Risk-Based Project Delivery Selection Model for Highway Design and Construction

Dai Q. Tran, Ph.D., A.M.ASCE[1]; and Keith R. Molenaar, Ph.D., M.ASCE[2]

Abstract: Project-delivery methods allocate risk for design and construction between contractual parties. State departments of transportation (DOTs) using federal funds employ three primary project-delivery methods: (1) design-bid-build (D-B-B); (2) design-build (D-B); and (3) construction manager/general contractor (CM/GC). Because the choice of a project-delivery method is best made early in the project-development process, it is a complex decision that is fraught with risk and uncertainty. This paper presents a risk-based modeling methodology to evaluate and quantify the potential differences in project cost attributable to the selection of a project-delivery method. The risk-based model consists of (1) an input structure of assessment and evaluation of delivery-risk factors; (2) a computational-modeling structure for calculating costs; and (3) an output structure to communicate model results and implementation. The assessment and evaluation process determines the risks that are incorporated into the delivery decision. It translates static cost and schedule uncertainty from project specifics to input variables (risk factors) and to decision variables (project outcomes). The computational model employs crossimpact analysis techniques and probabilistic inferences to capture uncertainties and interactions among the input and decision variables. The model result provides three approximate cost distributions associated with three project-delivery methods (D-B, D-B-B, and CM/GC) and a sensitivity result (i.e., tornado diagrams) that describes which risk factors have the most significant impact on these costs. The model was successfully tested on three highway projects which are discussed in detail in this paper. The findings from this paper add to the existing body of knowledge by providing a novel method to predict project costs based upon the owner's choice of alternative project-delivery methods. The approach combines multivariate analysis with crossimpact analysis to make the predictions and provide a sensitivity analysis for project risks. The findings also provide a systematic approach to quantitatively selecting an appropriate delivery method that encourages highway agencies to conduct risk analysis early in the project-development process. **DOI:** **10.1061/(ASCE)CO.1943-7862.0001024.** *© 2015 American Society of Civil Engineers.*

Author Keywords: Project delivery selection process; Risk analysis and management; Crossimpact analysis; Monte Carlo simulation; Project planning and design.

Introduction

The demand to deliver highway projects in less time with limited budgets has driven state departments of transportation (DOTs) to adopt innovations in project-delivery methods. State DOTs can employ a variety of innovative contracting systems to allocate design and construction risk between the agency, designer, and construction parties. The traditional design-bid-build (D-B-B) method is the predominant delivery model. However, D-B-B has been criticized for its lengthy schedule, separation of the design and construction processes, and latent adversarial relationships that it can cause (Ibbs et al. 2003; Touran et al. 2011; Love et al. 2012). As a result, state DOTs are using design-build (D-B) and construction manager/general contractor (CM/GC) more frequently to overcome these challenges. However, the choice of a delivery method is often made on an ad hoc basis with little quantitative insight on how the choice will impact final project risk allocation and resulting costs.

The selection of an appropriate delivery method is a complex decision process due in large part to the risk and uncertainty at the time of the decision. The growing use of alternative delivery methods has led researchers and practitioners to search for structured approaches to choose project-delivery methods. A range of delivery-selection techniques have been developed to help public and private owners make a systematic and defensible decision. These techniques include simple flowchart approaches (Gordon 1994; Tran et al. 2013) to more complex approaches, such as multiattribute utility/value theory (Oyetunji and Anderson 2006) and analytical hierarchical process/value engineering/multicriteria multiscreening (Alhazmi and McCaffer 2000; Mahdi and Alreshaid 2005). However, limited research has employed risk-based approaches to the delivery-selection process, which is surprising because project-delivery methods are vehicles for risk allocation at their core.

The transportation sector provides an opportunity to develop risk-based project delivery selection models. Federal and state policies limit the number of project-delivery options to predominately D-B-B, D-B, and CM/GC. State DOTs have recently gained a more quantitative understanding of risk through the application of probabilistic risk-based cost estimating on major highway projects (Molenaar 2005). However, these estimates are often performed independently from the project delivery selection process. The separation of the probabilistic-risk analysis and delivery-decision process leads to a limited understanding of how risk affects the project-delivery performance. Such a limitation may not only increase the chance of choosing an inappropriate delivery method, but may also impede potential benefits associated with each method.

---

[1] Assistant Professor, Dept. of Civil, Environmental, and Architectural Engineering, Univ. of Kansas, 1530 W. 15th St., 2150 Learned Hall, Lawrence, KS 66045 (corresponding author). E-mail: daniel.tran@ku.edu

[2] Professor, Dept. of Civil, Environmental, and Architectural Engineering, Univ. of Colorado, 428 UCB, 1111 Engineering Dr., Boulder, CO 80309-0428. E-mail: keith.molenaar@colorado.edu

Note. This manuscript was submitted on October 30, 2014; approved on April 27, 2015; published online on June 16, 2015. Discussion period open until November 16, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364/04015041(9)/$25.00.

To address the knowledge gap, the primary goal of this paper is to introduce a risk-based model that integrates probabilistic risk-based cost estimating into the project delivery selection process. The paper focuses on the following three research questions:

1. How do risks impact the delivery-selection process in highway design and construction projects?
2. How do the magnitude and dispersion of the risk factors influence project-delivery selection?
3. What new information would be gained by using a risk-based delivery selection approach?

Literature Review

Each project-delivery method provides unique opportunities and obstacles. Project-risk allocation differs with each delivery method. Risk allocation in D-B-B is clearly understood by the transportation design and construction community. The majority of design risk is borne by the transportation agency, and the majority of construction risk is borne by the contractor. The fact that design document and construction specifications must be complete and accurate creates risk for both parties in the D-B-B-delivery method (Rubin and Wordes 1998). Under D-B-B projects, the owner owns the details of the design and is generally responsible for errors or omissions in the drawings and specifications. The contractor assumes the risk of completing construction in compliance with the contract documents. The contractor also assumes the risks related to scheduling, coordinating, and administering work by subcontractors and suppliers. The potential for an adversarial relationship between the designer and the contractor exists because of the separation of design and construction.

In CM/GC project delivery, transportation agencies select construction managers based on their qualifications to (1) assist the project team to implement preconstruction services (e.g., cost estimating and constructability reviews) and (2) perform construction work after prices have been agreed upon. Construction managers are paid a fee for construction management services until a guaranteed maximum price (GMP) agreement for construction is reached, at which point the construction managers assume the risk for the final cost and time of construction. Gransberg and Shane (2010) conducted a synthesis of highway practice on the construction manager-at-risk (CMR) delivery method. The study concluded that the major advantages of the CMR-delivery method include enhanced constructability, real-time construction pricing capability, and the ability to create an environment with rich collaboration (Gransberg and Shane 2010). There are slight differences between CMR and CM/GC. Under the CMR-delivery method, the construction manager is forbidden to self-perform any work or only allowed to perform work for which they underbid all subcontractors (Minchin et al. 2014). Under the CM/GC-delivery method, the construction manager is allowed, or in most cases required, to self-perform a portion of the work (Minchin et al. 2014). To promote the use of CM/GC in the highway industry, the Federal Highway Administration (FHWA) established two every day counts (EDC) initiatives: (1) EDC-1 in 2010 and (2) EDC-2 in 2012. One of the main objectives of these two initiatives is to focus on shortening the project schedule and enhance innovative processes using alternative project-delivery methods (i.e., CM/GC and D-B). Recently, researchers stated the three major advantages of using CM/GC, including (1) freedom to innovate design and construction, (2) flexibility to allocate and re-allocate risk, and (3) potential for cost savings (Minchin et al. 2014; Ptschelinzew et al. 2013). Nonetheless, in CM/GC projects, the agency still has to manage multiple contracts and is ultimately responsible for design risks. Ptschelinzew et al. (2013) pointed out that under CM/GC, the agency must educate design teams to enhance and maintain the collaboration among all parties involved. The construction manager is responsible for quality control, checking and approving the design estimates, scheduling, and the estimate of construction costs.

D-B-project delivery uses performance-based contracting as opposed to providing the builder with complete designs. Risk in the D-B-delivery method often stems from the scope definition, statutory or regulatory restrictions, and environmental issues. Under D-B projects, the design-builder is solely responsible for all design and construction issues. However, Ghavamifar and Touran (2009) showed that simply choosing D-B to transfer risks to the contractor is problematic because risks affect the price proposal. To reduce risks in D-B projects, the owner must understand the scope of work and appropriately use performance criteria to communicate project goals at the time of contracting (Tran and Molenaar 2012; Tran and Molenaar 2014b). The American Association of State Highway Transportation Officials AASHTO (2008) provides state highway agencies with a four-step approach to selecting D-B projects by defining project goals, allocating risk, planning the evaluation, and writing the contract documents. However, it falls short of providing detailed selection guidance.

Highway design and construction projects can often be large in scope with total project costs in the hundreds of millions of dollars. They are long in design and construction durations with project-delivery processes that can last more than 10 years in some cases. Selecting an appropriate delivery method is a complex decision. Touran et al. (2011) developed a decision-support system for selecting delivery methods in transit and airport projects. The framework includes 24 pertinent issues that categorize factors into five groups: (1) project-level, (2) agency-level, (3) public policy/regulatory, (4) life cycle, and (5) others. Although this framework considers improving risk allocation a critical element, it does not describe how risk influences the selection process. Tran et al. (2013) proposed a simple but practical flowchart approach to selecting an appropriate delivery method for highways. Although this flowchart focuses on the impact of risk on the project delivery selection process, it was constructed based on a qualitative risk assessment and relies almost exclusively on agency-personnel judgment. Recently, Zeng et al. (2014) developed an approach to selection of multiple project-delivery methods for multiproject transportation systems based on the fuzzy-theory method and fuzzy-simulation algorithm. The objectives of the approach were to minimize the total cost and time of the multiple transportation projects. The approach included two main decision variables: (1) the selection of project-delivery methods including D-B-B, D-B, and CM/GC, and (2) the start time for each subproject. The approach did not include the impact of risk factors on their framework.

In 2002, the Washington State DOT began to employ probabilistic risk-based cost estimating through its cost estimating validation process (CEVP) (Molenaar 2005). The CEVP approach to cost estimating was viewed positively by the U.S. DOT and agencies across the nation. In 2004, the FHWA created a policy that requires projects over \$100 million in value to conduct probabilistic models at the planning/scoping stages (FHWA 2004). These milestones have resulted in a greater familiarity with probabilistic risk-based cost estimating and a rich data source of identified and quantified project risks. The authors believe that the result of the probabilistic estimates can be used to make more informed project delivery method selections. This paper presents a model to optimize the project delivery and contracting decision using this approach.

Risk-Based Project Delivery Selection Model

This research presents a model that captures risk and uncertainty and explains how individual risk factors impact the highway delivery decision process. The model is designed for highway projects greater than $100 million and must be used in conjunction with probabilistic risk-based cost estimating. The paper describes the model with an explanation of the delivery-risk factors and their initial probability estimates, the model computational structure and interactions, and interpretation of the model results.

Delivery-Risk Factors

Delivery-risk factors are the main input of the risk-based model. To capture the range of possible risks that impact a delivery decision, the authors reviewed literature on project-delivery methods and examined risks that were documented in probabilistic highway cost estimates conducted by transportation agencies. The literature consisted of articles, reports, guidebooks, and other work published by ASCE, the Transportation Research Board (TRB), and other journals from 1990 to 2012. The project data came from more than $10 billion in highway agency probabilistic cost estimates.

The result of the literature and project-risk review was a list of approximately 200 generic risk factors found in highway design and construction projects. To combine overlapping risks and remove risks that did not relate to project-delivery decisions, a two-phase screening process was employed. In the first phase, the authors took a conservative approach to removing overlapping and nonproject-delivery-related risks to be certain that no relevant risks were excluded; as a result, 39 risk factors relative to the project delivery selection process were identified. In the second phase, the authors conducted a survey using respondent-based questionnaires to determine how these 39 risk factors impact the D-B-B, D-B, and CM/GC project-delivery methods. The list of potential respondents was developed from the (1) TRB Project Delivery Committee; (2) TRB Construction Management Committee; (3) AASHTO Joint Technical Committee on Design-Build; (4) AASHTO Subcommittee on Construction; (5) AASHTO Standing Committee on Planning; (6) Colorado Department of Transportation's Innovative Contracting Advisory Committee; and (7) participants of the Design-Build Institute of America's Design-Build Transportation Conference.

The questionnaire requested information about the individual respondent's professional experience with risk and delivery methods in transportation projects. Respondents were asked to rate the impact of uncertainty of the 39 risk factors on each project-delivery method based on an ordinal scale (0 = NA; 1 = Very Low Impact; 2 = Low Impact; 3 = Moderate Impact; 4 = High Impact; and 5 = Very High Impact). This scale was designed to mitigate the discontinuity effect of the data by including numbers corresponding to different thresholds. The survey questions were distributed in a random order to eliminate sequence bias. The respondents who did not have knowledge about a risk factor could select NA; the authors treated NA as a missing value and excluded it from the analysis.

Altogether, 450 questionnaires were sent, and each respondent had a three-week time period to complete the survey. Following this time period, the authors sent follow-up emails to all contacts who did not respond reminding them to participate. A total of 152 valid responses were received, representing a response rate of 34%. To obtain reliable input, data from respondents with fewer than 10 years of professional experience were excluded from the analysis. As a result, 137 qualified responses were considered for further analysis. The results from the survey questionnaire indicated that eight of the factors were not applicable or of low impacts on project-delivery selection. The remaining 31 delivery risk factors were selected for inclusion in the risk-based model. A detailed description of these 31 delivery risk factors was presented in Tran and Molenaar (2014a). That list provides the standard set of risks for the model, but decision makers can add or remove risk variables based on the specific characteristics of the project in question.

Initial Estimates

The first input in the model requires decision makers to evaluate the initial probability of these risk factors for the project in question. This process is best done through a workshop with key project personnel to leverage the collective knowledge of the project team in estimating these probabilities (e.g., FHWA representative, project/program manager, designer, engineer, utility representative, and the contractor). Ideally, these are the same project personnel who have participated in the probabilistic risk-based cost estimating process. If they did not participate in the risk-based estimating process, they should be familiar with the results.

The initial probability of a risk variable, which is one of the main inputs for the risk-based model, is defined as the likelihood of each state of the variable occurring. Participants describe each risk variable by a set of three mutually-exclusive and collectively-exhausted events, which cover the full range of possible outcomes. Estimating initial probability assumes that the decision maker has some visual perception of risk variables and can produce subjective probabilities based on their expertise. For a given risk factor, based on the project conditions, historical data, and current state of knowledge, the decision maker can use a three-point estimation technique to produce an approximate probability distribution representing the risk's outcomes.

For example, a decision maker is required to estimate the initial probability corresponding to geotechnical investigation risk for a project in question. Based on the current state of knowledge for the project, the decision maker judges that the probability of high risk in the geotechnical investigation is 0.3, medium is 0.6, and low is 0.1. The risk register from the probabilistic cost-risk estimate process significantly reduces the burden of these assessments. Table 1 presents an example of initial probabilities of risk variables for the risk-based model.

Next, the model requires input of the values and initial probabilities of project outcomes (e.g., project cost). These input values can be directly taken from the cumulative probability distribution resulting from probabilistic risk-based cost estimating (Alarcon and Ashley 1996; Clemen and Reilly 2004). Fig. 1 shows an example of using five mutually-exclusive and collectively-exhaustive events (very low, low, average, high, and very high) to describe project

Table 1. Example of Initial Probability of Risk Variable for Risk-Based Model

Risk identifier	Risk title	Variable's status		Initial probability
		Status	Name	
1	Risks caused by scope definition	1	High	0.60
		2	Medium	0.30
		3	Low	0.10
		Sum		1.00
2	Risks caused by project complexity	1	High	0.80
		2	Medium	0.15
		3	Low	0.05
		Sum		1.00
3	Risks caused by geotechnical investigation	1	High	0.30
		2	Medium	0.60
		3	Low	0.10
		Sum		1.00

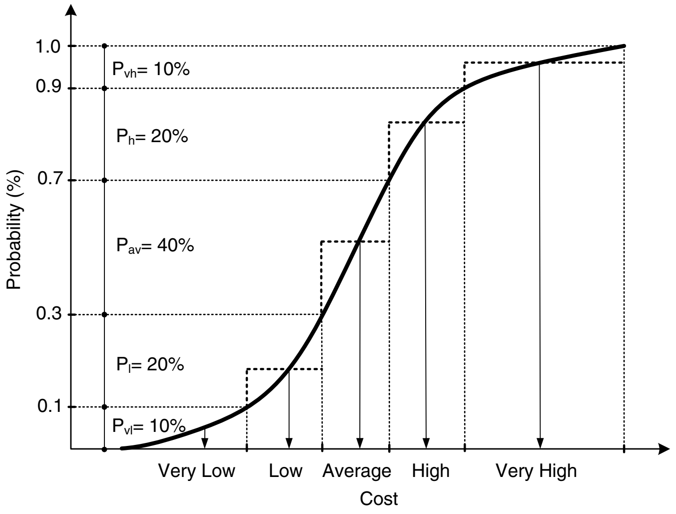

Fig. 1. Derivation of initial probability from cost-cumulative distribution

cost. The cost values and probabilities associated with these events can be determined from the cumulative-probability distribution of the previously completed risk-based cost estimate. For instance, the modeler can determine from Fig. 1 that there is a 10% chance that project cost will be at the *very low* state, 20% at the *low* state, 40% at the *average* state, 10% at the *high* state, and 10% at the *very high* state. Although these values can come directly from the risk-based cost estimate, the model does allow decision makers to make the adjustments for their estimates if they can be justified by historical data or other direct elicitation from project-team members.

Computational Structure and Model Interaction

The computational-model structure captures how the magnitude and dispersion of the risk factors impact project-delivery selection using crossimpact analysis (CIA). The CIA technique is an analytical approach to determine the overall effect on the probability of a variable based on chains of impact from related variables (Alarcon 1992). The CIA technique is suitable for this study because it is flexible and effective for predicting the outcome and combining scenarios of various alternatives, robust for assessing subjective probability, and relatively concise in its approach to evaluating expert judgments and defining outcome values (Han and Diekmann 2001).

Researchers have provided a number of improvements on the CIA technique. Alarcon and Ashley (1996) developed the general performance model based on CIA concepts to evaluate the impact of management decisions on project performance outcomes. The general performance model has been implemented in several areas in the construction industry, including selection of long-term strategies for construction firms (Venegas and Alarcon 1997), evaluation of project execution strategies for embassy projects (Alarcon and Ashley 2000), and selection of a contractor based on a set of performance criteria (Alarcon and Mourgues 2002). Han and Diekmann (2001) developed a go/no-go model that combines CIA with influence diagrams to capture the relationships between risk variables of international market entry decisions. Recently, Hallowell and Calhoun (2011) employed the CIA technique to quantify the interrelationship of highly effective and commonly implemented injury prevention strategies.

This study used *pattern* concepts developed by Alarcon and Ashley (1996) to capture the relationship between two variables. In the crossimpact relation pattern approach, the relationship between two variables is defined as (1) SIG+: significantly in the same direction; (2) MOD+: moderately in the same direction; (3) SLI+: slightly in the same direction; (4) SIG−: significantly in the opposite direction; (5) MOD− : moderately in the opposite direction; (6) SLI−: slightly in the opposite direction; and (7) NO: no impact.

Although using the pattern concepts significantly reduces the CIA knowledge acquisition, it still relies heavily on judgments of workshop participants. This reliance on participant judgment could be problematic (e.g., inaccurate and inconsistent results) because the decision involves a large number of risks and uncertainties. To overcome this burden, the risk-based model builds upon predefined multivariate analysis results to establish the CIA relationship between risk variables.

Based on the data collected from 137 experienced practitioners as previously described, the authors performed an exploratory factor analysis to investigate the interaction between delivery risk factor characteristics and project-delivery methods. In the factor-analysis model, the delivery-risk factor X_i can be expressed as a linear combination of common factors F_j and unique factors U_i as shown in Eq. (1) in which α_i = multiregression coefficients of delivery-risk factor X_i on unique factors U_i; β_{ij} = multi regression coefficients of delivery-risk factor X_i on common factors F_j; and m = number of common factors. Conversely, the common factors F_j can be expressed as a linear combination of factor loading W_{ij} and delivery risk factor X_i using Eq. (2) in which n = number of delivery risk factors constituting the common factors F_j

$$X_i = \sum_j^m \beta_{ij} F_j + \alpha_i U_i \tag{1}$$

$$F_j = \sum_i^n W_{ij} X_i \tag{2}$$

The factor analysis process and results were explained in detail in the previous study (Tran and Molenaar 2014a).

To establish the crossimpact analysis relationship between variables, the authors generated three-level nominal versions of loading factors and the percentage of explained variance based on data-mining techniques (Witten and Frank 2005). The 33.33 percentile rank values of the loading factors and the percentage of explained variance for the three delivery methods are 0.647 and 6.7%. The 66.67 percentile rank values of the loading factors and the percentage of explained variance for the three delivery methods are 0.751 and 10.6%. As a result, loadings smaller than 0.65 are coded as SLI+; loadings between 0.65 and 0.75 are coded as MOD+; and loadings greater than 0.75 are coded as SIG+. Similarly, the percentage of explained variance of critical-risk factors smaller than 6.7% is coded as SLI+; the percentage between 6.7 and 10.6% is coded as MOD+; and the percentage greater than 10.6% is coded as SIG+.

In addition, the strength of the relationship between two delivery risk factors can be identified based on the correlation-coefficient matrices. The strength of the relationship between two delivery risk factors is assigned the following rule: If the correlation coefficient between two variables is smaller than 0.3, the strength of the relationship between these two variables is coded as NO; from 0.3 to 0.4, it is coded as SLI+; from 0.4 to 0.5, it is coded as MOD+; and greater than 0.5, it is coded as SIG+.

Monte Carlo Simulation and Model Results

Using the crossimpact matrix, the risk-based model is simulated and experimentally modified to accurately depict the risk propagation from project conditions to project outcomes. The modified process (sensitivity analysis) can be used to determine the degree of impact resulting from the proposed changes. The crossimpact analysis technique requires an intensive mathematical computation through a Monte Carlo simulation to compute the posterior probability of risk variables and outcome variables. A Monte Carlo simulation is a computerized tool for modeling a stochastic process based on a random input from certain statistical distributions (Clemen and Reilly 2004). The outputs of a Monte Carlo simulation result from running a large number of iterations used to measure their risk and uncertainty.

In the proposed model, a Monte Carlo simulation provides a vehicle to model the varied probability of delivery-risk factors and to capture probabilistic information regarding the propagation of risk and uncertainty from project conditions to project outcomes. The results of the risk-based model provide three approximate cost distributions associated for three project-delivery methods (D-B, D-B-B, and CM/GC) and a sensitivity result (i.e., tornado diagrams) that describes which risk factors have the most significant impact on the cost of each delivery method.

Model Verification and Validation

Validation of the risk-based model included data validity, conceptual-model validation, and computerized-model verification. Additionally, the model was tested with one conceptual project and three actual projects with four separate highway agencies.

Sargent (2012) asserted that the data-validation process is critical to model integrity. In this research, as mentioned previously, the data used to build the risk-based model include 137 professionals with an average of 25 years of experience. More than 50% of these professionals have more than 30 years of experience. Respondents with less than 10 years of professional experience were removed from the data. The data collected from the professionals were rigorously analyzed using both univariate and multivariate statistical analysis techniques (Tran and Molenaar 2014a) to obtain appropriate and accurate data to construct the model.

Conceptual-model validation confirmed that the model correctly represents the delivery-selection process and that the model structure, mathematical relationships, and variable interactions are reasonable. To achieve these objectives, the conceptual framework of the risk-based model was presented in detail with 27 experienced practitioners in state DOTs and FHWA. The purpose of these discussions was to ensure that the model logic accurately depicts the project delivery selection process for highways. Additionally, the mathematical relationships and variable interactions in the risk-based model were confirmed using statistical results.

Computerized-model verification was conducted to ensure that the computer programming and implementation are correct and accurate. In this research, the crossimpact analysis computer simulation and programming module in the risk-based model were simplified by including only three variables. The result from this simplification was then compared with the manual calculation and previous known results from literature. Consequently, the verification procedure confirmed that the results from the risk-based model were practically the same (less than 2% compared with the manual calculation and previous known results from literature). Further, an independent researcher verified the C++ programming code. Finally, the risk-based model was tested with three highway projects. The results from the risk-based model are consistent with the delivery decision made by these three state DOTs. The detailed results from three testing projects are described in the following section for illustrative purposes.

Table 2. Case Project Summary

Project summary	Case project 1	Case project 2	Case project 3
Name/location	I-395 project, Florida	Lake bridges, Kentucky	I-76 project, New Jersey
Approximate cost	$834.5M	$583.2M	$ 872.8M
Probability cost estimate	December 2012	December 2011	August 2012
Delivery method	Design-build	Design-bid-build	Design-bid-build

Discussion

As mentioned previously, the risk-based model was designed for highway projects greater than $100 million and must be used in conjunction with probabilistic risk-based cost estimating. To obtain the appropriate candidates, the authors asked the FHWA major project support team for projects that have successfully conducted the probabilistic risk-based cost estimate recently. As a result, FHWA provided the research team with 16 highway projects (five D-B projects, four D-B-B projects, four projects related to public-private partnership (PPP), and three projects still in the selection process). Based on this pool of candidates, the authors selected the following three projects: (1) I-395 Reconstruction Project in Florida; (2) Lake Bridges Project in Kentucky; and (3) I-76 Project in New Jersey for testing the risk-based model. Table 2 summarizes the main information of these three case projects.

The I-395 Reconstruction Project involves the rebuilding of the I-395 corridor from its terminus west of the I-95/Midtown Interchange (I-95/State Road 836/I-395) to its corridor terminus at the West Channel Bridges of US 41/MacArthur Causeway, approximately 1.4 mi. The major work on this project includes (1) building new elevated ramps (one eastbound and one westbound) that will provide direct linkage between I-95 and I-395; (2) improving roadway design including updating the alignment and upgrading the roadway surface; (3) creating a visually appealing bridge; and (4) building vertically higher structures that will improve the visual quality of the bridge. The probabilistic cost risk analysis process was conducted in 2012 by the FHWA cost estimate review team and included professionals from the FHWA, Florida DOT, and engineering consultants. The result of probabilistic cost risk analysis specified that the project cost in year of expenditure (YOE) ranges from $572.4 million to $1,061.5 million. The estimate of the total project cost at the 70% confidence level was $834.5 million. The average total project cost was estimated at approximately $792 million, and the standard deviation was $124 million. The D-B-delivery method was originally selected for this project by Florida DOT (FDOT) without the benefit of a project delivery tool selection aid.

The Lake Bridges Project involves widening and improvements to the existing two-lane US 68/KY 80, from KY 94 at Aurora in Marshall County for approximately 17 mi to the western terminus of the Cadiz Bypass in Trigg County, including new bridges over Kentucky Lake and Lake Barkley. The primary purpose of this project is to correct numerous geometric deficiencies of the existing roadway and new bridges. The probabilistic cost risk analysis process was conducted in 2011 by the FHWA cost estimate review team and included professionals from the FHWA, Kentucky Transportation Cabinet, and engineering consultants. The result of probabilistic cost risk analysis specified that YOE total project cost ranges from $495.7 million to $643.9 million. The estimate of the total project cost at the 70% confidence level was $583.2 million. The average total project cost was estimated at approximately $573 million, and the standard deviation was $36.2 million. The D-B-B-delivery method was selected for this project without the benefit of a project delivery tool selection aid.

The I-76 Direct Connection Project involves constructing a direct connection on I-295 and other highway improvements that will reduce congestion and enhance traffic operations and safety throughout the project area. These improvements include a six-lane mainline which continues through the interchange, elimination of dangerous merging and weaving movements, upgrades to ramp geometry, and the addition of shoulders throughout the interchange. The probabilistic cost risk analysis process was conducted in 2012 by the FHWA cost estimate review team and included professionals from the FHWA, New Jersey DOT, and engineering consultants. The result of probabilistic cost risk analysis specified that YOE total project cost ranges from \$733.1 million to \$987.6 million. The estimate of the total project cost at the 70% confidence level was \$872.8 million. The average total project cost was estimated at approximately \$854 million, and the standard deviation was \$62.3 million. A series of D-B-B contracts was selected for this project by the New Jersey DOT without the benefit of a project delivery tool selection aid.

Risk-Based Project Delivery Selection Model Input

For each case project, several experienced engineers from FHWA and state DOTs (seven for the I-395 Reconstruction Project; eight for the Lake Bridges Project; and seven for the I-76 Project) were consulted to complete the risk-based project delivery selection model. These practitioners included project managers, program managers, engineers, lead designers, utility managers, and FHWA representatives. The majority participated in the probabilistic cost risk analysis and all were familiar with the previously conducted risk register and risk-assessment process.

The input process began with participants reviewing the conceptual model, delivery-risk factors, and the operation and function of the model to ensure that the model logic accurately described the delivery-selection process for this project. Based on the probabilistic cost risk analysis data, the participants performed the initial estimate of the likelihood for 31 delivery-risk factors. The participants were asked to determine the probabilities associated with three states (high, medium, and low) for each risk factor. The project-risk register from the probabilistic cost risk analysis was a useful reference during this workshop. In addition, the cumulative-probability distribution of total project costs from the previously completed probabilistic cost risk estimate provided the initial probabilities and cost values for five states (very low, low, average, high, and very high) of the total project cost for model input. Finally, the participants reviewed the model interaction and determined the crossimpact matrix for the final model.

Model Results

Based on the inputs collected from the risk-based delivery selection workshop, the model was run for 10,000 trials to reach convergence. The primary outputs of the risk-based model included approximate cost distributions associated with three delivery methods (D-B-B, D-B, and CM/GC) and sensitivity analysis results for a selected project-delivery method. Figs. 2–4 present the three approximate cost distributions corresponding to D-B, D-B-B, and CM/GC for each case project. The range of probable cost is shown along the horizontal access of each graph, and the probability of finishing the project at a cost is shown along the vertical access.

Based on the distributions, one can observe that D-B is the most appropriate delivery method for the I-395 Reconstruction Project because it provides the higher probabilities for the low cost and the lower probability for the high cost (Fig. 2). In particular, there is approximately a 25% chance that the total project cost is as low as \$632.2 million when using D-B versus a 19% chance for CM/GC and a 15% for D-B-B at this same cost. Likewise, there is only approximately a 13% chance that the total project cost can be as high as \$978 million when using D-B versus a 17% chance for CM/GC and a 23% chance for D-B-B at this same cost.

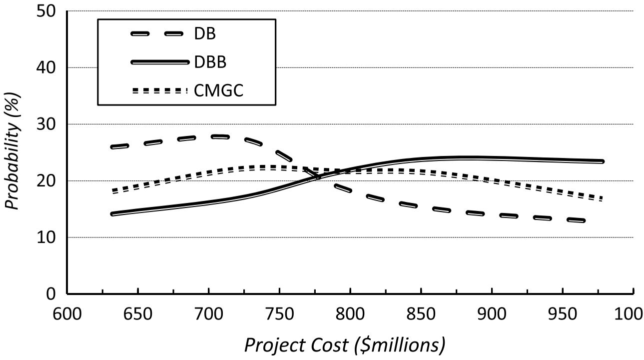

Fig. 2. I-395 cost distributions for D-B, D-B-B, and CM/GC

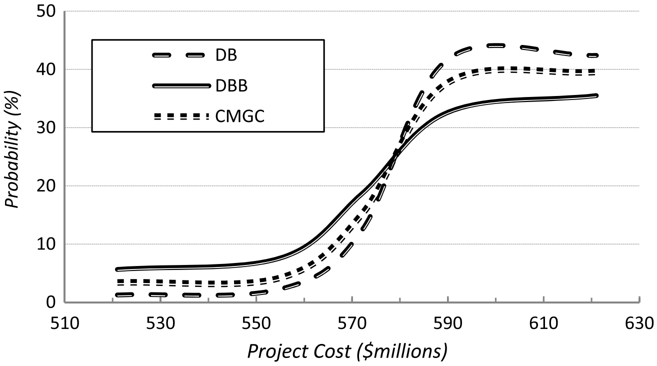

Fig. 3. Lake bridges cost distributions for D-B, D-B-B, and CM/GC

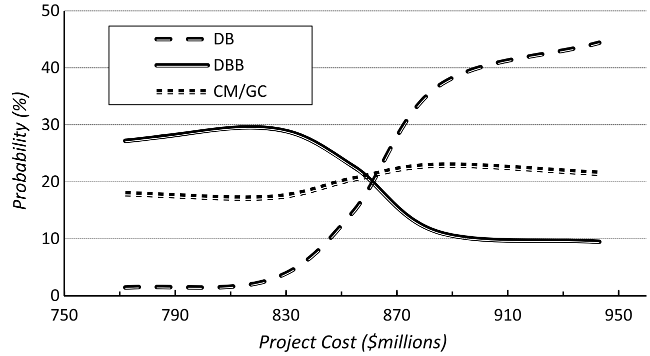

Fig. 4. I-76 cost distributions for D-B, D-B-B, and CM/GC

Different from the I-395 Reconstruction Project, Figs. 3 and 4 show that D-B-B provides the higher probabilities for the low-project cost and the lower probability for the high-project cost for both the Lake Bridges Project and I-76 Project. For example, Fig. 3 for the Lake Bridges Project indicates that there is approximately an 8% chance that the total project cost is as low as approximately \$520 million when D-B-B is selected versus approximately a 4% chance for CM/GC and a 1% for D-B at this same cost. Likewise, there is only approximately a 35% chance that the total project cost can be as high as approximately $620 million when D-B-B is selected versus a 40% chance for CM/GC and a 42% chance for D-B at this same cost.

The I-76 Project displays the largest impact from project-delivery selection of the three projects. Fig. 4 shows that there is approximately a 28% chance that the total project cost is as low as approximately $770 million when D-B-B is selected versus a 19% chance for CM/GC and a 1% for D-B at this same cost. Likewise, there is only approximately a 10% chance that the total project cost can be as high as approximately $940 million when D-B-B is selected versus a 21% chance for CM/GC and a 43% chance for D-B at this same cost.

It is also observed from Figs. 2–4 that the project cost distribution of using D-B-B, D-B, or CM/GC differs the least in the Lake Bridges Project, but it differs the most in the I-76 Project. Stated another way, the project-delivery decision has the greatest impact on the I-76 project. This variance is reasonable because the Lake Bridges Project was very well-defined in design and had less risk and uncertainty than the I-76 Project. These differences can be explained further by using sensitivity-analysis results from the risk-based model (Fig. 5).

Because the approximate cost distributions associated with each delivery method are being driven by the unique project risks and crossimpact analysis, the risk-based model can produce a sensitivity analysis in the form of a tornado diagram (Fig. 5). The sensitivity analysis provides the user with a better understanding of the risks that are driving the cost distribution and also provides for a *what-if* analysis of the results. The owner agency can learn how and why specific risks will impact the selected delivery method. These results will allow the agency to determine a mitigation strategy to minimize the risks and maximize the project performance.

Fig. 5 indicates that the risk caused by *environmental impact*, *work zone traffic control*, *geotechnical investigation*, and *construction QC/QA* had the most influence on the I-76 Project for the D-B-B selection. The risk related to environmental impact was obviously critical for this project. During the risk-based delivery selection workshop, the project team indicated that a list of environmental permits is required for this project, including New Jersey Department of Environmental Protection (NJDEP) Section 401 Water Quality Certification; NJDEP freshwater wetlands; NJDEP costal/tidal wetland; and NJDEP coastal zone management program. For example, the team pointed out that $22.8 million was added for disposal of regulated material that was not included in the previous estimates. The team also mentioned that the project was located in a dense traffic area (direct connection of I-295/I-76/Route 42) and maintenance of traffic during construction is critical for this project. In fact, the project team estimated the cost for maintenance of traffic was 4.0% of construction cost. Additional project risk existed because the project was divided into four main construction contracts. At the time of project-delivery selection, the final design was in progress for Contract 1, but had not progressed beyond preliminary design for Contracts 2, 3, and 4. These reasons might explain why the risk caused by geotechnical investigation and construction QC/QA was significant for D-B-B selection. After viewing how the alternative delivery methods would impact the most significant risks, the project team agreed that the output was reasonable. They commented that the project-cost range and sensitivity analysis provided them with new insights, and it helped to confirm their choice of the D-B-B-delivery method.

The risk-based model results depicted in Figs. 3–5 provide pre-mitigated results. Through the sensitivity analysis, the agency can see the impact of the various risks on project costs. This information will help them to make more informed decisions about risk

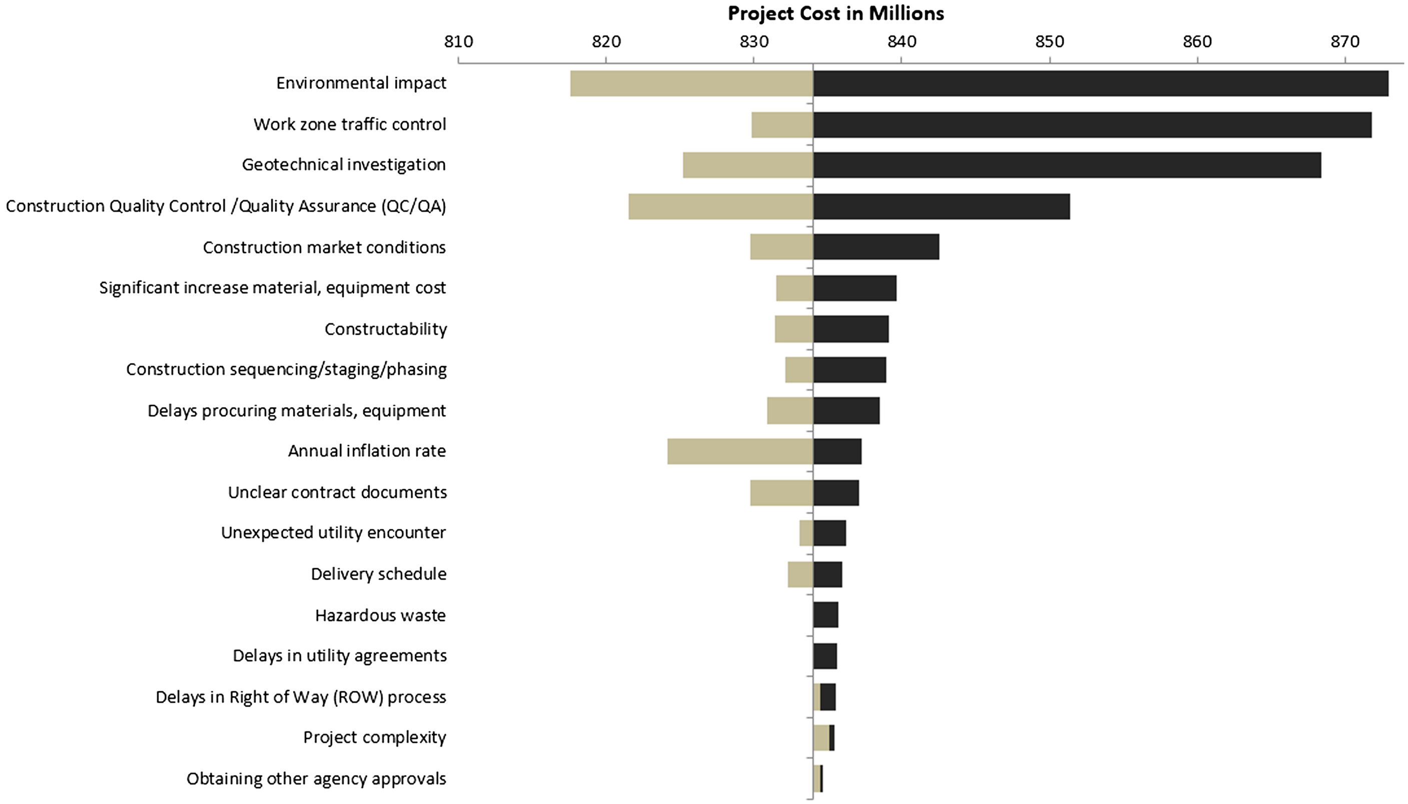

Fig. 5. I-76 sensitivity analysis results for D-B-B selection

mitigation in each delivery method. The agencies can run postmitigation models to help them explore the cost-benefit ratio of mitigation plans. For example, for the I-76 Project, if New Jersey DOT invests in mitigating some of the most influential risks, they can revise the inputs, rerun the simulation, and determine the effectiveness of their mitigation strategies. Although it is not likely in this case because D-B-B is clearly the most appropriate delivery method, postmitigated model runs may change the best choice delivery model (e.g., CM/GC or D-B may become the best choice after risks are mitigated).

Limitations and Future Research

Although the risk-based model presented in this paper provides a novel quantitative approach to selecting a highway project-delivery method, there are some limitations and areas for future research. First, although the model provides sensitivity-analysis results to better manage risk associated with each delivery method, it does not explicitly capture risk mitigation and allocation processes throughout the project life. Each project-delivery method allocates risk differently. For example, the CM/GC-delivery method offers an opportunity for dialogue about project risk between the agency and general contractor before the price is agreed upon. The model could potentially inform this dialogue and help the parties work together to reduce the overall project risk. Future research could consider the impact of mitigating and eliminating risk as the project proceeds to a fixed price. As previously mentioned, the postmitigated model may change the results from the premitigated model.

Second, the risk-based model was constructed for a large highway project (a project cost over \$100 million) on which a probabilistic risk-based cost estimate has been completed. Probabilistic risk-based cost estimates are typically not completed on projects of less than \$25 million in value. For highway projects in the \$25–\$100 million range, the model may not provide accurate results because of the embedded data in the model that was generated for projects greater than \$100 million. For small highway projects, when the probabilistic cost risk analysis results are not available, the data collection for the model input would also be a time-consuming process.

From a theoretical data modeling perspective, the model provides implicit results and does not fully take the risk-aversion of the participants into account. Several studies have recognized the importance of risk-aversion in the decision-making process (Keeney and Raiffa 1976; Stewart et al. 2011). Generally, risk-averse decision makers incline to overestimate possible losses and pay a large premium to avoid the risk. Research shows that governments and their regulatory agencies often show risk-neutral attitudes in their decisions, but for the low probability and high consequence risk events, they tend to be risk-averse (Stewart et al. 2011). In the aforementioned examples, the project manager, program manager, engineer, designer, utility manager, and other stakeholders likely had different risk tolerances. It would be beneficial to discover how the risk tolerances of each stakeholder impact the delivery decision. This avenue of research opens many interesting research topics such as integrating utility theory or cumulative-prospect theory into the risk-based model.

The risk-based model presented in this paper focuses on three fundamental delivery methods for highway projects: (1) D-B-B, (2) D-B, and (3) CM/GC. The model does not consider the public-private partnership method that is increasingly coming under consideration for infrastructure projects. Typically, the financial and economic aspects are one of the main reasons to use PPP. Thus, future work may need to consider additional risk factors and adjust the crossimpact matrix to include PPP in the model.

Conclusions

The selection of an appropriate delivery method is critical to the success of a highway project. Research shows that there is no single delivery method that is appropriate for all projects, but there exists an optimal delivery method for each individual project (Gordon 1994; Love et al. 1998, 2012; Miller et al. 2000; Ibbs et al. 2003; Gransberg et al. 2006; Touran et al. 2011; Tran et al. 2013). Researchers have been developing project delivery selection tools in an effort to allocate risks properly and maximize project performance. An array of techniques and tools has been developed, but they have been limited in their ability to quantify cost, risk, and opportunities associated with each delivery method.

The risk-based model presented in this paper provides a method to analyze project cost, risk, and uncertainty corresponding to three fundamental delivery methods in highway projects. The findings provide new insights for project management and other stakeholders. The results of the risk-based model help owner agencies to make sound decisions about the most suitable method for their project. The sensitivity analysis provides insights into how each delivery method mitigates risks. Regardless of the delivery method that is ultimately selected, the sensitivity analysis will improve the project-development process by providing a more complete understanding about the impacts of specific project risks. The risk-based model also provides a vehicle to better understand and communicate the risks inherent in large highway projects. This process will promote a better understanding of DOT risk management and will enhance collaboration among project participants.

A significant by-product of the risk-based model is the connection between the delivery selection model structure and the probabilistic risk analysis process for large highway projects. It has been shown that a probabilistic cost-risk analysis team can provide value engineering and constructability suggestions in addition to providing cost-risk analysis (Molenaar 2005). This study shows that these same team members can assist in project-delivery selection. Building upon the probabilistic risk analysis process, the risk-based project delivery selection model workshop leverages the probabilistic cost-risk estimate simultaneously with the project delivery decision process. The combination between the probabilistic risk analysis process and the delivery risk-based model will provide an effective, efficient, and transparent method to manage large highway projects.

This research endeavors to add to theoretical knowledge by introducing a model that combines the crossimpact analysis technique with multivariate analysis results. Previous research has shown that the crossimpact analysis technique is a powerful tool to capture risk and uncertainty, but it is a time-consuming process (Gordon and Hayward 1968; Mitchell 1977; Alarcon and Ashley 1996; Han and Diekmann 2001). The novel addition of the multivariate-analysis results significantly reduces the expert acquisition required for the crossimpact analysis. It also provides more accurate judgments because they are based on statistical analysis rather than experts' judgments.

Finally, previous research also indicated that the construction industry provides an excellent opportunity to develop and disseminate decision-support systems. However, these systems often do not provide decision makers with a direct solution, but rather they assist decision makers to better understand problems and add value to reach the optimal decision (Hastak 1994; Bhargava et al. 1995; Molenaar and Songer 2001; Bayraktar and Hastak 2009). The authors believe that the model presented in this paper offers a significant advancement in decision-support systems for project-delivery selection.

Acknowledgments

The writers would like to acknowledge the help and support provided by the FHWA and the Florida DOT, New Jersey DOT, and Kentucky Transportation Cabinet in the data collection for this research. Without their willingness to participate, this research would not have been possible. However, the findings and recommendations expressed in this paper are those of the writers alone and not necessarily the views or positions of the FHWA or these three state DOTs.

References

AASHTO. (2008). *Design-build procurement guide*, Washington, DC.

Alarcon, L. F. (1992). "Project performance modeling: A methodology for evaluating project execution strategies." Ph.D. dissertation, Dept. of Civil Engineering, Univ. of California, Berkeley, CA.

Alarcón, L., and Mourgues, C. (2002). "Performance modeling for contractor selection." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2002)18:2(52), 52–60.

Alarcón, L. F., and Ashley, D. B. (1996). "Modeling project performance for decision making." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1996)122:3(265), 265–273.

Alarcón, L. F., and Ashley, D. B. (2000). "Assessing project execution strategies for embassy projects." *Rep. to the Foreign Building Operations (FBO)*, U.S. Dept. of State, Washington, DC.

Alhazmi, T., and McCaffer, R. (2000). "Project procurement system selection model." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2000)126:3(176), 176–184.

Bayraktar, M. E., and Hastak, M. (2009). "A decision support system for selecting the optimal contracting strategy in highway work zone projects." *Autom. Constr.*, 18(6), 834–843.

Bhargava, H. K., King, A. S., and McQuay, D. S. (1995). "Decision net: An architecture for modeling and decision support over the World Wide Web." *Proc., 3rd Int. Conf. on Decision Support System*, International Society for Decision Support Systems, Austin, TX, 499–506.

Clemen, R. T., and Reilly, T. (2004). *Making hard decisions with decision tools suite*, Druxbury, Pacific Grove, CA.

FHWA (Federal Highway Administration). (2004). "Major project program cost estimating guidance." ⟨http://www.fhwa.dot.gov/ipd/project_delivery/tools_programs/cost_estimating/guidance.htm⟩ (Jul. 7, 2013).

Ghavamifar, K., and Touran, A. (2009). "Owner's risks versus control in transit projects." *J. Manage. Eng.*, 25(4), 230–233.

Gordon, C. M. (1994). "Choosing appropriate construction contracting method." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1994)120:1(196), 196–210.

Gordon, T., and Hayward, H. (1968). "Initial experiments with the cross impact method of forecasting." *Futures*, 1(2), 100–116.

Gransberg, D. D., Koch, J. A., and Molenaar, K. R. (2006). *Preparing for design-build projects: A primer for owners, engineers, and contractors*, ASCE, Reston, VA.

Gransberg, D. D., and Shane, J. S. (2010). "Construction manager-at-risk project delivery for highway programs." *National Cooperative Highway Research Program (NCHRP) Synthesis 402*, Transportation Research Board of the National Academies, Washington, DC.

Hallowell, M., and Calhoun, M. (2011). "Interrelationships among highly effective construction injury prevention strategies." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000354, 985–993.

Han, S. H., and Diekmann, J. E. (2001). "Approaches for making risk-based go/no-go decision for international projects." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2001)127:4(300), 300–308.

Hastak, M. (1994). "Decision support system for project cost control strategy and planning." Ph.D. thesis, Purdue Univ., West Lafayette, IN.

Ibbs, C. W., Kwak, Y. H., Ng, T., and Odabasi, A. M. (2003). "Project delivery systems and project change: Quantitative analysis." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2003)129:4(382), 382–387.

Keeney, R. L., and Raiffa, H. (1976). *Decisions with multiple objectives*, Wiley, New York.

Love, P. E., Skitmore, M., and Earl, G. (1998). "Selecting a suitable procurement method for a building project." *Constr. Manage. Econ.*, 16(2), 221–233.

Love, P. E. D., Edwards, D. J., Irani, Z., and Sharif, A. (2012). "Participatory action research approach to public sector procurement selection." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000440, 311–322.

Mahdi, I. M., and Alreshaid, K. (2005). "Decision support system for selecting the proper project delivery method using analytical hierarchy process (AHP)." *Int. J. Project Manage.*, 23(7), 564–572.

Miller, J. B., Garvin, M. J., Ibbs, C. W., and Mahoney, S. E. (2000). "Toward a new paradigm: Simultaneous use of multiple project delivery methods." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2000)16:3(58), 58–67.

Minchin, R., et al. (2014). "Guide for design management on design-build and construction manager/general contractor projects." *National Cooperative Research Program (NCHRP) Rep. 787*, Transportation Research Board of the National Academies, Washington, DC.

Mitchell, R. B. (1977). "Scenario generation limitation and development in CIA." *Futures*, 9(3), 205–215.

Molenaar, K. R. (2005). "Programmatic cost risk analysis for highway megaprojects." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2005)131:3(343), 343–353.

Molenaar, K. R., and Songer, A. D. (2001). "Web-based decision support systems: Case study in project delivery." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)0887-3801(2001)15:4(259), 259–267.

Oyetunji, A. A., and Anderson, S. D. (2006). "Relative effectiveness of project delivery and contract strategies." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2006)132:1(3), 3–13.

Ptschelinzew, L. R., et al. (2013). "Best practices in design process development for accelerated construction project delivery." *7th Int. Structural Engineering and Construction Conf.*, Research Publishing, Singapore.

Rubin, R., and Wordes, D. (1998). "FEATURE: Risky business." *J. Manage. Eng.*, 14(6), 36–43.

Sargent, R. G. (2012). "Verification and validation of simulation models." *J. Simul.*, 7(1), 12–24.

Stewart, M. G., Ellingwood, B. R., and Mueller, J. (2011). "Homeland security: A case study in risk aversion for public decision-making." *Int. J. Risk Assess. Manage.*, 15(5), 367–386.

Touran, A., Gransberg, D. D., Molenaar, K. R., and Ghavamifar, K. (2011). "Selection of project delivery method in transit: Drivers and objectives." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000027, 21–27.

Tran, D., Harper, C. M., Molenaar, K. R., Haddad, N. F., and Scholfield, M. M. (2013). "A project delivery selection matrix for highway design and construction." *Transportation Research Record 2347*, Transportation Research Board, Washington, DC, 3–10.

Tran, D., and Molenaar, K. R. (2012). "Critical risk factors in project delivery method selection for highway projects." *Construction Research Congress*, ASCE, Reston, VA, 331–340.

Tran, D., and Molenaar, K. R. (2014a). "Exploring critical delivery selection risk factors for transportation design and construction projects." *J. Constr. Archit. Manage.*, 21(6), 631–647.

Tran, D., and Molenaar, K. R. (2014b). "The impact of risk on design-build selection for highway design and construction projects." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000210, 153–162.

Venegas, C. P., and Alarcón, C. L. F. (1997). "Selecting long-term strategies for construction firms." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1997)123:4(388), 388–398.

Witten, I. H., and Frank, E. (2005). *Data mining: Practical machine learning tools and techniques*, Morgan Kaufmann, Burlington, MA.

Zeng, Z., Minchin, R. E., Ptschelinzew, L., and Zhang, Y. (2014). "Multi-objective decision-making to select multiple project delivery methods for multi-project transportation systems." *2nd Int. Structural Engineering and Construction Australasia and Southeast Asia Conf.*, Research Publishing, Singapore.