bridges (i.e., 60 ft to 130 ft).

Double-Tee and Decked Bulb-Tee Girders

The standard double-tee girder module has been available for many decades (PCI committee 1983). This module was originally developed for buildings and parking structure floors. Web thickness is the limiting factor in the prestressed girder design. Further, developing a moment connection detail at the flange with two layers of reinforcement is difficult due to limited flange thickness. Standard double-tee sections require a cast-in-place concrete deck. Hence, the use of these girders is limited to short-span bridges with low-traffic volume (Bergeron et al. 2005; Chung et al. 2008).

Due to the documented limitations of the standard double-tee girders, decked bulb-tee sections were developed (Shah et al. 2006; PCI 2011). Increased web thickness of decked bulb-tee sections accommodates post-tensioning to develop continuity details over the supports. This module is suitable for bridges up to short-to-medium span. As with any superstructure system, durability performance is a concern. The increased flange thickness of the decked bulb-tee section is suitable for developing durable flexure-shear transfer connection details (Graybeal 2010; UDOT 2010b; Culmo 2011b).

Decked Steel Girder Module

The proprietary INVERSET^{TM} module is designed for short and short-to-medium span bridges in non-corrosive environments. Even though the module is costlier than other modules, the specific manufacturing process precompresses the deck, which helps eliminate/reduce deck cracking. However, replacement or overlays to a precompressed deck is a challenge.

The non-proprietary decked steel girder module that was developed under the SHRP2 Project R04 (SHRP2 2013) utilizes conventional designs and manufacturing processes. Therefore, the superstructure system with this module could be economically specified for short and short-to-medium span bridges in non-corrosive environments.

Decked Box-Beam Module

The decked box-beam module was developed by Michigan DOT to provide a prefabricated element that inherits the benefits of an adjacent box-beam, and when assembled on site resembles a spread box-beam bridge. The decked box-beam module is suitable at sites with underclearance limitations. As the decked box-beam bridge resembles the spread box-beam bridge, utilities could be accommodated. The weight of the decked box-beam may be the factor limiting the use for short-span bridges (20 ft to 60 ft).

NEXT Beam Module

The NEXT F beam requires an 8 in. thick cast-in-place concrete deck on the typical 4.5 in. thick flange. Both the NEXT F and D beams are suitable for short and up to short-to-medium span bridges with a cast-in-place deck. As with any prefabricated superstructure system, joint durability is a concern. However, the use of flexure-shear transfer connections may improve joint durability. These connections need further investigation.

Pi-Girder Module

The pi-girder is a shallow section with a thin deck. At the current state of practice, this module is costly with the use of proprietary materials and requiring special forms for casting.

Trapezoidal Box Girder

The trapezoidal box girder was developed in 1998 for bridges up to short-to-medium spans. The girder was developed in two cross-sections: (1) a closed trapezoidal box, and (2) an open section requiring a cast-in-place concrete deck. Considering the difficulty in the casting of a closed trapezoidal box section, an open-top was preferred (Badie et al. 1999). The attributes of an open-top trapezoidal box girder are shown in Table A.6. Based on the data currently available, this particular section has not been specified for any ABC project.

Table A.6. Attributes of Trapezoidal Box Girders (Source: Badie et al. 1999)

	Depth range (in.)	**Spans up to (ft)**	**28 day concrete strength (psi)**
Trapezoidal box (totally closed)	23.5 – 31.5	~95	7,500
Trapezoidal box (open-top)	20 – 28	~86	9,000

Inverted-T Precast Slab

Inverted-T precast slab, which also provides a platform for the construction and formwork for the cast-in-place concrete deck, is suitable for short-span bridges with underclearance issues. The limitation of the superstructure system with this module is the additional time required to place and cure the cast-in-place concrete deck. The deck requires 7-day wet curing. Further, reflective deck cracking is a concern similar to observed on adjacent box-beam bridge decks.

A recent NCHRP project (French et al. 2011) investigated three aspects of the inverted-T precast slab: (1) stresses in the end zones of the precast section, (2) transverse reinforcement spacing at the connection, and (3) compatibility with AASHTO (2010) design specifications. The project concluded that AASHTO (2010) design specifications are not conservative for deep inverted-T sections (i.e., depth greater than 22in.), because more reinforcement is required than specified. This NCHRP project (French et al. 2011) developed a design guide for the inverted-T precast slab. However, the section with the incorporated new details has not been specified yet, so the reflective cracking cannot be assessed.

Precast Modified Beam in Slab

The superstructure system with precast modified beam in slab has steel girders embedded in concrete to protect against corrosion. This superstructure system is suitable for short-span bridges in corrosive environments. Durability performance of the longitudinal joints needs to be investigated.

Summary

In summary, the bridge superstructures using trapezoidal box, double-tee, inverted-T, or NEXT F beams require a cast-in-place concrete deck; hence project duration is extended. Generally, cast-in-place concrete decks require 7-day wet curing. Rectangular box-beams for adjacent box-beam bridges, decked bulb-tee beams, NEXT D beams, Pi-girders, INVERSET™, and decked steel girder modules do not require cast-in-place deck. Therefore, a hot-mix asphalt (HMA) layer with a waterproofing membrane, epoxy overlay, or latex modified concrete overlay is considered as a wearing surface on these modules by many states. There have been records of poor HMA overlay performance, which require further investigation. Adequately designed flexure-shear transfer details need to be implemented for improved durability. Moreover, suitable grout material is needed to prevent cracking or debonding at the interfaces. The majority of these modules were specified in several projects, and performance data may be available with respective DOTs.

Recommendations for superstructure elements

The recommendations for superstructure elements are developed after a critical review of the durability and constructability of bridges and presented in this section. In specifying a superstructure element for a project, it would be useful to review the potential challenges during construction and identify effective means to mitigate such challenges. To help with that effort, constructability challenges and other limitations of the superstructure elements are listed in this section. Further, topology, commonly used span ranges, and material properties associated with each element are presented where such information is available. Having such information is useful for identifying elements suitable for a particular project following the evaluation of site constraints. The source of information for each element is also included.

Precast concrete (PC) I-girder

Description: The AASHTO types I to IV girders were developed and standardized in the late 1950s, and AASHTO types V and VI girders were developed in 1960s. As a result of AASHTO standardization, precast plants invested in the formwork for PC I-girders. Thus, the design practices were simplified, and significant cost savings were observed in the construction of prestressed concrete bridges.

The performance of the PC I-girders is well documented. The performance data can be utilized in various assessment/evaluation procedures, such as the life-cycle cost calculation. These girders were also successfully implemented in Accelerated Bridge Replacement (ABR) projects where Self Propelled Modular Transporters (SPMTs) are used.

Sources of information: Chung et al. (2008); Abudayyeh (2010); MDOT (2014a); Attanayake et al. (2012).

Constructability evaluation: The PC I-girders are often used to build bridge superstructures that are moved into position using SPMT or the slide-in technique. The only difficulty in using PC I-girders in ABR is to design the girders and deck to accommodate the stresses developed during the bridge move. Partial-depth or full-depth deck panels are required along with the implementation of PC I-girders in ABC projects. However, partial-depth deck panels are not recommended because of reflective deck cracking potential. When PC I-girders are used with full-depth deck panels, the girder sweep needs to be controlled. Moreover, cast-in-place (CIP) construction and special details are required to develop continuity over the piers. Where needed, the curved spans can be constructed using straight PC I-girders.

The PC I-girders are appropriate for short-to-medium span bridges. The prestressing strands of 0.5 in. and 0.6 in. diameter, and a 28-day concrete strength ranging from 5000 psi to 7000 psi are commonly specified in these girders.

Precast bulb-tee girder

Description: In 1980, FHWA initiated a research project to develop an optimized, efficient and economic prestressed concrete girder. The research evaluated the AASHTO standard PC I-girders as well as state specific standard girders. The bulb-tee along with the Washington and Colorado girders were identified as the structurally efficient sections. The bulb-tee girder with a 6 in. web was proposed as a national girder for short-to-medium spans. Later, the PCI committee modified the bulb-tee section (Figure A.1) and in 1988, they standardized it as the AASHTO/PCI bulb-tee girder (TFHRC 2006). Russell et al. (1997) conducted a comprehensive study on the effect of strand size and spacing on capacity and cost for high-strength concrete bulb-tee girders. The results indicated that 0.7 in. diameter strands at 2 in. spacing in a precast bulb-tee girder with 10,000 psi strength would provide an economical design for longer spans.

Following evaluation of precast bulb-tee girder sections in the U.S, a series was standardized by the Utah DOT to be formally known as Utah Bulb-Tee (UBT) girders. The depth, span range, and corresponding concrete strength of the standard UBT girders are presented in Table A.7.

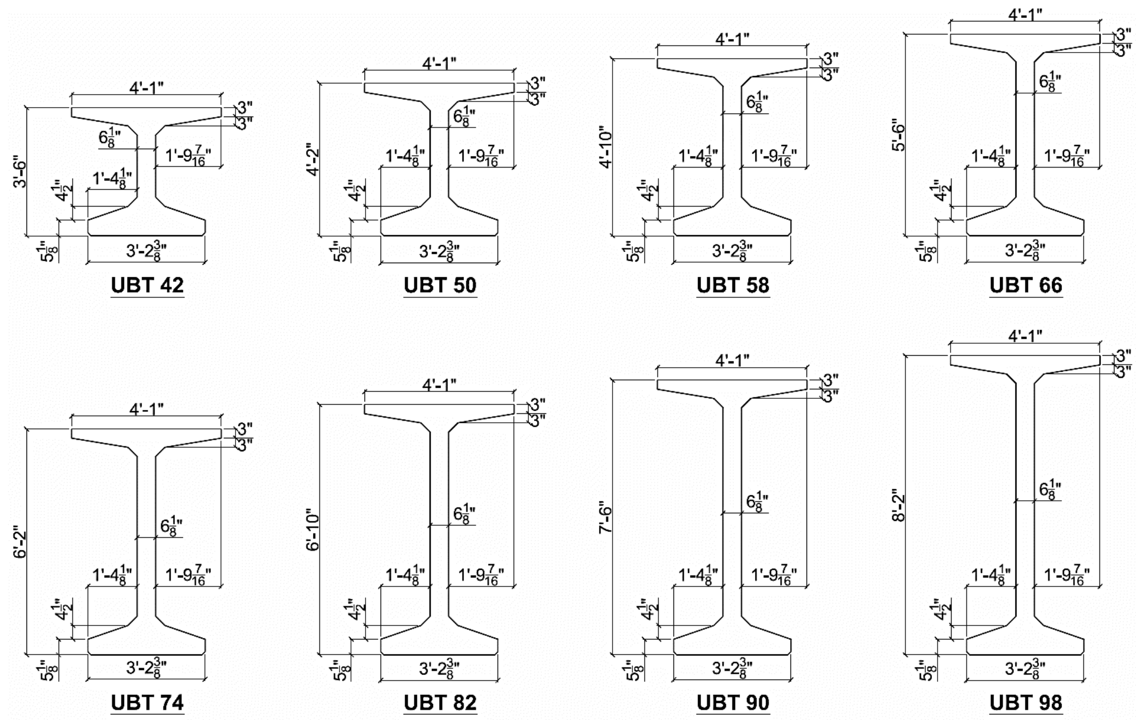


Figure A.1. Precast bulb-tee girders (Source: UDOT 2010b)

Table A.7. Depth and Span Range of Utah Bulb-Tee Girders (Source: UDOT 2010b)

	Depth (in.)	**Span (ft)**		**Diameter of prestressing strands (in.)**	**Number of strands**
		28-day concrete strength of 6,500 psi	**28-day concrete strength of 8,500 psi**		
Utah bulb-tee girders spaced at 8 ft	42	~85	~98	0.6	Varies
	50	~97	~117		
	58	~112	~131		
	66	~124	~146		
	74	~140	~157		
	82	~150	~167		
	90	~164	~177		
	98	~169	~186		

Sources of information: Lavallee and Cadman (2001); Castrodale and White (2004); Fouad et al. (2006); UDOT (2010b).

Constructability evaluation: The precast bulb-tee girders are appropriate for developing continuous spans. Special details and CIP construction are required to develop continuity over the piers.

ABC implementation can be accomplished with partial-depth or full-depth deck panels. As indicated earlier, the use of partial-depth deck panels is not recommended due to reflective deck cracking potential. When used with full-depth deck panels, the controlling girder sweep is critical due to slenderness of the section. The use of a wide bottom flange in the precast bulb-tee girders results in a stable section and accommodates a larger number of prestressing strands.

Precast box-beams

Description: These elements have been in use in Michigan since 1955 (Attanayake 2006). There is extensive experience with their design and performance. These elements are ideal for sites with underclearance limitations. The construction can be accelerated by specifying a wearing surface without a cast-in-pace deck directly over the box girders (Figure A.2). These elements possess high torsional stiffness and can be used for constructing aesthetically pleasing shallow-depth structures.

Sources of information: Aktan et al. (2009); Attanayake (2006); Chung et al. (2008); MDOT (2014a).

Constructability evaluation: Field inspection has documented grout spall and inadequate gaps between beams for forming the shear keys. Tighter fabrication tolerances need to be specified. Reflective cracking is common among the inventory constructed with a CIP deck. Therefore, a redesign of the transverse connectivity of the adjacent box-beams will mitigate the reflective cracking (Aktan et al. 2009). Box-beam attributes are shown in Table A.8.

Table A.8. Attributes of Precast Adjacent Box-beams Used in Michigan (Source: MDOT 2014a)

	Depth range (in.)	Spans up to (ft)	28 day concrete strength (psi)
Box-beam (36 in. wide)	17 – 42	~120	5,000 – 7,000
Box-beam (48 in. wide)	21 – 60	~150	5,000 – 7,000

Some of the considerations related to the use of these elements are as follows:

- Fabrication complexity due to the multi-step fabrication process of the box
- Inspection difficulties of the box-beam interior

- Difficulty in accommodating utilities underneath the superstructure
- Difficulty in replacing an individual beam due to transverse post-tensioning.

Figure A.2. Adjacent box-beams that require a wearing surface (Source: CPCI 2006)

Full-depth deck panels with transverse prestressing and longitudinal post-tensioning

Description: Full-depth deck panels have been used since the early 1970's (Issa et al. 1995). The full-depth deck panels can be used in the deck replacement, superstructure replacement and bridge replacement projects. The transverse prestressing allows casting deck panels as wide as 40 ft [i.e., dimension in transverse direction of the bridge (Figure A.3a)].

The UDOT (2010b) developed standard details for the full-depth deck panels. The UDOT (2010b) allows the use of skewed panels up to 15^{o} (Figure A.3b). For skew decks up to 45^{o}, rectangular interior panels with trapezoidal end panels are specified (Figure A.3c).

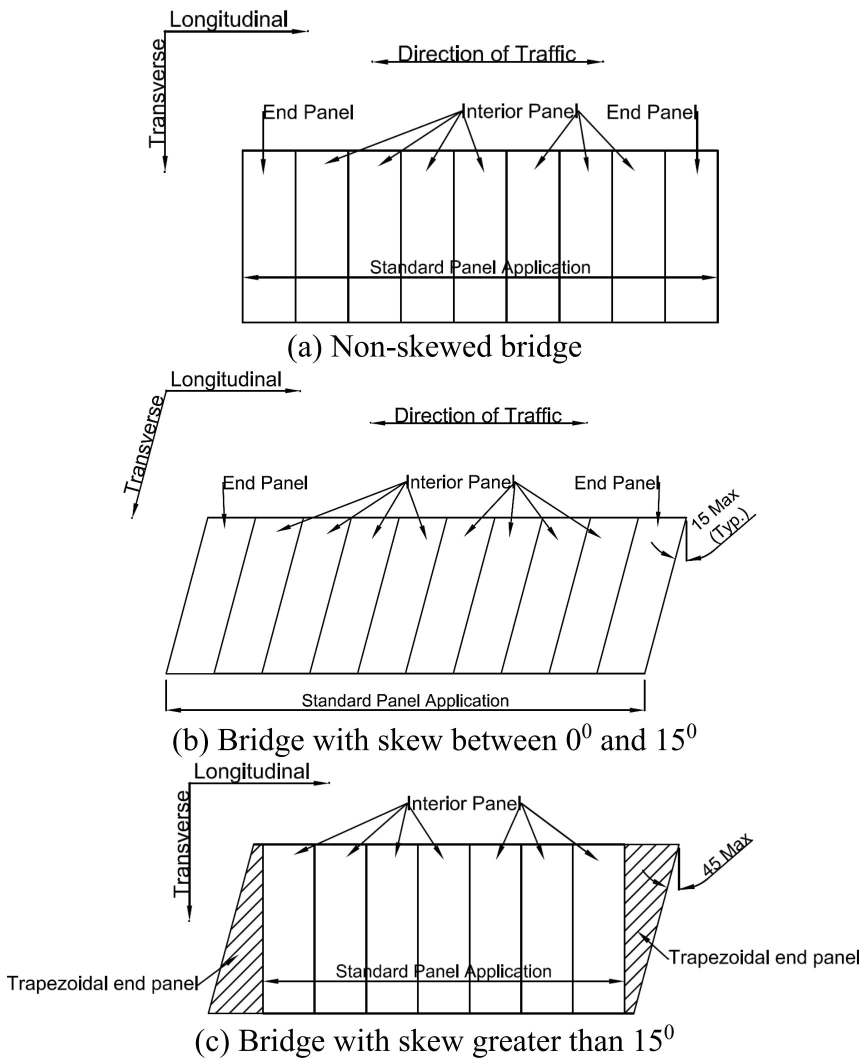


Figure A.3. Standard full-depth deck panel applications (Source: UDOT 2010b)

Full-depth deck panel length (in the direction of traffic) with transverse prestressing could vary from 8 ft to 16 ft. The panel width (in the direction transverse to traffic) could vary from 24 ft to 40 ft. Several projects specified a deck thickness of 8.5 in. with concrete strength of 4,000 psi at release and 5,000 psi at 28 days. The supporting girder spacing for the deck panels with transverse prestressing could vary from 8 ft to 12 ft. Steel girders with a minimum top flange width of 16 in., AASHTO types II to VI girders, or precast bulb-tee girders are commonly used.

Sources of information: Hieber et al. (2005); Badie et al. (2006); UDOT (2010b); Attanayake et al. (2012).

Constructability evaluation: The uncertainty related to the full-depth deck panel's durability performance is the tightness of transverse connections. Staged construction with full-depth deck panels is possible (Figure A.4). During staged construction, vibrations generated by the traffic may promote cracking within the cement matrix and at the interface of the longitudinal closure. Reinforcement overlapping conflicts at the closure are documented in post-construction reports. This can be addressed by educating the detailers of the issue, while specifying and enforcing the best practices for tolerances.

AASHTO (2010) specifies 250 psi compression at the panel transverse connection after all the prestressing losses. The continuous span structures should be analyzed in the vicinity of the piers to determine the level of post-tensioning required to achieve nominal 250 psi compression at connections. Transverse connections should be placed away from the pier locations to minimize the potential for developing tensile stresses. The maximum post-tension duct spacing should be less than panel length. Tolerances at the post-tension duct splicing locations should be appropriate to minimize misalignment. To reduce the difficulties associated with the strand placement in the post-tensioning ducts, round ducts are preferred over the flat ducts (Badie et al. 2006). Moreover, to prevent excessive friction during post-tensioning operation, adequate space should be maintained between the strands and the ducts. For example, if 4-0.6 in. diameter strands are allowed for a particular duct, the design may be based on 4-0.5 in. diameter strands.

The deck system contains several grouted connections thus making the construction challenging. Therefore, special provisions need to direct the contractor to identify the grouting procedures and to demonstrate the effectiveness of the procedures by performing mock-up testing. Proper tolerances at the shear pockets should be specified and verified. The following challenges are encountered when implementing full-depth deck panel systems:

- Specifying and enforcing the required tolerances during the fabrication process
- Enforcing the construction tolerances during the assembly process
- Transporting the trapezoidal end panels used in the high skew bridges
- Replacing a single girder or a panel in a system with post-tensioning.

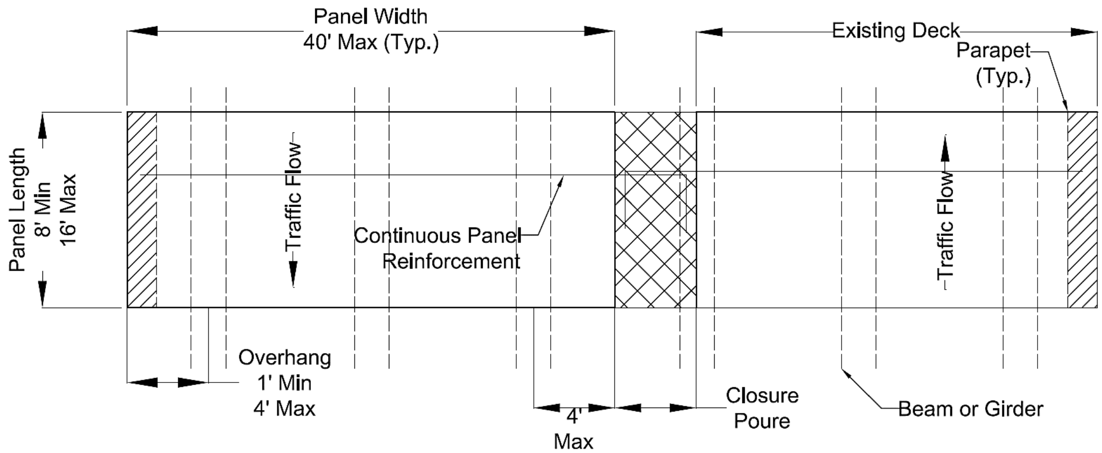


Figure A.4. Stage construction configuration for full-depth deck panels (Source: UDOT 2010b)

Decked bulb-tee girder module

Description: The decked bulb-tee girder (Figure A.5) was developed in 1969 by Arthur Anderson based on the standard tee girder. The standard tee girder was commonly specified for parking structures and the building industry in early 19th century. The New England states, Utah, and Florida have specified the decked bulb-tee girder section in several projects. The New York State DOT has implemented this section in a few projects since 2009.

The decked bulb-tee girders can be manufactured in a single pour, which makes the fabrication easier compared to a single cell box-beam. The decked bulb-tee girders provide the flexibility for accommodating utility lines. When compared to the double-tee girder elements, decked bulb-tee girders can be designed for a greater load carrying capacity for equal span lengths. A wearing surface, or an overlay, is required once the decked bulb-tee girders are assembled on the site (Figure A.6).

UDOT (2010b) standardized the decked bulb-tee girder with flange widths ranging from 4 ft to 8 ft, depths ranging from 35 in. to 98 in., and spans of up to 180 ft. The maximum span has not been implemented in ABC projects primarily due to limitations in transporting the sections to the bridge site.

Sources of information: PCI (2011); Shah et al. (2006); UDOT (2010b); Culmo (2011).

Constructability evaluation: As with any modular system, the connections between the decked bulb-tee girders can fail unless designed as a flexure-shear transfer connection. UDOT (2010b) specifies a span up to 180 ft. As with any other bridge system, use of deep girders for medium span bridges is not practical in most sites due to underclearance issues.

Some considerations related to the use of decked bulb-tee girders are as follows:

- The spacing of the diaphragms between the decked bulb-tee girders needs to be researched to achieve the desired level of torsional stiffness.
- The weight of the decked bulb-tee girders needs to be considered during the design process, to comply with transportation limitations.
- The crown of the riding surface on the decked bulb-tee girders can be formed by an overlay. There is preference for use of latex modified concrete or epoxy overlay over an asphalt overlay with a waterproofing membrane.

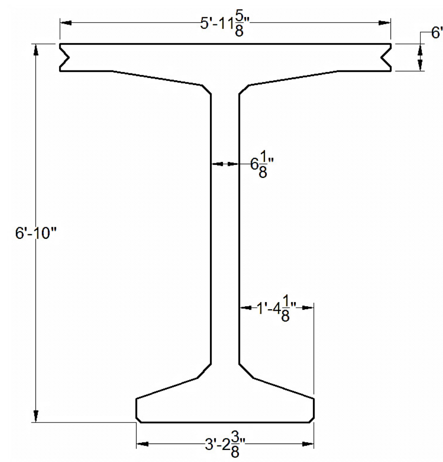


Figure A.5. Typical section of a decked bulb-tee girder (Source: PCI 2011)

Figure A.6. Decked bulb-tee girder (Source: PCI 2011)

Decked steel girder module

Description: The decked steel girder system was developed in a SHRP II project; it was implemented in the I-93 Fast 14 project in Medford, MA (MassDOT 2011) and the Keg Creek Bridge replacement project in Pottawattamie County, IA (IowaDOT 2011).

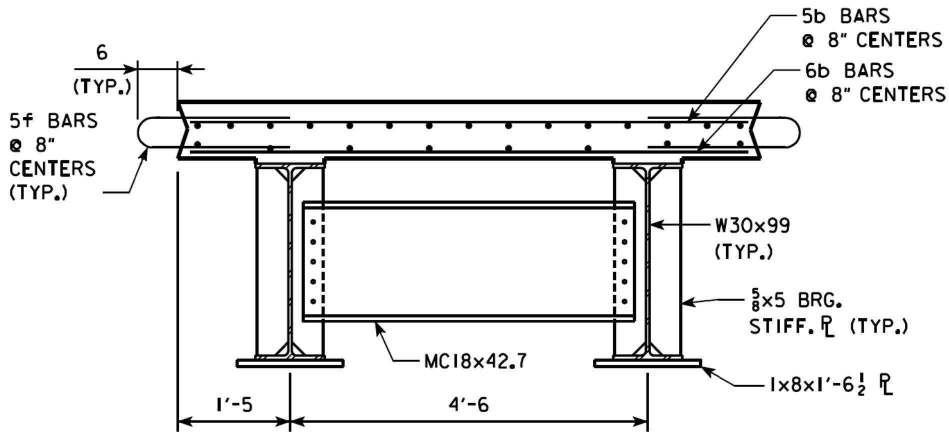
The modules consist of two W 30x99 (depth of 29.7 in.), ASTM A709 grade 50W steel girders, integral with a 7.5 in. to 8 in. deep precast deck (Figure A.7b). The section width ranges from 8 ft to 9 ft with a 28-day compressive strength of 4000 psi to 5000 psi. Up to 73 ft spans have been implemented with the section details shown in Figure A.7.

Sources of information: MassDOT (2011); IowaDOT (2011).

Constructability evaluation: Manufacture of this module requires steel fabricators and precasters to work together. The crown of the decked steel girder bridge could be formed in two ways: 1) increasing the thickness of the deck, and diamond grinding part of the deck to the desired crown, and 2) placing an overlay over the deck to form the crown.

Use of weathering steel can help with corrosion prevention. However, the system, even with weathering steel, is not suitable for Michigan exposure with aggressive winter maintenance. The past performance data of the decked steel girder system is limited. The success of the decked steel girder system is controlled by the performance of the longitudinal connections.

(a) Section elevation



(b) Section details

Figure A.7. Decked steel girder system (Source: MassDOT 2011; IowaDOT 2011)

Decked box-beam module

Description: The decked box-beam element is the traditional box-beam with a built-in deck (Figure A.8). The decked box-beam system was implemented for ABC in 2011 to replace M-25 over the White River Bridge (B01 of 32091) in Michigan. Transverse post-tensioning similar to side-by-side box-beam bridges, through the CIP diaphragms, was specified. The beam depth was 3 ft (including the deck) and spanned 47 ft. The top flange width of the beams was 5 ft-5 in. The specified 28-day compressive strength was 7000 psi.

Source of information: MDOT M-25 over White River Bridge plans (2010); MDOT (2014a).

Constructability evaluation: The decked box-beam section is new, and past performance data is limited. The longitudinal deck connection detail used with these beams needs to be designed to transfer both moment and shear. The designers should be aware of shipping and handling weight limitations while designing these sections for increased spans.

The typical sequence of precasting the decked box-beam is to fabricate the box-beam, place the deck reinforcement on top of the box-beam, and cast the deck. The deck reinforcement placement and the deck casting operation scheduling is critical to prevent a cold joint between the deck and the box-beam. Some of the considerations related to the use of decked box-beams are the following:

- Difficulty of inspection of the box-beam interior
- Difficulty in the fabrication, because of the multi-step process
- Difficulty in replacing the elements because of the transverse post-tensioning.

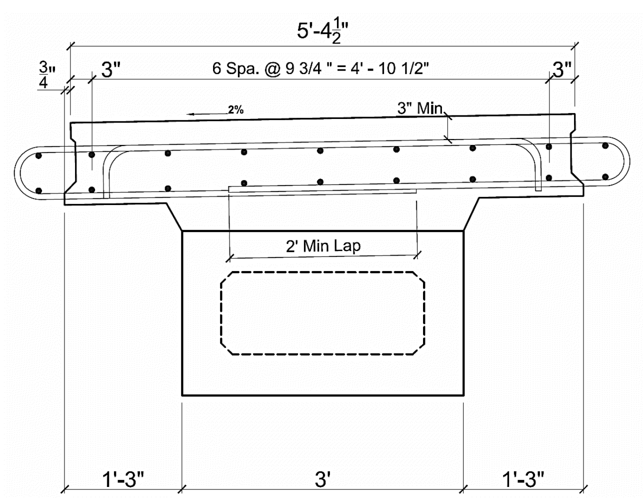


Figure A.8. Decked box-beam section (Source: MDOT M-25 over White River Bridge plans 2010)

Appendix B

Review of major activities in the ABC methods

Table B.1. Summary of Activities Included in the PBES Method

Project	Year	Summary of Activities
TH 53 Bridge over Paleface River, Minnesota (2012)	2012	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The precast deck panels and prestressed beams were fabricated at a plant and transported to the site. The substructure is constructed conventionally following the existing bridge demolition. The prestresses concrete I-beam were erected. Then, 9 in. precast concrete deck panles were erected and the deck connections were completed including longitudinal post-tensioning of deck panels. Two panels and a field-cast longitudinal closure joint were used to complete the width of the bridge.
Route 202 Bridge over Passaic River, New Jersey (2012)	2012	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. Traffic was maintained on the bridge with single lane traffic closures during two nights to drive steel H-piles. The piles were cut just below the roadway and the roadway was patched with asphalt prior to opening the bridge in the mornings. Precast abutment caps, precast backwalls, and precast wing walls were then fabricated at the precast plant and were transported to the site. Also, the steel beams were delivered to the precast plant, and concrete decks and backwalls were cast to form the modular decked beam units that were then transported to the site. Almost six months after the piles were driven, traffic was detoured as the 7-day road closure began. The bridge superstructure and backwall of the existing abutments were demolished. The existing abutments were left in place to serve as a scour prevention measure for the new abutments that were built behind them. A crane was used to erect the abutment cap segments over the piles, and the abutment cap pockets were filled with high-early-strength concrete. Then, the four modular decked beam units were erected onto the bearing pads. The 6-inch-wide reinforced longitudinal joints were filled with Rapid-Set DOT Cement to complete the deck connections. The precast approach slabs and sleeper slabs were installed. Architecturally treated precast panels resembling natural stone construction were placed to serve as stay-in-place forms on each side of the parapet steel that extended from the deck. A standard New Jersey asphalt Bridge Deck Waterproof Surface Course was placed over the concrete bridge deck; rather than having a separate waterproofing membrane.
US 6 over Keg Creek Bridge, Iowa (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. Before demolishing the existing bridge, concrete drilled shafts were constructed outside the bridge footprint at the two interior support locations. Also, the contractor fabricated the precast elements near the site and the components were transported for the short distance. After demolishong the existing bridge, abutment steel H-piles were driven and precast abutment stem and wingwalls were assembled. Then, the simple-span modular segments were erected with conventional cranes. UHPC joints were used for both the longitudinal joints between adjacent modular beam segments and the moment-resisting transverse superstructure joints at each pier. The precast approach slabs were assembled. Self-consolidating HPC was cast in the deck lifting loop pockets and in the precast approach pavement joints. The deck and approach slabs were diamond ground to final profile.

Table B.1. — Continued

Project	Year	Summary of Activities
Little Cedar Creek Bridge, Iowa (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The 14 waffle deck panels were fabricated in the summer and fall of 2010. The waffle deck panels were purchased and shipped to the job site under a separate contract between Wapello County and the panel supplier. The contractor closed the bridge. The bridge was then demolished conventionally, steel H-piles were driven, and the cast-in-place abutments were constructed. The beams were erected, followed by erection of the waffle deck panels. The connections between adjacent waffle panels and between the waffle panels and beams were completed using field-cast UHPC. The 3.83-ft-wide closure joints at the abutments and the bridge railing were cast with conventional concrete. No overlay was applied. Construction took approximately 40 working days.
UPRR Bridge, Kansas (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. Prior to bridge closure, abutment piles were driven through the existing fill and track ties were removed and replaced as needed to access pile locations. Pile driving was completed without train delays by coordinating with the UPRR operations center and driving the piles between train runs. Precast abutment caps, precast pile caps, and precast box girders were transported to the site. The bridge was then closed and demolished. The precast abutment and pile caps were set over the steel piles with a crane. The substructure connections were completed, and backfill and compact granular fill were placed behind abutments. Then, precast box girders were erected with the crane. The connections between the girders were completed by installing and welding steel cover plates. Track panels and ballast were placed. Precast ties were installed and track was raised. Finally, track was released to run trains.
Buffalo Creek Bridge, South Dakota (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The pretensioned double tee beams were fabricated at a precast plant and shipped to the bridge site. The bridge was closed and traffic detoured. Excavation was completed and H-piles were driven at each abutment location. Steel pile caps were erected onto the H-piles and the bearing dowel bars were welded to the bottom flange. The double tee beams were erected onto elastomeric bearing pads. A dowel pin was placed through the beam end and steel cap top flange and welded. The beams were also welded together at 5-ft spacing longitudinally. The shear keys between beams and the dowel bars were filled with non-shrink grout. The 7-inch x 4-inch x 5-inch blockouts at the ends of the beams were filled with grout. Railing was installed. No overlay was applied. The bridge was opened to traffic.
Volmer and Johnson Creek Bridges, Oregon (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The precast abutment caps, shear lugs, and approach slabs were fabricated at a precast plant. The recycled pretensioned concrete slab beams were transported from another project . The two bridges were replaced in three stages over a four-week construction period. During each week of the four weeks the contractor ran crews 24/7 to tear out half a bridge and replace it between Sunday night and Friday at 3:00 pm. In first stage, the traffic was reduced to one-lane and the pipe piles and sheet pile walls were driven in the closed lanes. Afterwards, the roadway of those lanes was covered and the traffic was diverted on them. The process was repeated for the remaining half of the bridge and the second bridge. In second stage, the traffic was reduced to one lane and first half of the existing bridge was demolished. The abutment caps were installed over the piles. The process was repeated at the other end of the bridge. Then, first half of the precast slab beams were erected on elastomeric bearing pads. Later, the precast sleeper slabs and approach slabs were erected. Waterproofing membrane and asphalt overlay were placed. Other finish work was completed and the bridge was opened by 3 pm on Friday. In the third stage, the second bridge was replaced following a similar process of second stage.

Table B.1. — Continued

Project	Year	Summary of Activities
Boothbay Bridge, Maine (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. Special provisions allowed the existing bridge to be closed to traffic for a maximum of 12 calendar days. The closures were limited to the hours of 8:30 am to 3:30 pm. The replacement bridge was built adjacent to the existing bridge on a new alignment; thus, the traffic was maintained throughout the construction with limited closures. Sixty-four 33-inch-deep winged Hybrid Composite Beams were transported to the site. Following the cast-in-place substructure construction, the beams were erected with the same barge and crane used for substructure construction. Adjacent beams were abutted so that the deck formwork was not required. A 7-inch-thick cast-in-place concrete deck was placed and the expansion joints are the abutments were installed. The waterproofing membrane and asphalt overlay were placed. The bridge was opened to traffic ahead of schedule.
Craig Creek Bridge, California (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The contractor launched a temporary bridge and detoured traffic onto the temporary bridge. The existing bridge was closed and demolished. Abutments were excavated. The precast abutment caps with backwalls were erected over the cast-in-steel shell piles and the abutment segment closure joints were cast. Eleven precast box beams were transported to the site. The beams were erected and abutted together. The transverse tie rods in ducts at mid-depth of the beams were stressed to 20 percent, and the shear keys between the beams were grouted (connection between the beams). The high-performance concrete (HPC) deck was constructed, and the transverse ducts in the beams were grouted. The new bridge was opened to traffic four days later.
TH 61 Bridge over Gilbert Creek, Minnesota (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low A+B bid contractor. The bridge consisted of 4th generation of MnDOT's Precast Composite Slab Span (PCSS) beams, precast abutments, and precast pier caps. The elements were transported to the site. This project was completed using staged construction. In each of the stages the contractor drove the steel pipe piles for the abutments and piers. A typical crane for this scale of project was used to install the precast abutments, pier caps and PCSS beams. The precast abutment pieces and precast caps were connected to the piles using high-strength flowable grout. The PCSS beams were erected and the longitudinal drop-in steel reinforcement and deck reinforcement was placed, and the deck was cast and cured.
South Punaluu Stream Bridge, Hawaii (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The contractor obtained approval for PBES with precast prestressed concrete triple-tee beams called tridecks. A precast decked tub member spanning between the abutments and piers supported a waterline. The precast tridecks and tub member were fabricated at a precast plant and shipped to the job site. The contractor assembled a temporary prefabricated steel truss bridge adjacent to the site. Traffic was shifted to the temporary bridge and the existing bridge was demolished. Drilled shafts were constructed and pier caps were cast over them with top surface of the caps confirming to roadway cross-slope. Cranes were used to erect the tridecks on the concrete seats. Keys between the tub member and tridecks were filled with non-shrink grout. Tridecks were connected to each other with weld ties spaced at 5 ft spacing. The deck was cast over the tridecks and into the reinforced closure joints over the piers and abutments. The deck was textured longitudinally by mechanical grooving, and the aesthetic concrete traffic railing was constructed. Traffic was switched to the replacement bridge, and the temporary bridge was removed.

Table B.1. — Continued

Project	Year	Summary of Activities
Vista Interchange Bridge, Idaho (2010)	2010	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The contractor obtained approval for PBES as a value engineering proposal. The new bridge was wider than the old bridge. The cast-in-place portions of the abutments and interior supports for the first half of new bridge were constructed while traffic remained on the existing bridge (part-width construction). Prefabricated girders and bent caps were transported to the site. The precast caps were positioned over the reinforcing bars extending from the cast-in-place portions of the abutments and interior columns, the caps were lowered into position, and the ducts and mechanical couplers were grouted to complete the cap-to-column connections. Beams were erected onto elastomeric bearing pads, and the deck was constructed conventionally. Then, the traffic was diverted onto the new bridge, the old bridge was demolished and the second half of the new bridge was built including the substructure. The lower portions of the substructures were cast in place because the construction staging did not benefit from accelerating the column construction.
US 17 Bridge over Tar River, North Carolina (2010)	2010	The DOT procured the project using the Design-Build method and specified incentive/disincentive clauses. The bridge was a new bypass structure over the river. The superstructure was designed by the contractor and consisted of seven 6-ft-deep pretensioned modified bulb-tee girders with an 8.5-inch-thick cast-in-place deck. The precast piles and bulb-tee girders were fabricated at a precast plant and trucked to the site. The contractor cast the precast pile caps onsite. Each precast cap was fabricated in three segments and post-tensioned together after erection. A 592-ft-long, 750-ton self-launching truss overhead gantry was assembled at each end of the bridge and worked from above toward the middle for top-down construction to avoid impact to the environmentally sensitive wetlands. The gantry system drove the 30-inch-square pretensioned concrete piles, erected the precast post-tensioned pile caps and the pretensioned bulb-tee girders, and assisted with casting the deck. Work on the bypass began in March 2007. The project was completed in February 2010, eight months earlier than the specified November 2010 completion date.
41st Street Bridge, South Dakota (2010)	2010	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low A+B bid contractor. The seven-lane replacement bridge has 19 adjacent precast pretensioned concrete box beams per span, with a composite 5.5-inch-thick cast-in-place concrete deck. The bridge was constructed in two stages with two 11-ft-wide lanes of traffic in each direction maintained during each stage. The steel H-pile concrete-encased wall piers were constructed prior to removal of the existing piers to accelerate construction. The beams were transported to the site, and erected and transversely post-tensioned with tie-rods. The deck was cast end-to-end with no transverse joints. A full-depth concrete closure joint was cast between the stages of construction. The actual construction duration was 113 days.
Kickapoo Bridge, Mississippi (2010)	2010	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of eight 1.5-ft-deep simple-span adjacent slab beams. The precast slab beams, caps, and wingwalls were fabricated at a precast plant and trucked to the bridge site. Traffic was detoured and the bridge was demolished. Four piles per support location were driven. The precast caps were erected over the piles. The precast wingwalls were attached to abutment caps with bolted connections. The substructure connection were completed by filling the cap pockets and grout holes with non-shrink commercial-type grout. The slab beams were then erected on elastomeric bearing pads. Webs of adjacent beams were bolted together transversely near the beam ends and at mid-span along the length of the span. Later, the precast concrete barrier rails were erected and transversely connected to the web of the outside beam with galvanized screw anchor and bolt connections. The connection between the slab beams was completed by using grout. The bridge was opened in 54 days.

Table B.1. — Continued

Project	Year	Summary of Activities
North Kahana Stream Bridge, Hawaii (2010)	2010	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of ten precast prestressed concrete planks with a minimum 7.5-inch-thick cast-in-place concrete topping. The deck planks were fabricated at a precast plant and shipped to the job site. The contractor assembled a temporary prefabricated steel truss bridge adjacent to the site and shifted the traffic on it. The existing bridge was demolished. Substructures for the replacement bridge were conventionally constructed. Cranes were used to erect the deck planks on elastomeric bearing pads. Shear keys between planks were filled with grout. A deck was cast over the planks and into the reinforced closure joints over the piers and abutments. The aesthetic concrete traffic railing was constructed. Finally, the traffic was switched to the replacement bridge and the temporary bridge was removed.
Biltmore Avenue Bridge, North Carolina (2010)	2010	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The DOT included disincentive clauses in the contract. The superstructure consists of six modular units. Each unit has two plate girders spaced at 6.13 ft and a composite concrete deck. The traffic was detoured (with an off-site 1-mile detour for 4 months) and the existing bridge was demolished. The contractor constructed the superstructure units at an adjacent staging area while the abutments were constructed using cast-in-place concrete and the bridge seat elevations verified before placement of the bearing assemblies. The superstructure units were erected, and the intermediate diaphragms were tightened. The units were connected with 12-inch-wide longitudinal cast-in-place concrete closure joints followed by grinding of the deck and approach slab for rideability. All work was completed on schedule.
640th Street over Branch Racoon River Bridge, Iowa (2009)	2009	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of seven adjacent pretensioned concrete box beams. The substructure consists of precast abutment caps on steel piles, with separate precast backwall/wingwall units. The precast caps, backwall/wingwall units, and box beams were fabricated in a precast plant and trucked to the site. Prior to being shipped to the bridge site, the individual precast elements were inspected and partially assembled to ensure proper fit-up in the field. The bridge was closed and traffic detoured. The existing bridge was removed in one day. The ten piles were driven and cut to the required length in one day. The abutment caps were erected over the piles with a mobile crane and supported on temporary blocking. The cap pockets were filled with concrete and allowed to cure over the weekend. The reinforcement bars for the backwall-to-cap connection were doweled into position. The beams were erected onto neoprene pads, with the middle beam erected first and the exterior beams erected last to ensure proper tolerances. The 1-inch-diameter transverse tie rods were threaded through the beams at third points, and coupling nuts at the blockouts between beams were tightened. After the ungrouted transverse tie assembly was tightened, 1.5-inch-diameter holes were drilled one foot into the abutment caps, using the holes in the precast beam ends as guides. A 2.25-ft-long 1.5-inch-diameter dowel was placed in each hole, and the holes were epoxied. An epoxy layer was placed on the top surface of the cap, and the reinforcement bars extending from the cap were threaded into the backwall/wingwall unit as it was lowered onto the epoxy layer. The remaining three backwall/wingwall units were similarly installed. The shear keys and blockouts between the beams and the voids between the backwall units and between the backwalls and box beams were filled with non-shrink grout. Finally, the dirt work and guardrails for the approaches to the new bridge were completed and the bridge was opened to traffic.

Table B.1. — Continued

Project	Year	Summary of Activities
Inyan Kara Creek Bridge, Wyoming (2009)	2009	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of four adjacent prestressed concrete deck bulb tee girders with attached precast abutment backwall and steel weld ties along deck edges. Steel plates were embedded in the precast abutment caps to connect to steel H-piles and precast wingwalls; similarly steel plates were embedded in the sides of the precast wingwalls to connect to the abutment caps. The precast elements were fabricated in a precast plant and trucked to the site. The bridge was closed and traffic detoured. The existing bridge was removed. Abutment piles were driven. Precast abutment caps were set on the piling and connection plates welded. The precast girders complete with abutment backwalls and curbs were erected, and deck ties between girders were welded. Precast wingwalls were erected and welded to the abutments. Backer rods between girders were placed and closure joints were filled with non-shrink grout. The bridge rail was installed. The roadway was graded with crushed base, and the bridge was opened to traffic.
MD Route 362 over Monie Creek Bridge, Maryland (2009)	2009	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of eleven prestressed concrete solid slab beams that are post-tensioned together transversely, with a 5-inch-thick reinforced cast-in-place modified latex concrete overlay and precast curbs. The abutments consist of precast abutment caps on steel pipe piles, and precast wings. The contractor drove the piles using single-lane weekend closures prior to closing the bridge. Steel caps were field-welded on top of the piles and covered with asphalt to allow traffic to be maintained. Precast elements were delivered to the site. The bridge was then closed, the superstructure demolished, and the piles excavated. The piles were cut to the correct elevation and filled with concrete to 20 ft below the bottom of footing elevation. The caps were then lowered over the piles. The closure joints and cap pockets were then cast. The contractor then placed the slab beams, grouted the shear keys between beams, post-tensioned the beams together, and added reinforcement for the cast-in-place overlay. The contractor then placed the overlay after applying a horizontal bond breaker between the abutment cap and overlay to create a semi-integral connection that allows for the typical ¼-inch movement. While the overlay cured for seven days, the contractor finished casting the wing walls, installed the bridge railing, and did other finish work. The bridge was then opened for traffic.
Black Cat Road Bridge, Idaho (2009)	2009	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of six pretensioned modified bulb tee beams with an 8-inch-thick cast-in-place reinforced concrete deck. The pretensioned bulb tee beams and precast reinforced concrete cap and two columns were fabricated in a precast plant and shipped to the bridge site. Bridge was closed and traffic detoured. The contractor demolished the bridge in two overnight closures of I-84 from 10 pm to 7 am. The mechanically stabilized earth (MSE) walls were constructed. Steel shell piling was driven at abutments and interior pier, and filled with concrete. Abutments were constructed conventionally. The precast columns were erected and mechanical couplers were grouted. The precast cap was erected onto the precast columns, and the mechanical couplers were grouted. The superstructure was constructed conventionally. The bridge was opened to traffic.

Table B.1. — Continued

Project	Year	Summary of Activities
I-85 / Kia Boulevard Bridge, Georgia (2008)	2008	The DOT procured the project using the Design-Build method and specified the contractor to use PBES. Superstructure was designed by the contractor. Each of the three interior substructures consists of eight square precast columns with four square precast pier caps joining two columns each. Abutments were conventional cast-in-place backwalls and wingwalls on steel H piles. The conventional superstructure cross-section consists of fourteen deep pretensioned bulb tee girders, and twelve AASHTO Type II pretensioned beams and bulb tee girder fascia beams. The precast caps and columns were fabricated offsite in a controlled environment, shipped to the site using conventional semitrailers, and temporarily stored onsite after delivery. Lane closure of I-85 was kept to a minimum, normally for 1.5 hours or less, and occurred during non-peak traffic hours. Cast-in-place column footings were constructed with protruding reinforcing steel that fit into a specialized coupler on the bottom of the columns. A bed of high-early-strength grout was placed on the footing to receive the column, the column was erected, and additional specialized grout supplied by the manufacturer was hand pumped into the coupler's inlet holes. The pier caps were placed on top of the columns. Decks were cast-in-place after beam erection.
Jakway Park Bridge, Iowa (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The middle span's cross-section consists of three adjacent pretensioned UHPC pi-girders with 4.13 inches thick deck between webs and deck tapered from 6.88 inches to 5.25 inches outside the webs at the deck edge. The 50-ft-long simple-span pi-girders were fabricated in three separate pours on three separate weeks at a plant in Canada. Ready-mix trucks were used to batch the UHPC mix to reduce costs. While the pi-girders were being fabricated, the contractor graded the bridge site and constructed the conventional cast-in-place integral abutments on steel H-piles and cast-in-place pier caps on steel H-piles encased in concrete. The pi-girders were trucked to the site and erected. They were tied together transversely with No. 8 reinforcement bars in grouted pockets at 18-inch spacing and with steel diaphragms across the bottom of the flanges at quarter points. The contractor encased the pi-girder ends in cast-in-place diaphragms. The two reinforced concrete slab end spans were constructed conventionally. The bridge was re-opened in a total of 52 days.
MD 28 over Washington Run Creek Bridge, Maryland (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of ten slab beams that are post-tensioned together transversely, with a cast-in-place reinforced concrete overlay. The slab beams were fabricated at a precast plant and shipped to the site. The contractor demolished the existing bridge and constructed the abutments using conventional construction techniques. Cranes were used to place the slab beams on elastomeric bearing pads. The construction crew then tensioned the transverse tie-rods, grouted the shear keys between beams, and placed reinforcement for the cast-in-place overlay. The contractor then cast the special-mix Portland cement concrete overlay and integral abutment backwalls as a continuous placement. During the seven days that the overlay cured, the contractor installed the bridge railing and did other finish work prior to opening the bridge to traffic.

Table B.1. — Continued

Project	Year	Summary of Activities
Parkview Avenue Bridge, Michigan (2008)	2008	During the study phase of the project, precasters and contractors in the state partnered with the DOT. Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The replacement bridge consists of precast integral abutments on single rows of H-piles, precast caps on precast multi-column piers, seven AASHTO Type III pretensioned beams in each span, and skewed full-depth precast longitudinally post-tensioned deck panels. The precast beams and substructure components were fabricated in Kalamazoo, Michigan while the 48 full-depth deck panels were fabricated at a plant 170 miles from the site in Midland, Michigan. The abutments were cast with oversized pockets for the steel H-pile connections. The four round precast columns at each interior support were supported on cast-in-place spread footings. The 65-ton pier caps required two cranes for erection. The 19-ton skewed full-depth precast longitudinally post-tensioned deck panels had grouted transverse joints and a closure pour at the crown point. The contractor had an expedited schedule with the open to traffic date one month prior to completion.
Riverdale Road Bridge over I-84, Utah (2008)	2008	The superstructure was designed by the designer in coordination with DOT and contractor using CMGC procurement method. The cross-section consists of twenty steel plate girders with a non-composite full-depth precast deck. The precast abutments are founded on steel HP piles. The interior pier consists of four separate precast caps, each supported on two precast columns, also founded on steel HP piles. Other prefabricated elements include precast end diaphragms and precast approach slabs. The contractor match-cast the prefabricated elements at an onsite casting yard. The bridge remained open throughout construction, which consisted of two phases. In Phase I, two 42.21-ft-wide bridges were constructed on either side of the existing bridge while traffic was maintained on the existing bridge. In Phase 2, traffic was shifted to the new bridges, the existing bridge was demolished, and the middle half of the new bridge was built and connected to the Phase I bridges. In Phase 1, piles were driven. Post-tensioning bars and ducts, dead anchor accessories, and anchorage zone reinforcement were placed in the footing forms. The footing reinforcement was placed, and the footings were cast. The abutment stems were erected over the embedded post-tensioning bars in the footings. Adjoining faces were epoxy coated prior to erection. After the top segment was erected and the epoxy reached strength, the vertical post-tensioning strands were stressed and duct connections were grouted. The precast columns were erected onto the cast-in-place footings and similarly connected to the footings. The precast caps were erected and post-tensioned to the columns, and the steel plate-girders were erected on the caps. The non-composite precast deck panels were erected; there were no shear studs connecting the panels to the girders. The longitudinal post-tensioning ducts were coupled and tendons were threaded through the ducts. The transverse deck joints were grouted. The longitudinal post-tensioning tendons were stressed and ducts were grouted. Haunches over the girder flanges were grouted. The precast end diaphragms were then bolted onto the backs of the girders. The precast approach slabs were placed, and a closure joint was cast to connect the deck, end diaphragm, and approach slabs. Bridge parapets and sidewalks were cast. Then, in Phase 2, the traffic was switched to the two new outside bridges, and a similar process was followed for the middle portion of the bridge after demilishing the exisitng bridge.

Table B.1. — Continued

Project	Year	Summary of Activities
MD 450 over Bacon Ridge Branch Bridge, Maryland (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of eleven slab beams. The slab beams were fabricated at a precast plant. The contractor demolished the existing bridge and constructed the abutments using conventional construction techniques. Cranes were used to place the slab beams on elastomeric bearing pads. The construction crew then tensioned the transverse tie-rods, grouted the shear keys between beams, and placed reinforcement for the cast-in-place overlay. The contractor was required to place the reinforcing mat such that it could be lifted off the bridge just prior to placement of the overlay to permit the entire deck to be cleaned. The contractor cast the special-mix Portland cement concrete overlay and integral abutment backwalls as a continuous placement. During the seven days that the overlay cured, the contractor installed the bridge railing and did other finish work prior to opening the bridge to traffic.
Kimberly Bridge, Oregon (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The pretensioned slab beams and precast reinforced concrete abutment caps were fabricated in the field and trucked a short distance to the site. Using single-lane closures, the contractor drove steel pipe piles for the approach spans. Traffic was then detoured and the bridge closed. Spans 5 and 6 were demolished. The ground surface at the abutment piles was graded. Steel support collars for the cap were installed on the piles. A crane was used to erect the cap onto the piles, and the space between the pile and the pocket cast into the cap was filled with grout. The precast slab beams were erected. The contractor then similarly replaced Span 1. Transverse connections between beams were made with tensioned rods, and keyways between the beams were grouted. Steel posts for the traffic railing were attached to the curbs, and the railing was installed. The wingwalls were constructed conventionally. The bridge was opened to traffic.
Route 70 Bridge over Manasquan River, New Jersey (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of twelve 71-inch-deep pretensioned concrete bulb tee girders spaced at 8 ft with a 9-inch-thick cast-in-place high performance concrete (HPC) deck. Staged construction was used to maintain traffic and minimize right-of-way requirements. In Stage 1, a portion of the eastbound side of the existing bridge was demolished to provide clearance to construct the 47.33-ft-wide eastbound half of the bridge. The existing bridge was used as a working platform to erect the girders for the eastbound bridge. The deck and continuity diaphragms at the piers were cast, and a temporary cantilevered sidewalk was constructed. Four 10.92-ft-wide temporary traffic lanes were striped, and traffic was transferred to the new eastbound half of the bridge. In Stage 2, the existing bridge was demolished and the westbound half of the new bridge was constructed similar to the eastbound bridge. The temporary sidewalk on the eastbound bridge was removed, and a permanent sidewalk constructed. The westbound bridge was then opened, with traffic lanes on both bridges in their final configuration.

Table B.1. — Continued

Project	Year	Summary of Activities
NC 12 Bridge over Molasses Creek, North Carolina (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of twelve adjacent pretensioned cored slabs, with two 1-ft-diameter voids. The precast bent caps were founded on nine prestressed concrete composite piles with bolted HP 10x57 pile extensions. The precast abutments were each founded on six prestressed piles and consisted of precast caps, backwalls, wingwalls, and wing footings. Additional precast elements included parapets and end posts. The precast elements were trucked to the bridge site. Prior to closing the bridge, the contractor closed one of the two traffic lanes to drive piles through the existing deck. Traffic was then detoured and the bridge was demolished. No debris was allowed to fall in the creek. The remaining piles were driven. A crane was used to erect the precast abutment caps and bent caps onto the piles with a 1-inch-wide joint between segments. The abutment wing spread footings were placed, and the wingwalls were placed on dowels located in the footings. The cap voids and dowel connections were grouted. Backfill was placed. The adjacent cored slab beams were erected onto elastomeric bearing pads. The precast backwalls were erected over the dowels extending from the tops of the abutment caps. Transverse 0.5-inch-diameter post-tensioning strands were threaded through 2-inch-diameter holes in the beams at quarter points and stressed; the ducts were not grouted. Backwall connections to the abutment cap and shear keys between beams were filled with grout. The metal railing was attached to the precast parapets. An asphalt overlay was applied without a waterproofing membrane, and the bridge was opened to traffic.
SH 290 Bridge over Live Oak Creek, Texas (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The bridge has four AASHTO Type IV pretensioned concrete beams per span, with a full-depth precast concrete deck. The project was a pilot project with limited traffic and constructed detour. No time constraints or special financial incentives were introduced. The traffic was detoured onto the planned detour route. Then, the existing bridge was demolished, drilled shafts constructed, and conventional concrete abutments and interior supports were constructed on the drilled shafts. The beams were erected. The panels were erected over concentrated groups of three headed anchor rods with a heavy hex nut to allow for any potential height adjustment due to camber variations in the beams. The shear connection blockouts were composed of 14-inch x 6-inch steel Hollow Structural Sections (HSS) precast into the panels to ensure confinement of the concentrated horizontal shear connection into the panel. Grout insert and vent tubes precast into the panels at the horizontal shear blockout locations permitted pressure grouting of the interface and ensured full grouting of the haunch region between beams and panels, as well as the horizontal shear connection regions. The transverse connection between adjacent panels used grouted joints with shear keys cast into the edges of the precast panels. For practical fabrication the panels were cast flat with no cross-slope, and cross-slope for drainage was introduced with variable depth asphaltic overlay that ensured a uniform surface and allowed the use of polymer header expansion joints that avoided special blockouts in the panels for this function.

Table B.1. — Continued

Project	Year	Summary of Activities
Madison County Bridge, Iowa (2007)	2007	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The superstructure cross-section consists of six adjacent pretensioned box beams. The integral abutment was precast. All precast elements were fabricated in the precast plant. The precast footings were cast with five full-depth pockets to go over the piles. The contractor drove the piles, and then welded the shear studs along the length of pile to be inserted into the abutment cap pocket. The abutment footings were set in place, and a high-early-strength concrete mix was used to fill the pockets. The beams were erected onto the abutment footings in an hour and a half. The contractor then stopped operations for the winter. In the spring the contractor returned to the site and constructed cast-in-place abutment backwalls on top of the precast abutment footings. The longitudinal keyways between beams were filled with non-shrink grout, and the transverse tie located at midspan was hand-tightened. The remainder of the bridge, including cast-in-place wingwalls and railings, were constructed conventionally.
Parker River Bridge, Massachusetts (2007)	2007	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The bridge consists of precast concrete piles, abutments, pier caps, and slab beams that were precast at a plant and shipped to the site. The traffic was closed and an alignment template was used to drive the twenty precast prestressed piles. The abutments and caps were lowered over the pile assemblies and grouted into position. The slab beams were erected onto elastomeric bearing pads, shear keys were grouted, a tie rod was threaded transversely through precast holes in the middle of each span and stressed with hydraulic jacks to perform as a unit, and the recesses at tie rod anchorages were filled with non-shrink epoxy grout. A waterproof membrane strip was placed on top of the longitudinal joints between the beams as an added measure of protection against water leakage through the joints. An 8-inch-thick cast-in-place high-performance concrete (HPC) deck was cast over a mid-depth mat of steel reinforcement to complete the composite section. The bridge was opened to traffic.
Mackey Bridge, Iowa (2006)	2006	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The superstructure cross-section consists of four prestressed I-beams and a full-depth precast deck. The superstructure design was similar to NUDECK precast panel system. The skewed 8-ft-long, 18.6-ft-wide transversely pretensioned deck panels span half the width of the bridge, joined by a 1-ft-wide longitudinal cast-in-place construction joint. The 32 interior panels were identical, and the four end panels had post-tensioning anchorage zones. The substructure consisted of precast integral abutment footings supported on steel H piles, and precast pile caps supported on steel pipe piles for the interior supports. All precast elements were fabricated in the precast plant and transported to the site. The traffic was detoured and the existing bridge was demolished. The piles were driven. The abutment footings were set in place over the H piles. Similarly, the pile caps were placed over the pipe piles at cap pocket locations. A high-early-strength concrete mix was used to fill the pockets.The beams were erected onto the abutments and piers. The panels were erected onto the beams and leveled. The transverse joints were filled with concrete and allowed to cure overnight. Twelve post-tensioning strands were then placed in two layers in each longitudinal channel over the beams and stressed. The four post-tensioned channels over the beams, the longitudinal joint at the center of the bridge, and the abutment diaphragms were then cast. The excavated areas behind the abutments and wingwalls were backfilled and compacted, the road was graded to the bridge deck elevation, and the bridge deck was ground smooth; no overlay was applied. After the bridge deck was ground, the completed bridge was opened to the public.

Table B.1. — Continued

Project	Year	Summary of Activities
O'Malley Bridge, Alaska (2005)	2005	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of six adjacent pretensioned decked double-tee girders with 6.5-ft-wide top flange and 4.5 ft depth. The interior pier consists of a cast-in-place concrete pile cap on steel pipe pile extensions. The cast-in-place abutment is founded on steel H-piles. The new bridge was an extension of a bypass route. Traffic remained open throughout the construction. The girders were fabricated at a precast plant and trucked to the site. The contractor drove the steel H-piles and constructed the cast-in-place abutments, and drove the steel pipe piles and constructed the cast-in-place pile cap. The girders were erected with a truck crane onto elastomeric bearing pads. They were welded to each other at embedded shear connectors spaced at 4 ft along flange edges. Grout was placed in the longitudinal shear keys and the shear connector blockouts between girders. Closure joints at the ends of the girders were cast. Curbs were cast, and metal railing was installed. A waterproof membrane was placed on the deck, followed by an asphalt overlay. These bridges were part of a large roadway project. These bridges were built in about 60 days. They would likely have been opened to traffic sooner, but the bridge subcontractor had to wait for the earthwork to catch up.
Mill Street Bridge, New Hampshire (2004)	2004	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The two-lane replacement bridge consists of a pretensioned concrete adjacent box beam superstructure on full-height cantilevered precast concrete abutments founded on precast concrete spread footings. All precast segments were shipped 170 miles from the precast plant to the jobsite. The spread footings and other substructure components were fabricated in segments as determined by the contractor and precaster to facilitate shipping and handling, and were standardized to reduce fabrication costs. The precaster used a template in the plant fabrication to ensure adequate tolerances between the abutments, wingwalls, and footing segments. The existing bridge was closed and demolished. Following placement of the footings, a minimum 3-inch thick flowable grout bed was injected through grout tubes in the footings to provide a sound bearing surface for the roughened bottom surfaces of the footings. Proper grading was assured by using leveling screws cast in the corners of each footing segment. The abutment walls and wingwalls were lowered into place, and the splice sleeves were then grouted to complete the bar splices. The beams were erected. Full-depth shear keys were then cast between each box beam, and the span was transversely post-tensioned in six locations to complete the connection between beams. A waterproofing membrane was applied to the top surfaces of the box beams, followed by an asphalt overlay. The low traffic volume crossing the bridge in combination with a short half-mile detour allowed complete closure of the bridge during its replacement.

Table B.1. — Continued

Project	Year	Summary of Activities
SH 86 over Mitchell Gulch, Colorado (2002)	2002	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The DOT had awarded the construction contract to replace the deteriorated bridge with a conventional 3-cell cast-in-place concrete box culvert. However, the contractor teamed with a local design firm to submit a value engineering change proposal to build the single-span totally prefabricated bridge over a weekend to limit the onsite exposure time of his crew. The DOT accepted the value engineering change proposal, with no change to the project funding. The cross-section of the new single span bridge consists of 8 side-by-side precast slab beams welded onto precast abutments and precast wingwalls welded to driven steel H piles. Each of the four wingwalls is a separate precast piece. Prior to the bridge closure, the contractor constructed a short detour to divert traffic for the weekend, and also drove 40-ft-deep steel H piles at the abutments in the stream banks just outside the existing roadway width (outside the bridge footprint). The precast concrete abutments, wingwalls, and slab beams were fabricated at an offsite plant and shipped to the site just before being installed. At 7 pm on Friday the bridge was closed and traffic diverted to the detour. The existing timber bridge was demolished. Early Saturday morning, the abutment units and wingwalls were erected with a crane and welded to the steel H piles and to each other prior to placing flowable fill behind the abutments. On Saturday afternoon, the eight slab beams were erected, including the edge beams complete with precast railing. The units were then transversely post-tensioned and grouted. Work stopped at 11 pm. At 7 am Sunday, work resumed. The earthwork was completed and the asphalt overlay was placed, with membrane applied between the first two exterior precast slabs. The bridge was reopened to traffic at 5 pm on Sunday, 13 hours earlier than the required 6 am Monday opening. The bridge was closed for 46 hours, but only 38 hours of actual construction work was needed.
Keaiwa Stream Bridge, Hawaii (2001)	2001	The exisitng bridge was closed due to flood and needed replacement. Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The contractor demolished the existing bridge and constructed the spread footings, abutments, and wall piers using conventional construction techniques. The precast prestressed concrete deck planks were fabricated at a precast plant and shipped to the job site. Cranes were used to erect the deck planks on elastomeric bearing pads. The connections between the planks were completed using non-shrink grout. A 6 inch thick cast-in-place concrete deck was cast over the planks and into the reinforced concrete closure joints over the piers. The bridge was opened to two-way two-lane traffic seven months after the flooding.
I-5 / South 38th Street Bridge, Washington (2001)	2001	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The superstructure consisted of partial-depth precast stay-in-place deck panels over post-tensioned precast open-top trapezoidal box girder segments. The bridge was closed and the conventional concrete columns were constructed on spread footings. The precast elements were transported to the site. The precast open-top trapezoidal box girder segments were erected with three segments per span. The partial-depth precast deck panels were then erected and adjusted with leveling screws. Grout was placed below the panels to provide continuous support. The composite deck topping was cast, and girder segments were longitudinally post-tensioned together.

Table B.2. Summary of Activities Included in the SPMT Move Method

Project	Year	Summary of Activities
LA 3249 (Well Road) Bridge, Louisiana (2011)	2011	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low A+B bid contractor. The contractor prepared the staging area and constructed the superstructure spans on temporary steel pipe trestle supports at the staging area within the interchange. Prior to bridge closure, the existing substructure was strengthened by adding spread footings between existing pile footings at interior supports and adding abutment extensions on columns/drilled shafts at the ends of the existing abutments. Bridge and I-20 were closed on Friday at 7 pm. Two sets of SPMTs were used to individually remove two of the existing spans. The existing abutments and interior piers were repaired as needed. The second two sets of SPMTs were then used to individually install the first two replacement spans. The process was repeated for the remaining two existing and replacement spans. Polymer concrete was placed at the abutment backwalls, and preformed silicone joint seals were installed. Standard strip seals were installed at the interior span joints. The bridge was opened on Sunday evening, 10 hours ahead of the scheduled 3-day closure.
I-15 / Sam White Lane Bridge, Utah (2011)	2011	The DOT procured the project using the Design-Build method and specified the contractor to use SPMT move. Superstructure was designed by the contractor. Staging area was prepared approximately 500 ft from the bridge location. The new superstructure was built at the staging area. In the meantime the Sam white traffic was closed and the old bridge was demolished. The abutments and interior support were constructed conventionally with concrete-filled pipe pile foundations. On Saturday evening, I-15 was closed at 11 pm. Minor travel path preparation was completed, and the two-span unit was lifted off the temporary supports using four lines of SPMTs and moved 500 ft across eight lanes of I-15 to the final bridge location. On Sunday morning the bridge was set in place at 4 am. I-15 was re-opened at 7 am, three hours ahead of schedule. The abutments were made integral after the move, and a thin-bonded polymer overlay was placed. Later, the bridge (Sam white lane) was opened to traffic.
Willis Avenue Bridge over Harlem River, New York (2010)	2010	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The contractor obtained approval for the value engineering proposal to use SPMT move. The new bridge was built on a new alignment, adjacent to existing bridge. This was the final position of the bridge. The traffic remained open on the old bridge throughout the construction. The river pier foundations were constructed. Precast concrete modular pier boxes (precast cap shells) were fabricated off site and barged to the site. The modular pier boxes are an integral part of the pier caps. The swing span was assembled over an 18-month period at approximately 10 miles south of Albany, NY. The assembly took place on land in a riverfront yard and the 2,400-ton assembled span was then transported on SPMTs onto barges. In the next 24 hours, the span was floated 130 miles down the Hudson River on the barges. The span was floated into place on top of the new piers. Once the span was in place, the concrete infill was placed in the pre-installed grid deck; the concrete was filled for partial depth plus an integral 1.6-inch-thick overfill. Traffic was shifted to the new swing span within 60 days of the float-in and the existing swing span was floated out.
I-215 / 4500 South Bridge, Utah (2007)	2007	The superstructure was designed by the designer in coordination with DOT and contractor using CMGC procurement method. The replacement superstructure was built at the staging area on temporary supports while the replacement abutments were built below the existing bridge (4500 South) with 4500 South (facility carried) and I-215 (feature intersected) traffic maintained. On Friday evening I-215 and 4500 South bridges were closed. On Saturday the two existing spans crossing I-215 were removed in seven hours with SPMTs, while the two smaller existing end spans and substructures were demolished conventionally. On Sunday SPMTs moved the replacement superstructure into place. The removal and replacement took 53 hours over a weekend. On Monday at 3 a.m. I-215 was reopened to traffic with the 4500 South Bridge reopened 10 days later. Precast approach slabs helped speed the bridge reopening.

Table B.2. — Continued

Project	Year	Summary of Activities
Sauvie Island Bridge, Oregon (2007)	2007	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The new bridge was built on a new alignment adjacent to existing bridge. The contractor chose to assemble the steel span off site and barge into place. The existing bridge remained in service the entire time while the new bridge was being built adjacent to it. The steel tied arch span was fabricated and assembled in a fabrication plant, disassembled, and shipped to a dock at the Port of Portland nine miles from the bridge site (staging area), where it was reassembled. At the staging area the arch span was transferred from its temporary supports to SPMTs and driven onto barges. The barges transported the span to the site. At high tide, self-climbing jacks on four barge-mounted jacking towers were used to raise the span 60 feet into position over its final supports. The bridge was lowered into place with the falling tide. A high-performance concrete (HPC) deck was placed.
Graves Avenue Bridge, Florida (2006)	2006	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The superstructure was designed for conventional construction; minimal structural design changes were required to field change the use of SPMTs into the contract. The cross-section in each span consists of eight Florida bulb-tee beams with 8-inch-thick composite concrete deck. The substructure consists of conventional cast-in-place reinforced concrete abutments and piers with pretensioned concrete driven pile foundations. The beams for the two replacement spans were pretensioned concrete beams fabricated offsite, shipped to the staging area a quarter mile from the bridge site, and erected on the temporary supports that were identical in relative elevation to the onsite pier configuration. The bridge was closed to traffic. Existing bridges were removed using SPMT in January 2006. A 20-minute rolling roadblock was implemented for removing the exisitng bridges. Concurrent construction of the substructures onsite and superstructure in the staging area took place from January to June. The new spans were built five feet off the ground on temporary supports at the staging area while I-4 was widened and the abutments and interior bent were built conventionally onsite. Several days before the scheduled move, the span to go over I-4 West was lifted off its temporary supports by SPMTs, with each end supported by a set of four six-axle SPMT units. The span was then jacked in stages to its setting height and supported on sectional barges atop the SPMTs. On June 3, both directions of I-4 were closed along a 4-mi length shortly before midnight, and traffic shifted to a 5-mi detour. In about 30 minutes the SPMTs carried the span along I-4 to the bridge site. As the SPMTs approached the substructure, the operator lifted the SPMT platforms to provide clearance over the neoprene bearing pads in position on the substructure bearing seats. Proper alignment of the beams onto the bearing seats took about two hours. The process was repeated a week later for installation of the new span over I-4 East. The bridge required a short closure time because it is near a high school and needed to be open in time for the start of school in the fall.

Table B.3. Summary of Activities Included in the SIBC Method

Project	Year	Summary of Activities
OR213 Bridge over Washington Street, Oregon (2012)	2012	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The contractor built temporary substructure next to the existing OR213 and constructed the new superstructure on them. Meanwhile, the permanent foundations for the new bridge were constructed on existing alignment while maintaining five existing travel lanes of traffic on the old bridge during the day and temporary lane closures during the night. The bridge was closed completely and the OR213 traffic was detoured onto two-lane city streets. The old bridge was demolished. Then, the new superstructure was jacked and moved to final location. The lateral move and lowering onto the bearings took a total of 22 hrs. Precast impact panels were installed during the closure along with asphalt paving of roadway approaches.
Hardscrabble Creek Bridge, California (2008)	2008	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. Temporary supports were built next to existing bridge and the new bridge was built conventionally on them. Then, the traffic was diverted onto the new bridge. The old bridge was then demolished, and concrete abutments were constructed on the existing alignment. Drilled pile foundation was changed to spread footing for abutments to accelerate the construction. The contractor closed the bridge on a Monday night. Full road closure was allowed for a maximum of 8 hours. The new bridge superstructure was jacked up and slid approximately 48 feet into place on the new abutments. The lateral slide took 8 hours. Jacking loads were applied simultaneously to prevent distortion and excessive stresses that would damage the structure.
Elk Creek Bridge, Oregon (2008)	2008	The DOT procured the project using the Design-Build method and specified the contractor to use SIBC. The cross-section consists of three steel I-beams with a cast-in-place concrete deck. The replacement superstructure was built adjacent to the existing bridge and laterally slid into position over a weekend. With traffic maintained on the existing bridge (1) a new substructure was constructed for the replacement bridge under the existing bridge (cast-in-place drilled shafts, columns, and caps); (2) a temporary substructure was constructed for the existing superstructure on one side of the existing bridge; (3) a temporary substructure was constructed for the replacement superstructure on the other side of the existing bridge. Friday evening The existing bridge was closed to traffic at 8 pm, with traffic detoured for the two-day closure. Preliminary work included removing the asphalt overlay, bridge railings, and approach slabs. Saturday - Sunday The old superstructure was lifted and slid laterally onto temporary supports using hydraulic jacks mounted on sliding rails. Similarly, the replacement bridge was slid laterally onto the original alignment. The moves took about four hours to complete. Backfill was placed. Precast wingwalls, sleeper slabs, and approach slabs were installed. Finish work required prior to opening the bridge was completed. Monday morning The bridge was opened to traffic at 5:00 am. Subsequently the old superstructure was demolished and the temporary supports were dismantled.

Table B.3. — Continued

Project	Year	Summary of Activities
San Francisco Yerba Buena Island Viaduct, California (2007)	2007	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. Demo-Out-Move-In strategy was implemented: Building a new structure next to the existing structure and then quickly demolishing the old structure and moving in the new structure. New support columns and foundations were built to the side of existing Viaduct (outside of existing footprint) while the Viaduct was in service. The superstructure consists of CIP/PS box girder with transverse girders and large edge beams. The basic construction sequence was as follows: (1) Prepare a level staging area adjacent to the existing structure for construction of the new superstructure, (2) Build the new support columns to the side of the existing Viaduct, (3) Build the new superstructure, including temporary support columns, in the staging area, (4) Place the moving equipment, including skid shoe rails and rail foundations, (5) Close the facility carried to traffic for up to 3 days, (6) Demolish the existing structure, (7) Move the new structure, (8) Set the new structure down on support columns and place the column pins, (9) Place the closure pour between the new and exisitng viaduct, and (10) Open the facility carried to traffic.
Hood Canal Bridge, Washington (2005)	2005	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of five prestressed bulb tee girders, with a cast-in-place concrete deck. Each new cast-in-place substructure consists of a cap on two round columns founded on drilled shafts. Prefabricated elements included precast abutment backwalls and precast approach slabs. While traffic was maintained on the existing bridge, the contractor built the new substructures underneath the bridge, clear of existing piers. Work trestles and temporary supports were then built underneath and beside the existing bridge. At 8 pm on a Sunday in August the bridge was closed. The existing deck was cut at both ends, and jacks were placed under the spans. The old spans were jacked up onto rollers and rolled onto temporary false work by 4 pm on Monday. The precast abutment backwalls were erected. The upper portions of the existing piers were removed. Multiple synchronized jacks lifted the new spans onto rollers. The spans were then rolled into place as a unit. The new spans were in place by 12 am Tuesday morning. Permanent bearing pads were set at each pier. Jacks were removed. Precast approach slabs and expansion joints were installed. No overlay was applied. Finish work was completed and the bridge was re-opened to traffic on Tuesday at 8:40 pm, for a 49-hr total closure.
I-405 / Northeast 8th Street Bridge, Washington (2003)	2003	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The cross-section consists of eleven steel I-girders with a cast-in-place reinforced concrete deck. The reinforced concrete abutments and four-column interior pier are founded on spread footings. The DOT chose a total prefabrication design that allowed it to stage the bridge beside the highway during construction and then move it into place. The construction sequence included four stages that allowed all traffic lanes to remain open during replacement of the bridge. South half of the new bridge was constructed on temporary piers on the south-side of the old bridge. Three lanes were diverted onto the new portion and other three lanes remained on south-half of the old bridge. The north half of old bridge was demolished and rebuilt conventionally. Three traffic lanes were then diverted onto the new north half of the bridge and the old south portion was demolished and substructures were constructed. On a Friday evening in September, traffic lanes on Northeast 8th Street and I-405 were re-routed, and the bridge was closed. The new south half of the bridge was jacked off its temporary piers and rolled 64 ft north to its permanent location in about 12 hours. I-405 and westbound Northeast 8th Street traffic lanes were re-opened before noon on Saturday. The remainder of Saturday and Sunday were spent installing permanent bridge bearings, constructing approaches, and striping. All lanes were opened for Monday morning commuters.

Table B.3. — Continued

Project	Year	Summary of Activities
Carniquez Strait Bridge, California (2003)	2003	Superstructure was designed by the designer for the DOT and the DOT awarded the construction contract to low bid contractor. The new bridge was constructed on a new alignment. The traffic remained open on the old bridge throughout the construction. The new superstructure units were each 79 to 163 ft in length. They could not be erected using a gantry mounted on the main cable because the adjacent bridge scheduled for demolition was only 40 to 60 ft from the new bridge. Some units were raised directly into their final locations and connected to their permanent suspenders. Some units in the main span were raised into a temporary position, then were transferred along the main cable by a series of trapeze-like swings to their final locations in the main span. The units in the side spans were raised onto temporary supports and jacked into position for final erection in the side spans.

Appendix C

Ontologies and parameter correlations for SPMT Move and SIBC

Ontologies

Self-propelled modular transporter (SPMT) move

The Task-Actor-Relation-Table (TART) for SPMT move based on the major activities and agents described in Chapter 6 is shown in Figure C.1. The ontology of SPMT move is represented as shown in Figure C.2.

AGENTS

ACTIVITIES	DOT	Designer	Contractor	Prefabricator	SPMT Subcontr.	Geotech. Consultant	Utility Reloc. Consultant	Public
1 Design superstructure	X	X						
2 Prepare staging area	X		X		X	X	X	
3 Construct superstructure at staging area	X		X	X	X			
4 Repair/Construct permanent substructure on existing alignment	X		X			X		
5 Close the facility carried and feature intersected for traffic	X							X
6 Prepare travel path (Excavation/placing level pad)	X		X		X	X	X	
7 Jack and move the superstructure to permanent substructure	X		X		X			

X Agent involved with the activity

<-> Network depicting communication among the agents

Figure C.1. TART for SPMT move

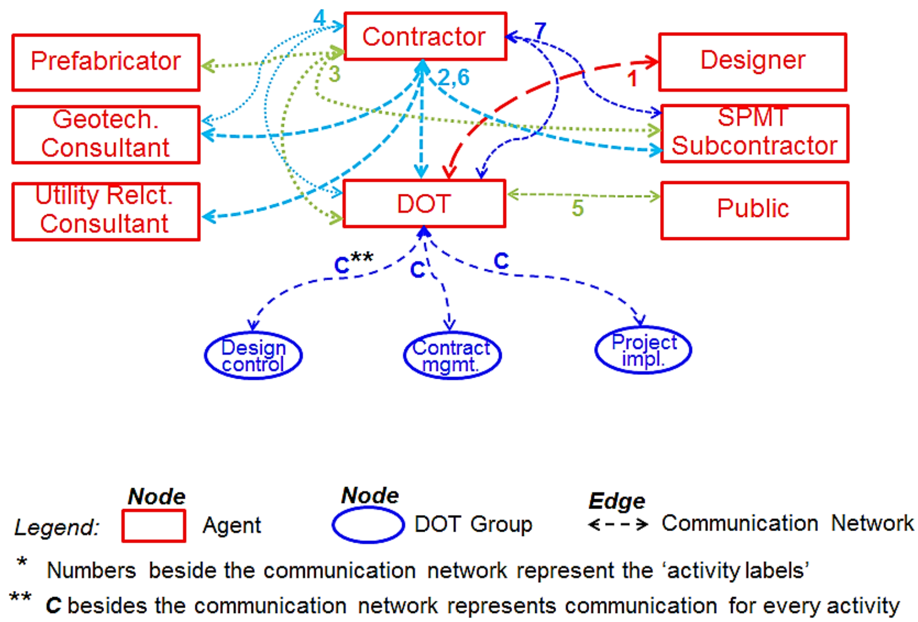


Figure C.2. Ontology for SPMT move

Slide-in bridge construction (SIBC)

The following are SIBC cases described in Chapter 6:

1) Case-1: SIBC with diverting traffic on new superstructure while old bridge is demolished and new substructure constructed. In this case, full-width or part-width of the new superstructure can be used for traffic diversion and is termed *temporary run-around*. This case is generally implemented when the existing substructure cannot be reused and the facility carried cannot be closed to traffic for a long duration.
2) Case-2: SIBC without traffic diversion on new superstructure. In this case, the facility carried is completely closed to traffic while the old superstructure is demolished and the existing substructure is repaired. This case is implemented only if the existing substructure can be reused with minor repairs or improvements.
3) Case-3: SIBC with sliding of both old and new superstructures. This case is implemented only if the existing substructure can be reused with minor repairs or improvements, and demolishing the old superstructure on existing alignment is a concern.

The TARTs for SIBC case-1, case-2, and case-3 based on the major activities and agents described in Chapter 6 are shown in Figure C.3, Figure C.4, and Figure C.5, respectively. The ontologies for SIBC case-1, case-2, and case-3 are shown in Figure C.6, Figure C.7, and Figure C.8, respectively.

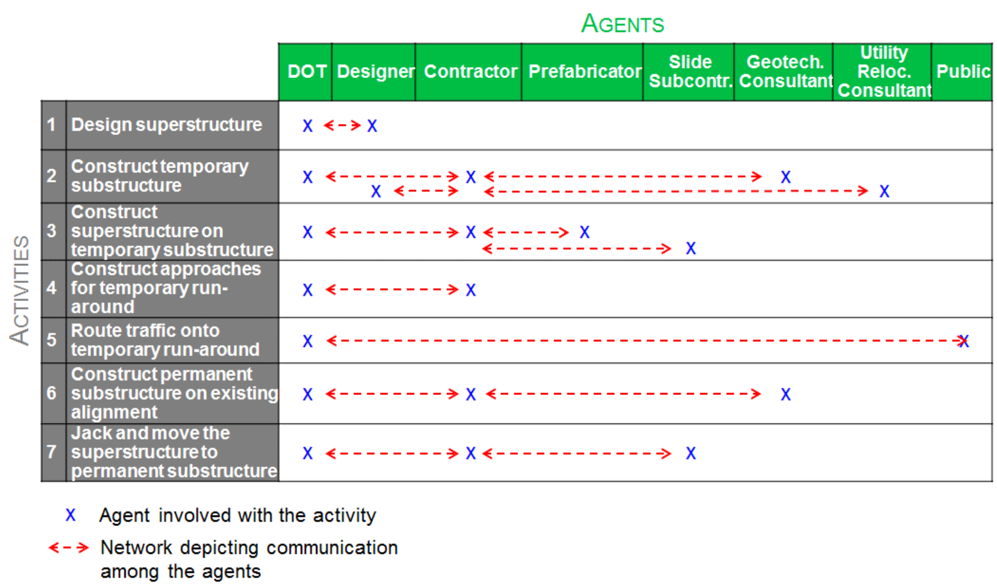


Figure C.3. TART for SIBC with diverting traffic on new superstructure

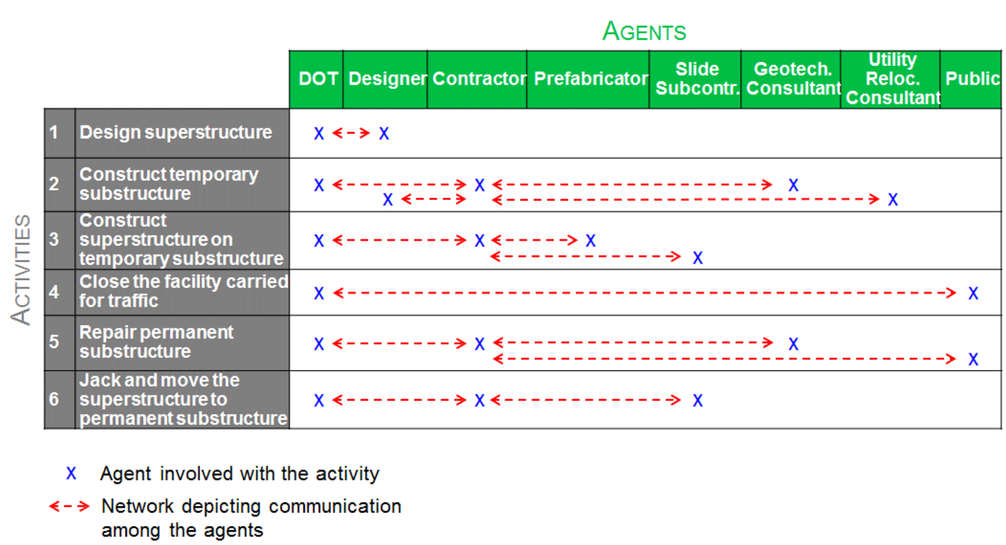


Figure C.4. TART for SIBC without traffic diversion on new superstructure

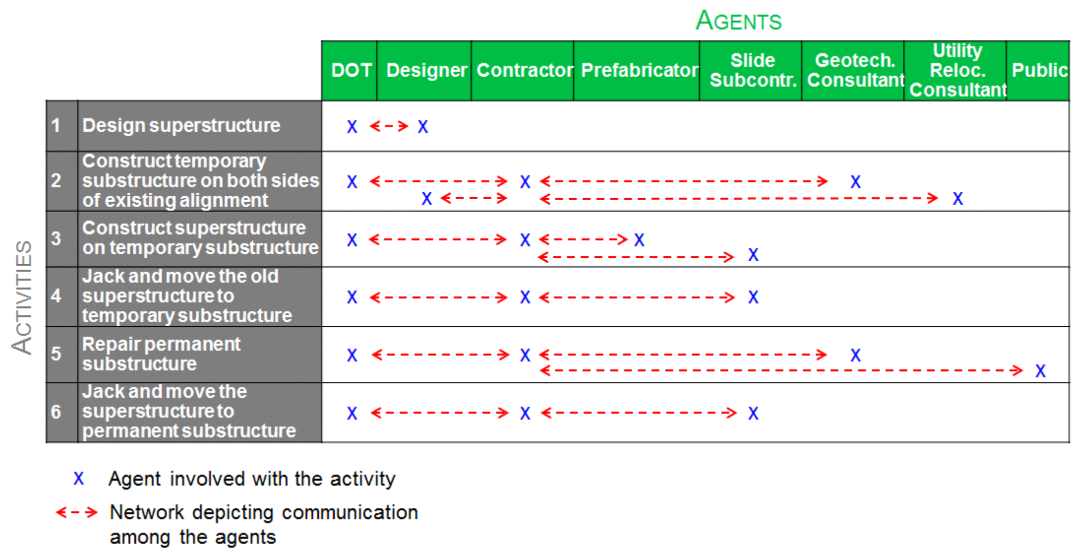


Figure C.5. TART for SIBC with sliding of both old and new superstructures

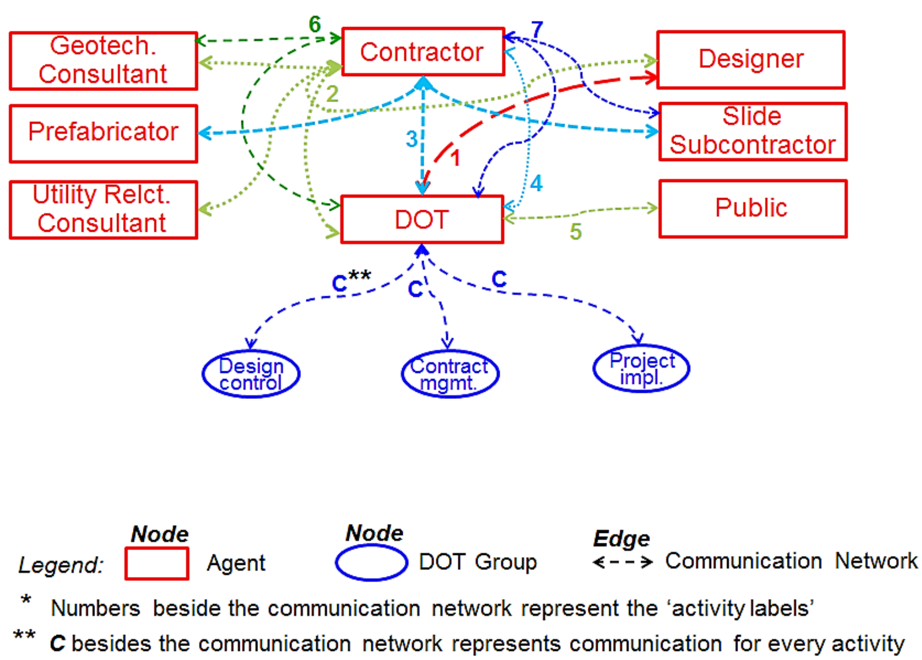


Figure C.6. Ontology for SIBC with case-1

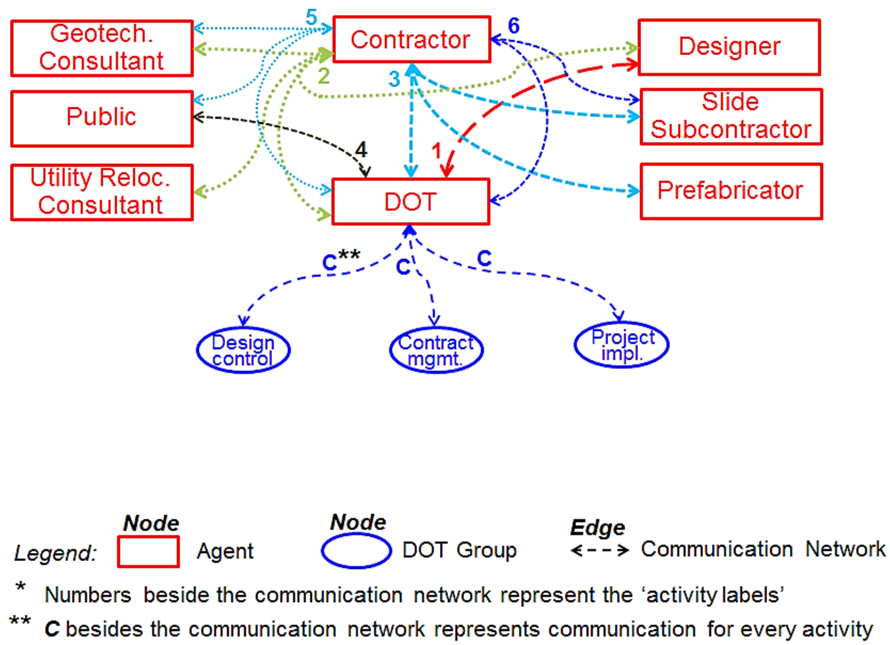


Figure C.7. Ontology for SIBC with case-2

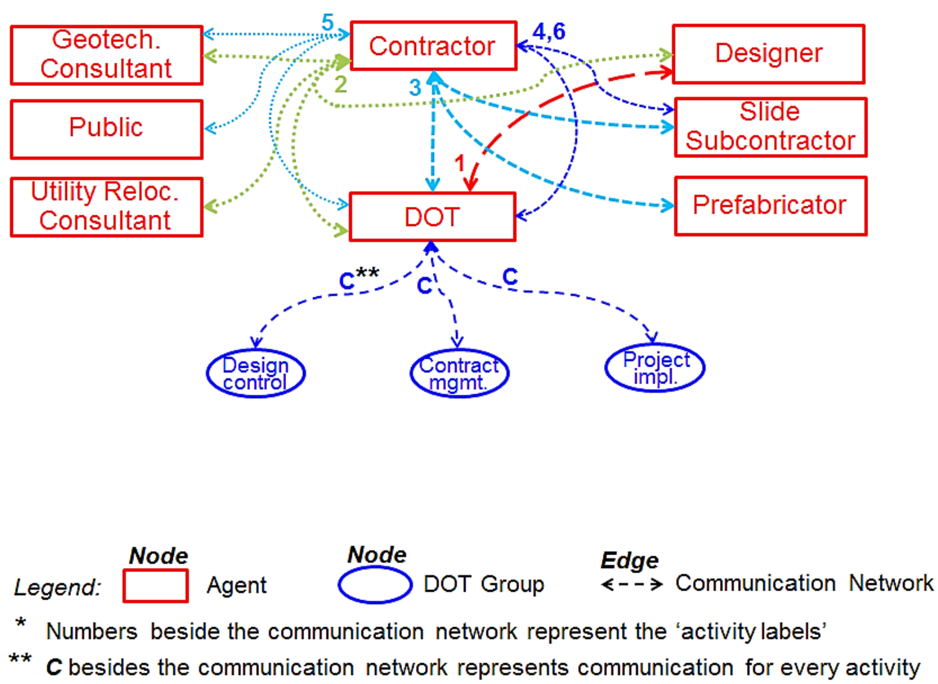


Figure C.8. Ontology for SIBC with case-3

Parameter correlations with site-specific data

Self-propelled modular transporter (SPMT) move

Using a similar format described in Chapter 6, the parameter correlations developed for SPMT move are shown in Table C.1 to Table C.7.

Table C.1. Parameter Correlations for the SPMT Move Activity: Design Superstructure

Parameters for 'Design Superstructure'	Site-Specific Data (Options)	Uncertainty Rating: PC I-girder & CIP deck system	Uncertainty Rating: Steel girder & CIP deck system	Reasoning for Ratings
Span length[1] (L)	L < 60 ft	VL	VH	The PC I-girders such as the most popular AASHTO I-girders are typically used for spans up to 140 ft, and the steel girders are typically used for spans up to 170 ft (PCI 2011; FHWA 2015b). For short spans steel girders system is not preferred because of cost of steel.
	60 ft ≤ L < 80 ft	VL	VL	
	80 ft ≤ L < 140 ft	VL	VL	
	L ≥ 140 ft	L	VL	
Beam spacing[1] (S)	S < 6 ft	VL	VL	For a wide bridge, large beam spacing is preferred for economy. However, the beam spacing is decided based on the span length as it is inversely proportional to the span length. High uncertainty of PC I-girder system for SPMT move with large beam spacing (WSDOT 2008; UDOT 2010; Hughes et al. 2011).
	6 ft ≤ S < 10 ft	L	VL	
	10 ft ≤ S < 12 ft	M	L	
	S ≥ 12 ft	H	L	
Skew (θ)	θ = 0° (no skew)	VL	VL	With high skew, the SPMT move operation with steel girder system is preferred because of the steel flexibility (Chung et al. 2008; FHWA 2015b).
	θ ≤ 30°	VL	VL	
	30° < θ ≤ 45°	L	VL	
	θ > 45°	M	VL	
Underclearance[1] (UC) (existing)	UC < 14.25 ft	VH	H	The underclearance is inversely proportional to the span length. If the span length increases the girder depth increases, thus, the underclearance is reduced. If the existing underclearance is low, the system requiring deep girders for a particular span is less preferred (UDOT 2010; Graybeal 2010; Abudayyeh 2010; Grace et al. 2015).
	14.25 ft ≤ UC < 15 ft	H	M	
	15 ft ≤ UC < 16.25 ft	M	L	
	UC ≥ 16.25 ft	L	VL	
Aesthetic requirements	None/ Low	VL	VL	PC I- girder system cannot incorporate significant aesthetic requirements such as different architectural concepts that steel girder system can accommodate (Culmo 2011b).
	Moderate	M	VL	
	High	H	VL	

Table C.1. — Continued

Parameters for 'Design Superstructure'	Site-Specific Data (Options)	Uncertainty Rating		Reasoning for Ratings
		PC I-girder & CIP deck system	Steel girder & CIP deck system	
Geometric complexity (curved bridge)	Low	L	VL	Short length PC I- girders can be used for curved bridges; however, difficulty increases with increase in geometric complexity of a bridge. On the other hand, a steel girder system can be curved or built to accommodate the complex geometry of a bridge (Chung et al. 2008; FHWA 2015b).
	Moderate	H	VL	
	High	VH	VL	

[1] Dependent parameters

Table C.2. Parameter Correlations for the SPMT Move Activity: Prepare Staging Area

Parameters/Sub-Parameters for 'Prepare Staging Area'	Site-Specific Data (Options)	Uncertainty Rating
Availability of staging area for SPMT move	Unavailable	VH
	Limited and additional area purchase required (temporary easement)	M
	Available at a distance suitable for SPMT move	VL
Number of spans for SPMT move	1	VL
	2	L
	3	M
	4	H
	More than 4	VH
Environmental sensitivity of staging area	None/ Low	VL
	Moderate	M
	High	VH
Complexity of constructing temporary substructure (piles, etc.)	None/ Low	VL
	Moderate	L
	High	M
Base preparation requirement based on allowable ground bearing pressure	None/ Low	VL
	Moderate	M
	High	H
Impact on overhead & underground utilities	None/ Low	VL
	Moderate	M
	High	VH
Complexity of agreement with private/ public utility company	None/ Low	VL
	Moderate	M
	High	H
	Very High	VH
Complexity of relocating utilities	None/ Low	VL
	Moderate	M
	High	H
	Very High	VH

Table C.2. — Continued

Parameters/Sub-Parameters for 'Prepare Staging Area'	Site-Specific Data (Options)	Uncertainty Rating
DOT/Contractor coordination	Flexible for change orders	VL
	Moderate	M
	Restricted for change orders	VH
SPMT subcontractor experience	Low	VH
	Moderate	M
	High	L

Table C.3. Parameter Correlations for the SPMT Move Activity: Construct Superstructure at Staging Area

Parameters/Sub-Parameters for 'Construct Superstructure at Staging Area'	Site-Specific Data (Options)	Uncertainty Rating	
		PC I-girder & CIP deck system	Steel girder & CIP deck system
Prefabricator experience	Low	VH	VL
	Moderate	H	VL
	High	L	VL
	Very High	VL	VL
Material availability	Low	M	VH
	High	VL	L
Contractor experience	Low	VH	M
	Moderate	M	L
	High	L	VL
Constructability of design	Not difficult	VL	VL
	Moderate	VL	VL
	Difficult	VL	VL
Equipment malfunction possibility	Low	M	L
	Moderate	H	M
	High	VH	H
Project special provisions	None/ Limited	H	M
	Moderate	M	L
	Comprehensive	L	VL
Complexity of lifting and moving the superstructure	None/Low	M	VL
	Moderate	H	L
	High	VH	M
SPMT subcontractor experience	Low	VH	VH
	Moderate	M	M
	High	L	L

Table C.4. Parameter Correlations for the SPMT Move Activity: Repair/Construct Permanent Substructure on Existing Alignment

Parameters/Sub-Parameters for 'Repair/Construct Permanent Substructure on Existing Alignment'	Site-Specific Data (Options)	Uncertainty Rating
Right-of-way (ROW) on feature intersected (FI) for equipment staging	Limited	VH
	Moderate	H
	Unrestricted	VL
Lane closure/ traffic shift restrictions on FI	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH
Vertical grade/slope of superstructure at final alignment	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH
Quality assurance of repair (Quality expected based on available contractors)	Moderate	M
	High	L
	Very High	VL
Environmental protection near and within site	None/Low	VL
	Moderate	M
	High	VH
Scour or hydraulic issues	None	VL
	High	VH
Complexity of constructing new foundation when bridge is in service	None/Low	VL
	Moderate	M
	High	H
	Very High	VH

Table C.5. Parameter Correlations for the SPMT Move Activity: Close the Facility Carried and Feature Intersected for Traffic

Parameters/Sub-Parameters for 'Close the Facility Carried and Feature Intersected for Traffic'	Site-Specific Data (Options)	Uncertainty Rating
Average daily traffic (ADT) on facility carried (FC)	1 ≤ ADT < 5,000	VL
	5,001 ≤ ADT < 20,000	L
	20,001 ≤ ADT < 50,000	M
	50,001 ≤ ADT < 100,000	H
	100,001 ≤ ADT	VH
Average daily traffic (ADT) on feature intersected (FI)	1 ≤ ADT < 5,000	VL
	5,001 ≤ ADT < 20,000	L
	20,001 ≤ ADT < 50,000	M
	50,001 ≤ ADT < 100,000	H
	100,001 ≤ ADT	VH
Financial and political risks	Low	VL
	Moderate	M
	High	H
	Very High	VH
Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH
Impact on nearby major intersection/highway-rail grade crossing due to closure of FI	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH
Detour availability/ Length of detour	Short	VH
	Moderate	M
	Very Long or Unavailable	VL
Stakeholder (nearby property owners) limitations	None	VL
	Low	VL
	Moderate	VL
	High	L
	Very High	L
Impact on local communities	None	VL
	Low	VL
	Moderate	L
	High	L
	Very High	M

Table C. 6. Parameter Correlations for the SPMT Move Activity: Prepare Travel Path

Parameters/Sub-Parameters for 'Prepare Travel Path'	Site-Specific Data (Options)	Uncertainty Rating
Travel path complexity	None/ Low	VL
	Moderate	L
	High	M
Number of spans for SPMT move	1	VL
	2	L
	3	M
	4	H
	More than 4	VH
Underclearance (UC) at final alignment	Existing UC < 14.25 ft	VH
	14.25 ft ≤ Existing UC < 15 ft	H
	15 ft ≤ Existing UC < 16.25 ft	M
	16.25 ft ≤ Existing UC	L
Vertical grade/slope of superstructure	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH
Base preparation requirement based on allowable ground bearing pressure	None/ Low	VL
	Moderate	M
	High	H
Impact on overhead & underground utilities	None/ Low	VL
	Moderate	M
	High	VH
Complexity of agreement with private/ public utility company	None/ Low	VL
	Moderate	M
	High	H
	Very High	VH
Complexity of relocating utilities	None/ Low	VL
	Moderate	M
	High	H
	Very High	VH
DOT/Contractor coordination	Flexible for change orders	VL
	Moderate	M
	Restricted for change orders	VH
SPMT subcontractor experience	Low	VH
	Moderate	M
	High	L

Table C.7. Parameter Correlations for the SPMT Move Activity: Jack and Move the Superstructure

Parameters/Sub-Parameters for 'Jack and Move the Superstructure'	Site-Specific Data (Options)	Uncertainty Rating
Project special provisions	None/ Limited	H
	Moderate	M
	Comprehensive	L
Equipment malfunction possibility	Low	M
	Moderate	H
	High	VH
Vertical grade/ slope of superstructure	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH
SPMT stroke availability	Limited	VH
	Sufficient	VL
Limitations for SPMT move operation (e.g., weather) (based on the proposed schedule and the region)	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH
DOT coordination	Flexible for change orders	VL
	Moderate	M
	Restricted for change orders	VH
Safety assurance (based on available SPMT subcontractor experience)	Moderate	H
	High	L

Slide-in bridge construction (SIBC)

Using a similar format described in Chapter 6, the parameter correlations developed for SIBC are shown in Table C.8 to Table C.16.

Table C.8. Parameter Correlations for the SIBC Activity: Design Superstructure

Parameters for 'Design Superstructure'	Site-Specific Data (Options)	Uncertainty Rating			Reasoning for Ratings
		PC I-girder & CIP deck system	Steel girder & CIP deck system	Precast spread box beam & CIP deck system	
Span length[1] (L)	L < 60 ft	M	VL	VL	Use of box beam system and steel girder system is preferred with SIBC. The PC I-girders such as the most popular AASHTO I-girders are typically not used with SIBC (UDOT 2010; Aktan and Attanayake 2015).
	60 ft ≤ L < 80 ft	H	VL	VL	
	80 ft ≤ L < 140 ft	VH	VL	VL	
	L ≥ 140 ft	VH	VL	L	
Beam spacing[1] (S)	S < 6 ft	VL	VL	VL	For a wide bridge, large beam spacing is preferred for economy. However, the beam spacing is decided based on the span length as it is inversely proportional to the span length. High uncertainty of PC I-girder system for SIBC with large beam spacing (WSDOT 2008; UDOT 2010; Hughes et al. 2011).
	6 ft ≤ S < 10 ft	L	VL	VL	
	10 ft ≤ S < 12 ft	M	L	VL	
	S ≥ 12 ft	H	L	VL	
Skew (θ)	θ = 0° (no skew)	VL	VL	VL	With high skew, the bridge slide operation with steel girder system is preferred because of the steel flexibility (Chung et al. 2008; FHWA 2015b).
	θ ≤ 30°	VL	VL	VL	
	30° < θ ≤ 45°	L	VL	L	
	θ > 45°	M	VL	M	
Underclearance[1] (UC) (existing)	UC < 14.25 ft	VH	H	VL	The underclearance is inversely proportional to the span length. If the span length increases the girder depth increases, thus, the underclearance is reduced. If the existing underclearance is low, the system requiring deep girders for a particular span is less preferred (UDOT 2010; Graybeal 2010; Abudayyeh 2010; Grace et al. 2015). Box beams system is more preferred with low underclearance (MDOT 2014a; Grace et al. 2015).
	14.25 ft ≤ UC < 15 ft	H	M	VL	
	15 ft ≤ UC < 16.25 ft	M	L	VL	
	UC ≥ 16.25 ft	L	VL	VL	

Table C.8. — Continued

Parameters for 'Design Superstructure'	Site-Specific Data (Options)	Uncertainty Rating			Reasoning for Ratings
		PC I-girder & CIP deck system	Steel girder & CIP deck system	Precast spread box beam & CIP deck system	
Aesthetic requirements	None/ Low	VL	VL	VL	The PC I- girder system cannot incorporate significant aesthetic requirements such as different architectural concepts (Culmo 2011b).
	Moderate	M	VL	M	
	High	H	VL	H	
Geometric complexity (curved bridge)	Low	L	VL	L	Short length PC I- girders can be used for curved bridges; however, difficulty increases with increase in geometric complexity of a bridge. Box beams system is not preferred for bridges with geometric complexity (MDOT 2014a). On the other hand, a steel girder system can be curved or built to accommodate the complex geometry of a bridge (Chung et al. 2008; FHWA 2015b).
	Moderate	H	VL	VH	
	High	VH	VL	VH	

[1] Dependent parameters

Table C.9. Parameter Correlations for the SIBC Activity: Construct Temporary Substructure

Parameters/Sub-Parameters for 'Construct Temporary Substructure'	Site-Specific Data (Options)	Uncertainty Rating
Average daily traffic (ADT) on feature intersected (FI)	1 ≤ ADT < 5,000	VL
	5,001 ≤ ADT < 20,000	L
	20,001 ≤ ADT < 50,000	M
	50,001 ≤ ADT < 100,000	H
	100,001 ≤ ADT	VH
Right-of-way (ROW) on FI for equipment staging	Limited	VH
	Moderate	H
	Unrestricted	VL
Lane closure/ traffic shift restrictions on FI	None	VL
	Low	VL
	Moderate	L
	High	L
	Very High	M
Vertical grade/slope of superstructure	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH
Environmental protection near and within site	None/Low	VL
	Moderate	M
	High	VH
Loads on superstructure at temporary location (based on SIBC case-1, case-2, or case-3 and ADT on FC)	Marginal	VL
	Moderate	VL
	Heavy	L
Site constraints for parallel replacement structure construction	Minor	VL
	Moderate	M
	High	VH
Available ROW for SIBC	Limited	VH
	Moderate	H
	Unrestricted	VL
Scour or hydraulic issues	None	VL
	High	VH
Complexity of constructing new foundation	None/Low	VL
	Moderate	M
	High	H
	Very High	VH
Impact on overhead & underground utilities	None/ Low	VL
	Moderate	M
	High	VH
Complexity of relocating utilities	None/ Low	VL
	Moderate	M
	High	H
	Very High	VH

Table C.10. Parameter Correlations for the SIBC Activity: Construct Superstructure on Temporary Substructure

Parameters/Sub-Parameters for 'Construct Superstructure on Temporary Substructure'	Site-Specific Data (Options)	Uncertainty Rating		
		PC I-girders & CIP deck system	Steel girders & CIP deck system	Precast spread box beams & CIP deck system
Prefabricator experience	Low	VH	VL	VL
	Moderate	H	VL	VL
	High	L	VL	VL
	Very High	VL	VL	VL
Material availability	Low	M	VH	M
	High	VL	L	VL
Contractor experience	Low	VH	M	M
	Moderate	M	L	L
	High	L	VL	VL
Constructability of design	Not difficult	VL	VL	VL
	Moderate	L	M	VL
	Difficult	M	H	L
ROW on FI for equipment staging	Limited	VH	VH	VH
	Moderate	H	H	H
	Unrestricted	VL	VL	VL
Lane closure/ traffic shift restrictions on FI	None	VL	VL	VL
	Low	VL	VL	VL
	Moderate	L	L	L
	High	L	L	L
	Very High	M	M	M
Equipment malfunction possibility	Low	M	L	M
	Moderate	H	M	H
	High	VH	H	VH
Project special provisions	None/ Limited	H	M	H
	Moderate	M	L	M
	Comprehensive	L	VL	L
Complexity in sliding the superstructure	None/Low	M	VL	M
	Moderate	H	L	H
	High	VH	M	VH
SIBC subcontractor experience	Low	VH	VH	VH
	Moderate	M	M	M
	High	L	L	L

Table C.11. Parameter Correlations for the SIBC Activity: Construct Approaches for Temporary Run-Around

Parameters for 'Construct Approaches for Temporary Run-Around'	Site-Specific Data (Options)	Uncertainty Rating
Complexity of constructing temporary run-around	None/Low	VL
	Moderate	M
	High	H
	Very High	VH
Average Daily Traffic (ADT) on facility carried (FC)	1 ≤ ADT < 5,000	VL
	5,001 ≤ ADT < 20,000	L
	20,001 ≤ ADT < 50,000	M
	50,001 ≤ ADT < 100,000	H
	100,001 ≤ ADT	VH
Restriction on closure of curb-lanes on FC	None	VL
	Low	VL
	Moderate	L
	High	L
	Very High	M
ROW on FC for equipment staging	Limited	VH
	Moderate	M
	Unrestricted	VL
Vertical grade/ slope of superstructure	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH

Table C.12. Parameter Correlations for the SIBC Activity: Route Traffic onto Temporary Run-Around

Parameters/Sub-Parameters for 'Route Traffic onto Temporary Run-Around'	Site-Specific Data (Options)	Uncertainty Rating
Average daily traffic (ADT) on facility carried (FC)	1 ≤ ADT < 5,000	VL
	5,001 ≤ ADT < 20,000	L
	20,001 ≤ ADT < 50,000	M
	50,001 ≤ ADT < 100,000	H
	100,001 ≤ ADT	VH
Financial and political risks	Low	VL
	Moderate	M
	High	H
	Very High	VH
Stakeholder (nearby property owners') limitations	None	VL
	Low	VL
	Moderate	VL
	High	L
	Very High	M
Risk of traffic within work zone	Low	L
	Moderate	M
	High	H
	Very High	VH
Detour availability/ Length of detour	Short	VH
	Moderate	M
	Very Long or Unavailable	VL

Table C.13. Parameter Correlations for the SIBC Activity: Construct Permanent Substructure on Existing Alignment

Parameters/Sub-Parameters for 'Construct Permanent Substructure on Existing Alignment'	Site-Specific Data (Options)	Uncertainty Rating
ROW on FI for equipment staging	Limited	VH
	Moderate	H
	Unrestricted	VL
Lane closure/ traffic shift restrictions on FI	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH
Vertical grade/slope of superstructure	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH
Environmental protection near and within site	None/Low	VL
	Moderate	M
	High	VH
Scour or hydraulic issues	None	VL
	High	VH
Complexity of constructing new foundation	None/Low	VL
	Moderate	M
	High	H
	Very High	VH

Table C.14. Parameter Correlations for the SIBC Activity: Close the Facility Carried for Traffic

Parameters/Sub-Parameters for 'Close the Facility Carried for Traffic'	Site-Specific Data (Options)	Uncertainty Rating
Average daily traffic (ADT) on facility carried (FC)	1 ≤ ADT < 5,000	VL
	5,001 ≤ ADT < 20,000	L
	20,001 ≤ ADT < 50,000	M
	50,001 ≤ ADT < 100,000	H
	100,001 ≤ ADT	VH
Financial and political risks	Low	VL
	Moderate	M
	High	H
	Very High	VH
Stakeholder (nearby property owners) limitations	None	VL
	Low	VL
	Moderate	VL
	High	L
	Very High	M
Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH
Detour availability/ Length of detour	Short	VH
	Moderate	M
	Very Long or Unavailable	VL
Impact on local communities	None	VL
	Low	VL
	Moderate	L
	High	L
	Very High	M

Table C.15. Parameter Correlations for the SIBC Activity: Repair Permanent Substructure

Parameters/Sub-Parameters for 'Repair Permanent Substructure'	Site-Specific Data (Options)	Uncertainty Rating
ROW on FI for equipment staging	Limited	VH
	Moderate	H
	Unrestricted	VL
Lane closure/ traffic shift restrictions on FI	None	VL
	Low	VL
	Moderate	L
	High	L
	Very High	M
Vertical grade/slope of superstructure	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH
Quality assurance of repair (Quality expected based on available contractors)	Moderate	M
	High	L
	Very High	VL
Environmental protection near and within site	None/Low	VL
	Moderate	M
	High	VH
Scour or hydraulic issues	None	VL
	High	VH
Stakeholder (nearby property owners) limitations	None	VL
	Low	VL
	Moderate	VL
	High	L
	Very High	M
Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH
Detour availability/ Length of detour	Short	VH
	Moderate	M
	Very Long or Unavailable	VL
Impact on local communities	None	VL
	Low	VL
	Moderate	L
	High	L
	Very High	M

Table C.16. Parameter Correlations for the SIBC Activity: Jack and Move the Superstructure

Parameters/Sub-Parameters for 'Jack and Move the Superstructure'	Site-Specific Data (Options)	Uncertainty Rating
Project special provisions	None/ Limited	H
	Moderate	M
	Comprehensive	L
Equipment malfunction possibility	Low	M
	Moderate	H
	High	VH
Vertical grade/ slope of superstructure	4% or less	VL
	4-6%	M
	Up to 8%	H
	More than 8%	VH
Safety assurance (based on available SIBC subcontractor experience)	Moderate	H
	High	L
Impact of sliding forces on the structure (based on proposed SIBC configuration)	None/ Low	VL
	Moderate	H
Limitations of operation (e.g., weather limitations, geometric complexity, and superstructure getting stuck in skid tracks.)	None	VL
	Low	L
	Moderate	M
	High	H
	Very High	VH

Appendix D

Base estimates and simulation platform for decision-making framework implementation

Overview

The base cost and base duration estimates for the implementation example described in Chapter 7 (M-50 over I-96 project) are presented in Table D.1. The simulation platform described in Chapter 7 is developed using Excel® worksheets and VBA scripts. Screen shots of the simulation platform are presented in Figure D.1 to Figure D.12.

Figure D.1 shows the simulation table that allows specifying the alternatives and respective base estimates. Figure D.2 shows the simulation table that allows agent interactions and provides data to the simulation table shown in Figure D.1. Figure D.3 shows the input table for specifying activities and agents of the PBES method. Figure D.4 and Figure D.5 show the input table for specifying project-specific uncertainty ratings for PBES alternatives. Figure D.6 shows the input table for specifying activities and agents of the SPMT Move method. Figure D.7, Figure D.8, and Figure D.9 show the input table for specifying project-specific uncertainty ratings for SPMT Move alternatives. Figure D.10 shows the input table for specifying activities and agents of the SIBC method. Figure D.11 and Figure D.12 show the input table for specifying project-specific uncertainty ratings for SIBC alternatives.

VBA script that enables agent interactions and Monte Carlo simulations in the simulation platform is provided later in this Appendix. Excel headings are shown in the screen shots (Figure D.1 to Figure D.12) for assistance in the understanding of the VBA script.

Table D.1. Base Cost and Base Duration Estimates for M-50 over I-96 Project

	PBES-X	PBES-Y	PBES-Z	SPMT Move-X	SPMT Move-Y	SIBC-X	SIBC-Y	SIBC-Z
	Decked bulb tee girder system	Precast concrete I-girders and full-depth deck panels system	Steel girders and full-depth deck panels system	Precast concrete I-girders and cast-in-place deck system	Steel girders and cast-in-place deck system	Precast concrete I-girders and cast-in-place deck system	Steel girders and cast-in-place deck system	Precast spread box beams and cast-in-place deck system
Cost of material and labor ($)	1978577	2909390	3240352	1978577	2204297	1978577	2204297	1978577
Weight (kips)	4514	2751	3936	2751	3936	2751	3936	4416
Temporary structure cost ($)				945203	945203	214575	307007	344421
Specialty equipment or sub for SPMT move or SIBC specific cost ($)				162307	232224	385135	551039	618191
No. of SPMT Axles				58	72			
Staging area preparation for SPMT move ($)				56881	56881			
Travel path preparation for SPMT move ($)				70567	70567			
Mobilization for SPMT move ($)				7250	9000			
Cost Prorating Ratio								0.66
Estimated Base Project Cost:	$1,978,577	$2,909,390	$3,240,352	$4,866,546	$5,315,904	$3,895,673	$4,627,060	$4,444,000
Estimated Base Constr Duration (days):	58	86	90	4	3	14	8	10

Selected activity affecting Cost, Duration, or Both	Random Interaction No.		Uncertainty Variate Range		% Change Range	
Both	PBES	3	0	0.05	0	1
	PBES	10	0.05	0.2	1	3
	PBES	2	0.2	0.4	3	6
	SPMT	13	0.4	0.7	6	10
	SPMT	3	0.7	1	10	25
	SIBC	5				
	SIBC	15				
	SIBC	14				

RUN SIMULATION AND GENERATE RESULTS

Agent Interactions for Alternative:	Activity Row	Activity No.	1st Subsequent Activity No.	2nd Subsequent Activity No.	3rd Subsequent Activity No.	1st Antecedent Activity No.	Sub-Activities Exist?	No. of Sub-Activities	Is Sub-Activity?	Cost Change %	Duration Change %	Base Cost ($)	Base Duration (days)	Updated Cost Estimate ($)	Updated Duration Estimate (days)
PBES X	9	50	60	61	0	41	No	0	No	20.28329961	20.28329961	$ 1,978,577	58	2379898	70
PBES Y	4	21	30	31	40	20	No	0	Yes	0	0	$ 2,909,390	86		
PBES Z	7	40	41	50	60	31	Yes	1	No	23.37310153	23.37310153	$ 3,240,352	90	3997722	111
SPMT Move X	10	40	41	50	51	32	Yes	1	No	23.37310153	23.37310153	$ 4,866,546	4	6004008	5
SPMT Move Y	4	21	22	23	30	20	No	2	Yes	0	0	$ 5,315,904	3		
SIBC X	3	20	21	22	23	10	Yes	3	No	23.4741705	23.4741705	$ 3,895,673	14	4810150	17
SIBC Y	15	70	71	0	2	61	Yes	1	No	23.37310153	23.37310153	$ 4,627,060	8	5708547	10
SIBC Z	12	51	60	61	70	50	No	0	Yes	0	0	$ 4,444,000	10		

No. of Sub-Activities	Main Activity	Sub-activity	Agent w/ 'A'	Agent w/ 'B'	Agent w/ 'C'	Agent w/ 'C' Calc. Un. Est. $\{1-\pi(1-P_i)\}$	Agent w/ 'B' Calc. $\pi(1-P_i)$	Agent w/ 'B' Calc. Activity Un. $\{1-\pi(1-P_i)\}$	% Change Value	Cost Change %	Duration Change %	Agent w/ 'A' getting % change cost	Agent w/ 'A' getting % change duration
0	20		Yes	Yes			0.094334008	0.905665992	20.28329961	Yes	Yes	20.28329961	20.28329961
1	20		Yes	Yes				0.967462031	23.37310153	Yes	Yes	23.37310153	23.37310153
		21		Yes	Yes	**0.655076996**	0.094334008						
2	20		Yes	Yes				0.96948341	23.4741705	Yes	Yes	23.4741705	23.4741705
		21		Yes	Yes	**0.655076996**	0.094334008						
		22		Yes	Yes	**0.062123709**							
3	20		Yes	Yes				0.970402228	23.52011139	Yes	Yes	23.4741705	23.4741705
		21		Yes	Yes	**0.655076996**	0.094334008						
		22		Yes	Yes	**0.062123709**							
		23		Yes	Yes	**0.030108795**							

RunAgentInteractions | AgentNodeClass | PBES | SPMTmove | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.1. Main simulation table for calculating updated cost and duration

Interaction Parameters

PBES	
X	
PBES X	
1	sub
21	sub label

AGENT W/ NODE CLASS A

Act	=	Calc. for PBES_X_20
MnAgent		DOT
ChC%		23.3731
ChD%		23.3731
UpC		2379897.551
UpD		69.76431378

AGENT W/ NODE CLASS B

Act	=	20
ResAgent		Contractor
ActUn		0.9675
ChC%		23.3731
ChD%		23.3731

Activity & ABC System: 20X

Project-Specific Uncertainty Ratings for Respective Activity	Parameter Probability of Affecting the Project Perfromance (P_f)	$1-P_f$
H	0.6414	0.3586
M	0.3521	0.6479
H	0.5939	0.4061
0		
0		
0		
	Product:	0.0943

AGENT W/ NODE CLASS C

SubAct	=	21
Agent		Prefabricator
SubUn		0.6551

Sub-Activity & ABC System: 21X

Project-Specific Uncertainty Ratings for Respective Sub-Activity	Parameter Probability of Affecting the Project Perfromance (P_f)	$1-P_f$
H	0.6414	0.3586
VL	0.0380	0.9620
0		
0		
0		
0		
	Product:	0.3449

Significance	Uncertainty Variate Range	
VL	0	0.05
L	0.05	0.2
M	0.2	0.4
H	0.4	0.7
VH	0.7	1

Random No.	No.	Random No.
0.80481924	1	0.7032
0.760343772	2	0.2932
0.64648442	3	0.3426
0.533641503	4	0.6421
0.969295269	5	0.0396
0.664510797	6	0.1706

RunAgentInteractions | **AgentNodeClass** | PBES | SPMTmove | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.2. Simulation table that performs agent interactions and provides data to the main simulation table

PBES Activity No.	Agent	Node Class	Agent	Node Class	Act. Impacts?
0	N/A		N/A		
10	DOT	A	Designer	B	Cost
20	DOT	A	Contractor	B	Both
21	Contractor	B	Prefabricator	C	
30	DOT	A	DOT	B	Duration
31	DOT	B	Public	C	
40	DOT	A	Contractor	B	Duration
41	Contractor	B	Geotech. Consult.	C	
50	DOT	A	Contractor	B	Cost
60	DOT	A	Contractor	B	Both
61	Contractor	B	Designer	C	
0	N/A		N/A		

Activity No.	Activity Name
0	N/A
10	Design superstructure
20	Transport the elements
21	Fabricating elements
30	Close the facility carried for traffic
31	Impact on public
40	Repair/Const. perm. substr on existing align.
41	Subsurface considerations
50	Erect the elements
60	Connect the elements (Connection details)
61	Interagency agreements
0	N/A

RunAgentInteractions | AgentNodeClass | **PBES** | SPMTmove | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.3. Input table for specifying PBES activities and agents based on respective ontology

PBES X: Decked bulb tee girder system
PBES Y: Precast concrete I-girders and full-depth deck panels system
PBES Z: Steel girders and full-depth deck panels system

[1] Dependent Paramaters

Activity No.	10	10X	10Y	10Z	20	20X	20Y	20Z	21	21X	21Y	21Z	30	30X	30Y	30Z	31	31X	31Y	31Z
PBES Alt.		X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z
Parameters/Sub-Parameters Data	Span length [1]	M	VL	VL	Transportation limitations	H	M	M	Prefabricator experience	H	H	H	Average daily traffic (ADT) on facility carried (FC)	L	L	L	Stakeholder (nearby property owners) limitations	VH	VH	VH
	Beam spacing [1]	VL	VL	VL	Safety requirement	M	M	L	Material availability	VL	VL	L	Financial and political risks	H	H	H	Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	VL	VL	VL
	Skew	VL	VL	VL	Equipment malfunction possibility	H	M	M					Site condition complexities	VL	VL	VL	Detour availability/ Length of detour	VH	VH	VH
	Underclearance [1] (existing)	VL	M	M													Impact on local communities	H	H	H
	Aesthetic requirements	VL	VL	VL																
	Geometric complexity (curved bridge)	L	L	VL																

RunAgentInteractions | AgentNodeClass | PBES | SPMTmove | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.4. Part-I input table for project-specific uncertainty ratings for PBES alternatives based on the knowledgebase of parameter correlations

40	40X	40Y	40Z	41	41X	41Y	41Z	50	50X	50Y	50Z	60	60X	60Y	60Z	61	61X	61Y	61Z
	X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z
Right-of-way (ROW) on feature intersected (FI) for equipment staging	VL	VL	VL	Scour or hydraulic issues	VL	VL	VL	Lane closure/ traffic shift restrictions on FI	VH	VH	VH	Material availability	H	VH	VH	Constructability of design	VL	VL	VL
Lane closure/ traffic shift restrictions on FI	VH	VH	VH	Complexity of constructing new foundation when bridge is not in service	VL	VL	VL	ROW on FI for equipment staging	VL	VL	VL	Contractor experience	L	M	M	Non-conformances in element fabrication/ tolerances	L	H	M
Vertical grade/slope of superstructure	VL	VL	VL					Crane set-up difficulty	M	M	M	Equipment malfunction possibility	L	M	M				
Quality assurance of repair	VL	VL	VL																
Environmental protection near and within site	VL	VL	VL																

RunAgentInteractions | AgentNodeClass | **PBES** | SPMTmove | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.5. Part-II input table for project-specific uncertainty ratings for PBES alternatives based on the knowledgebase of parameter correlations

	A	B	C	D	E	F	G	H	I–L
1	SPMT Move Activity No.	Agent	Node Class	Agent	ɔde Cla	Act. Impacts?		Activity No.	Activity Name
2	0	N/A		N/A				0	N/A
3	10	DOT	A	Designer	B	Cost		10	Design superstructure
4	20	DOT	A	Contractor	B	Duration		20	Prepare staging area
5	21	Contractor	B	Utility Consult.	C			21	Subsurface considerations
6	22	Contractor	B	Geotech Consult.	C			22	Utility relocation considerations
7	23	Contractor	B	SPMT Subcontr.	C			23	SPMT subcontractor coordination
8	30	DOT	A	Contractor	B	Cost		30	Construct superstructure at staging area
9	31	Contractor	B	Prefabricator	C			31	Material procurement
10	32	Contractor	B	SPMT Subcontr.	C			32	Move specific details
11	40	DOT	A	Contractor	B	Duration		40	Repair/Construct permanent substr on existing alignment
12	41	Contractor	B	Geotech Consult.	C			41	Subsurface considerations
13	50	DOT	A	DOT	B	Duration		50	Close the facility carried and feature intersected for traffic
14	51	DOT	B	Public	C			51	Impact on public
15	60	DOT	A	Contractor	B	Cost		60	Prepare travel path
16	61	Contractor	B	Utility Consult.	C			61	Subsurface considerations
17	62	Contractor	B	Geotech Consult.	C			62	Utility relocation considerations
18	63	Contractor	B	SPMT Subcontr.	C			63	SPMT subcontractor coordination
19	70	DOT	A	Contractor	B	Both		70	Jack and move the superstructure
20	71	Contractor	B	SPMT Subcontr.	C			71	Contractor coordination
21	0	N/A		N/A				0	N/A

RunAgentInteractions | AgentNodeClass | PBES | **SPMTmove** | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.6. Input table for specifying SPMT Move activities and agents based on respective ontology

SPMT Move X: Precast concrete I-girders and cast-in-place deck system
SPMT Move Y: Steel girders and cast-in-place deck system
SPMT Move Z: -

[1] Dependent Paramaters

Activity No.		10	10X	10Y	10Z	20	20X	20Y	20Z	21	21X	21Y	21Z	22	22X	22Y	22Z	23	23X	23Y	23Z
SPMT Move Alt.			X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z
Parameters/Sub-Parameters Data	Span length [1]		VL	VL		Availability of staging area	M	M		Complexity of constructing temporary substructure (piles, etc.)	M	M		Impact on overhead & underground utilities	VH	VH		DOT/Contractor coordination	M	M	
	Beam spacing [1]		L	VL		Number of spans for SPMT move	L	L		Base preparation requirement based on allowable ground bearing pressure	H	H		Complexity of relocating utilities	VH	VH		SPMT subcontractor experience	VH	VH	
	Skew		VL	VL		Environmental sensitivity of staging area	VH	VH													
	Underclearance [1] (existing)		M	L																	
	Aesthetic requirements		VL	VL																	
	Geometric complexity (curved bridge)		L	VL																	

RunAgentInteractions | AgentNodeClass | PBES | **SPMTmove** | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.7. Part-I input table for project-specific uncertainty ratings for SPMT Move alternatives based on the knowledgebase of parameter correlations

30	30X	30Y	30Z	31	31X	31Y	31Z	32	32X	32Y	32Z	40	40X	40Y	40Z	41	41X	41Y	41Z
	X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z
Contractor experience	VH	M		Material availability	VL	L		Project special provisions	H	M		Right-of-way (ROW) on feature intersected (FI) for equipment staging	VL	VL		Scour or hydraulic issues	VL	VL	
Constructability of design	VL	VL		Prefabricator experience	VL	VL		Complexity of lifting and moving the superstructure	H	L		Lane closure/ traffic shift restrictions on FI	VH	VH		Complexity of constructing new foundation when bridge is in service	VH	VH	
Equipment malfunction possibility	M	L						SPMT subcontractor experience	VH	VH		Vertical grade/slope of superstructure	VL	VL					
												Quality assurance of repair	VL	VL					
												Environmental protection near and within site	VL	VL					

RunAgentInteractions | AgentNodeClass | PBES | **SPMTmove** | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData

Figure D.8. Part-II input table for project-specific uncertainty ratings for SPMT Move alternatives based on the knowledgebase of parameter correlations

50	50X	50Y	50Z	51	51X	51Y	51Z	60	60X	60Y	60Z	61	61X	61Y	61Z
	X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z
Average daily traffic (ADT) on facility carried (FC)	L	L		Impact on nearby major intersection/ highway-rail grade crossing with full closure of FC	VL	VL		Travel path complexity	M	M		Base preparation requirement based on allowable ground bearing pressure	H	H	
ADT on FI	M	M		Impact on nearby major intersection/ highway-rail grade crossing due to closure of FI	VL	VL		Number of spans for SPMT move	L	L					
Financial and political risks	M	M		Detour availability/ Length of detour	VL	VL		Underclearance at final alignment	M	M					
				Stakeholder (nearby property owners') limitations	L	L		Vertical grade/slope of superstructure	VL	VL					
				Impact on local communities	L	L									

62	62X	62Y	62Z	63	63X	63Y	63Z	70	70X	70Y	70Z	71	71X	71Y	71Z
	X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z
Impact on overhead & underground utilities	VH	VH		DOT/Contractor coordination	M	M		Project special provisions	H	H		DOT coordination	M	M	
Complexity of relocating utilities	VH	VH		SPMT subcontractor experience	VH	VH		Equipment malfunction possibility	VH	VH		Safety assurance	L	L	
								Vertical grade/ slope of superstructure	VL	VL					
								SPMT stroke availability	VH	VH					
								Limitations for SPMT move operation (e.g., weather)	L	L					

RunAgentInteractions | AgentNodeClass | PBES | SPMTmove | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.9. Part-III input table for project-specific uncertainty ratings for SPMT Move alternatives based on the knowledgebase of parameter correlations

SIBC Activity No.	Agent	Node Class	Agent	Node Class	Act. Impacts?
0	N/A		N/A		
10	DOT	A	Designer	B	Cost
20	DOT	A	Contractor	B	Cost
21	Contractor	B	Designer	C	
22	Contractor	B	Geotech Consult.	C	
23	Contractor	B	Utility Consult.	C	
30	DOT	A	Contractor	B	Cost
31	Contractor	B	Prefabricator	C	
32	Contractor	B	Slide Subcontr.	C	
40	DOT	A	Contractor	B	Duration
50	DOT	A	DOT	B	Duration
51	DOT	B	Public	C	
60	DOT	A	Contractor	B	Duration
61	Contractor	B	Geotech Consult.	C	
70	DOT	A	Contractor	B	Both
71	Contractor	B	Slide Subcontr.	C	
0	N/A		N/A		

Activity No.	Activity Name
0	N/A
10	Design superstructure
20	Construct temporary substructure
21	Design considerations
22	Subsurface considerations
23	Utility relocation considerations
30	Construct superstructure on temporary sub.
31	Material procurement
32	Move specific details
40	Construct approaches for temp. run-around
50	Route traffic onto temporary run-around
51	Impact on public
60	Construct permanent substructure
61	Subsurface considerations
70	Jack and move the superstructure
71	Contractor coordination
0	N/A

RunAgentInteractions | AgentNodeClass | PBES | SPMTmove | SIBC | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.10. Input table for specifying SIBC activities and agents based on respective ontology

SIBC X: Precast concrete I-girders and cast-in-place deck system
SIBC Y: Steel girders and cast-in-place deck system
SIBC Z: Precast spread box beams and cast-in-place deck system

[1] **Dependent Paramaters**

Activity No.	10	10X	10Y	10Z	20	20X	20Y	20Z
SIBC Alt.		X	Y	Z		X	Y	Z
Parameters/Sub-Parameters Data	Span length [1]	VH	VL	VL	Average daily traffic (ADT) on feature intersected (FI)	M	M	M
	Beam spacing [1]	L	VL	VL	Right-of-way (ROW) on FI for equipment staging	VL	VL	VL
	Skew	VL	VL	VL	Lane closure/ traffic shift restrictions on FI	M	M	M
	Underclearance [1] (existing)	M	L	VL	Vertical grade/slope of superstructure	VL	VL	VL
	Aesthetic requirements	VL	VL	VL	Environmental protection near and within site	VL	VL	VL
	Geometric complexity (curved bridge)	L	VL	L				

Activity No.	21	21X	21Y	21Z	22	22X	22Y	22Z
SIBC Alt.		X	Y	Z		X	Y	Z
Parameters/Sub-Parameters Data	Loads on superstructure at temporary location	L	L	L	Scour or hydraulic issues	VL	VL	VL
	Site constraints for parallel replacement structure construction	VL	VL	VL	Complexity of constructing new foundation	VL	VL	VL
	Available ROW for SIBC	VL	VL	VL				

Activity No.	23	23X	23Y	23Z	30	30X	30Y	30Z
SIBC Alt.		X	Y	Z		X	Y	Z
Parameters/Sub-Parameters Data	Impact on overhead & underground utilities	VL	VL	VL	Contractor experience	M	L	L
	Complexity of relocating utilities	VL	VL	VL	Constructability of design	L	M	VL
					ROW on FI for equipment staging	VL	VL	VL
					Lane closure/ traffic shift restrictions on FI	M	M	M
					Equipment malfunction possibility	M	L	M

Activity No.	31	31X	31Y	31Z	32	32X	32Y	32Z
SIBC Alt.		X	Y	Z		X	Y	Z
Parameters/Sub-Parameters Data	Material availability	VL	L	VL	Project special provisions	M	L	M
	Prefabricator experience	VL	VL	VL	Complexity in sliding the superstructure	M	VL	M
					SIBC subcontractor experience	M	M	M

RunAgentInteractions | AgentNodeClass | PBES | SPMTmove | **SIBC** | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.11. Part-I input table for project-specific uncertainty ratings for SIBC alternatives based on the knowledgebase of parameter correlations

40	40X	40Y	40Z	50	50X	50Y	50Z
	X	Y	Z		X	Y	Z
Complexity of constructing temporary run-around	M	M	M	ADT on FC	L	L	L
ADT on facility carried (FC)	L	L	L	Financial and political risks	VL	VL	VL
Restriction on closure of curb-lanes on FC	L	L	L				
ROW on FC for equipment staging	VL	VL	VL				
Vertical grade/ slope of superstructure	VL	VL	VL				

51	51X	51Y	51Z	60	60X	60Y	60Z
	X	Y	Z		X	Y	Z
Stakeholder (nearby property owners') limitations	M	M	M	ROW on FI for equipment staging	VL	VL	VL
Risk of traffic within work zone	L	L	L	Lane closure/ traffic shift restrictions on FI	VH	VH	VH
Detour availability/ Length of detour	VL	VL	VL	Vertical grade/slope of superstructure	VL	VL	VL
				Environmental protection near and within site	VL	VL	VL

61	61X	61Y	61Z	70	70X	70Y	70Z	71	71X	71Y	71Z
	X	Y	Z		X	Y	Z		X	Y	Z
Scour or hydraulic issues	VL	VL	VL	Project special provisions	M	M	M	Safety assurance	L	L	L
Complexity of constructing new foundation	VL	VL	VL	Equipment malfunction possibility	H	H	H	Impact of sliding forces on the structure	VL	VL	VL
				Vertical grade/ slope of superstructure	VL	VL	VL				
				Limitations of operation (e.g., weather limitations, geometric complexity, and superstructure getting stuck in skid tracks.)	M	M	M				

RunAgentInteractions | AgentNodeClass | PBES | SPMTmove | **SIBC** | CostPlots | DurationPlots | CostCalc. | DataStorage | RawCostData | RawDurationData | DescprStat

Figure D.12. Part-II input table for project-specific uncertainty ratings for SIBC alternatives based on the knowledgebase of parameter correlations

VBA Script for performing agent interactions and Monte Carlo simulations using tables (Figure D.1 to Figure D.12) in the simulation platform

```
*****************************
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*****************************

Private Sub RunButton_Click()

    Application.ScreenUpdating = False
    Dim n, a, b, c, d, e, f, g, h, i, j, k
    Application.Calculation = xlCalculationAutomatic
    Sheet7.Range("A4:P5003").ClearContents
    n = 1

For a = 15 To 22
 c = 2 * n
    Application.Calculation = xlCalculationAutomatic
    b = Sheets("RunAgentInteractions").Range("A" & a).Value
    Sheets("AgentNodeClass").Range("A3").Value = Left(b, 4)
    Sheets("AgentNodeClass").Range("A4").Value = Right(b,1)
    Sheets("AgentNodeClass").Range("A5").Value = b

For i = 1 To 5000
Application.Calculation = xlCalculationAutomatic

Sheets("RunAgentInteractions").Range("B" & a).Value =
Sheets("RunAgentInteractions").Range("C" & a - 11).Value

j = Sheets("RunAgentInteractions").Range("J" & a).Value
k = "No"

If j = k Then

Sheets("RunAgentInteractions").Range("B26").Value =
Sheets("RunAgentInteractions").Range("C" & a).Value

Sheets("RunAgentInteractions").Range("B27").Value =
Sheets("RunAgentInteractions").Range("C" & a).Value
```

```
Sheets("RunAgentInteractions").Range("B29").Value =
Sheets("RunAgentInteractions").Range("C" & a).Value

Sheets("RunAgentInteractions").Range("B32").Value =
Sheets("RunAgentInteractions").Range("C" & a).Value

Else

Sheets("RunAgentInteractions").Range("B26").Value = 0

Sheets("RunAgentInteractions").Range("B27").Value = 0

Sheets("RunAgentInteractions").Range("B29").Value = 0

Sheets("RunAgentInteractions").Range("B32").Value = 0

End If

e = Sheets("RunAgentInteractions").Range("I" & a).Value
Sheets("AgentNodeClass").Range("A6").Value = e
f = Sheets("RunAgentInteractions").Range("H" & a).Value
g = "Yes"

If f = g And e > 0 Then
     For d = 1 To e
         Application.Calculation = xlCalculationAutomatic

         Sheets("AgentNodeClass").Range("A7").Value =
Sheets("RunAgentInteractions").Range("C" & d + 32).Value

     For h = 1 To 6

     Sheets("AgentNodeClass").Range("A" & h + 13).Value =
Sheets("AgentNodeClass").Range("C" & h + 13).Value

     Next h

         Sheets("RunAgentInteractions").Range("G" & d +
32).Value = Sheets("AgentNodeClass").Range("K6").Value
```

```
         Application.Calculation = xlCalculationManual

         Sheets("DataStorage").Cells(i + 3, c - 1).Value =
Sheets("RunAgentInteractions").Range("O" & a).Value

         Sheets("DataStorage").Cells(i + 3, c).Value =
Sheets("RunAgentInteractions").Range("P" & a).Value

    Next d

Else

Sheets("AgentNodeClass").Range("A7").Value = 0
      For h = 1 To 6

      Sheets("AgentNodeClass").Range("A" & h + 13).Value =
Sheets("AgentNodeClass").Range("C" & h + 13).Value

      Next h
Application.Calculation = xlCalculationManual

Sheets("DataStorage").Cells(i + 3, c - 1).Value =
Sheets("RunAgentInteractions").Range("O" & a).Value

Sheets("DataStorage").Cells(i + 3, c).Value =
Sheets("RunAgentInteractions").Range("P" & a).Value

End If

Next i
n = n + 1
Next a

Application.Calculation = xlCalculationAutomatic

Application.ScreenUpdating = True

End Sub
```