# A Risk Analysis and Mitigation Methodology for Infrastructure Projects

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With the shift from the Design-Bid-Build approach to new project delivery methods in the context of projects that are more and more complex, it has become increasingly important to understand the risks associated with construction projects. This work proposes a methodology for identifying project risks and analyzing their impact on project cost. The methodology uses Monte Carlo simulation to combine the conventional deterministic estimate, the variability of the estimate, and the elicited project risk to create a Risk Based Estimate (RBE). The probabilistic cost curve from the RBE provides insightful information about project cost. In a pilot implementation, the methodology effectively predicted that an infrastructure project in Northern California would suffer a significant reduction in profit. This methodology can be used by the project team and decision-making practitioners to better justify their decisions and to implement strategies that mitigate project risk.

**Keywords:** risk management, construction, design-build, infrastructure, Monte Carlo

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## I. INTRODUCTION

In recent years, there has been a shift from the conventional *Design-Bid-Build* approach in construction contracts to procurement methods that give the owner more control in making decisions within the contracting process (Ling et al., 2004; Lee et al., 2009). In the past, the owner (state or county) of the project chose a contractor based on the lowest bid. While this approach led to a highly competitive market for contractors who could reduce cost, it also led to reduced experience, quality, safety, and innovation on the part of the contractor selected by this method. Also, this approach caused projects to face considerable risk of budget and schedule overruns.

New approaches such as *Construction Manager at Risk (CM @ Risk)* and *Design-*

*Build* delivery methods are value-based, which allow for the owner, construction manager (i.e., general contractor) and architect/engineer to work as a unified team. In these delivery methods, contracts are not awarded on the basis of the lowest bid alone. Rather, there is a points system that is used to select the most qualified contractor.

In the *Design-Build* delivery method, the responsibility for both design and construction are given to the same entity which is usually a joint venture between an architect-engineer firm and a general contractor. In this approach, the construction team is involved in the design process from the beginning, therefore eliminating many of the design issues that may surface during construction. This also eliminates any finger pointing between the design and construction teams in case of any issues arising during construction, because both are part of the same team.

The *Construction Management (CM)* delivery method puts a Construction Management firm in charge of the day-to-day management of the project, without assuming any financial risk. The Construction Management firm acts as an agent of the project owner and all construction contracts are between the owner and the general contractor and between the general contractor and subcontractors. The *CM @ Risk* delivery method is a revised version of the *CM* approach in that the construction management firm assumes some of the risks of the project in the form of forfeiture of part of their fee.

These approaches have helped owners achieve reduced costs, shorter project delivery times, and appropriate allocation of risks to the parties who are best able to manage them. Within these new project delivery frameworks, the identification, analysis, and mitigation of risks are critical for achieving project objectives on time and within budget. Furthermore, the impact of risk increases with the size, complexity, and time constraints of a project (Jin, et al., 2010), and risk management has therefore gained increased importance within the construction industry (Akintoye et al., 1997; Xie, et al., 2007). With the increased degree of risk associated with construction projects, in which uncertainties can lead to higher costs, delays, safety issues, and reduced quality overall, many companies are creating their own risk management departments or reaching out to external consultants.

Despite research showing the benefit of risk identification and assignment of risk to the parties best able to manage it, not every contractor has the background to effectively perform this task. Generally contractors review the risk associated with the project during the bidding phase and in the construction phase, after the risk has occurred. With the shift away from low-bid contracting *(Design-Bid-Build)* to more robust contract forms, project managers must understand, identify, and evaluate the risks associated with each stage of a project beforehand.

The overall goal of this article is to delineate ways in which managers can identify, analyze, and mitigate the risks associated with each stage of a project.

## II. LITERATURE REVIEW

### 2.1. Risk in Infrastructure Projects

A risk is a chance that an event could have a potential positive or negative effect on a project's overall objective. A properly conducted Risk Management process will increase the likelihood and impact of positive events, and decrease the impact and likelihood of negative events. The Project Management Body of Knowledge (PMBOK, Project Management Institute, 2012) provides a comprehensive guide to handle the Project Risk Management process by following these five steps: (a) plan the risk management process, (b) identify the risks, (c) perform a qualitative and quantitative analysis, (d) plan risk responses (risk mitigation) and (e) control risks.

The Risk Management Plan defines how risks associated with a project will be identified, analyzed, monitored, controlled and reported throughout the life of the project. It also provides templates for tracking and reporting risks. The Risk Management Plan will provide the necessary information that senior project managers will use to make informed decisions when preparing the project estimate prior to construction and to mitigate risk before and during construction.

Researchers and practitioners have applied and adapted the steps outlined in the Project Risk Management process to incorporate risk analysis and mitigation into infrastructure projects. For instance, research by Tummala and Burchett (1999) proposed the use of a risk management process (RMP), structured in a similar fashion to a quality management process, to assess and mitigate risk for both external and internal customers. Marcelino-Sadaba et al. (2013) proposed a fast and clear documentation method to create records for making decisions throughout the project. Olson (2007) proposed that risk should be considered for each function of the management process (i.e., sales, marketing, and technical) to ensure a comprehensive risk analysis.

## 2.2. Risk Elicitation

One key aspect of risk management is risk elicitation, which consists of proper risk identification and assessment. The PMBOK (Project Management Institute, 2012) recommends the use of a data flow chart to facilitate the identification of project risks. They advise to interview professionals involved in the management of the project, team members and subject matter experts to identify all relevant project risks. Sadeghi (2010) proposed the use of human experts during initial risk elicitation. While most risks are likely to be observed by construction management professionals, specialized expertise is needed to properly account for and mitigate their impacts.

Kaplan and Mikes (2012) propose a new framework to elicit risk , which consist of identifying and classifying risks in three categories: (a) preventable risks, which have always a negative impact and shall be eliminated or mitigated by implementing an integrated corporate culture and compliance model, (b) strategy risks, which are taken to achieve superior strategic returns, and should be managed by allocating resources to critical risk events, and (c) external risks, which are uncontrollable but can be mitigated by envisioning the risks using techniques such as *tail-risk assessment, scenario planning,* and *war-gaming.*

Cretu et al. (2011) identified three main methods to conduct risk elicitation in infrastructure projects: (1) one-on-one, (2) large-group, and (3) small-group interviews. Though one-on-one interviews lack group synergies, large-group interviews can lead to group think and the opportunity for an individual to take over the meeting with his or her own agenda. Through one-on-one and small-group interviews, it is easier to obtain the true risks within a project as long as the right experts are involved. Lam, Wang, and Lee (2007) proposed that subject matter experts be recruited to aid in the elicitation process. These experts should have experience with similar projects and direct knowledge of project delivery methods.

## 2.3. Risk Analysis and Monte Carlo Simulation

After each risk has been elicited, a mathematical model is needed to compute the overall effect on the project. Different methods have been proposed. For example, Jui-Sheng et al. (2009) focused on a probabilistic simulation to develop a likely distribution of project cost. Jong et al. (2009) proposed the use of a Bayesian belief network to manage risk in large engineering projects. Van Dorp and Duffy (1999) analyzed statistical dependence in risk analysis within construction projects at the project network level. Jaffari (2001) used a life-cycle project management approach to manage uncertain risks within a project. Peckienea et al. (2013) proposed the use of cooperative game theory for risk allocation to the construction parties. Dikmen et al. (2008) developed a tool for post-project risk assessment. Samani and Shahbodaghlou (2012) used the Fuzzy DEMATEL Method to quantify risk in a large bridge project.

While different methods are available to analyze the combined effect of different risks, the Monte Carlo simulation has been most widely used due to its relative simplicity and capacity to evaluate a large number of risks and calculate overall project cost and economic risk (Wei et al., 2009; Zhao and Liu, 2008; Li et al., 2008). This method has been applied to such large projects as the construction of an electric power plant (Wei et al, 2009) and transportation infrastructure (Cretu, 2009).

## III. PROJECT OBJECTIVE

The primary goal of this paper is to develop an applied methodology to assist project managers in identifying, classifying, analyzing, and mitigating the impact of risks for infrastructure construction projects. Such methodology enhances the owner's ability to plan, mitigate, accept, avoid, or transfer (assign) risks to the most appropriate parties. A secondary objective of this project is to streamline the evaluation of project risks by creating a Monte Carlo-based risk analysis interface that can be used effectively by project managers in the office or field.

## IV. PROPOSED METHODOLOGY

The proposed methodology aims to evaluate the cost effect that variability and risk have on the deterministic cost estimate of a project. Therefore, the methodology is based on three main components: (1) the *deterministic base estimate*, (2) the *variability of the base estimate*, and (3) the *occurrence of risks*. Each risk is assumed to be independent and defined by the probability of its occurrence and its stochastic impact.

The process is initiated by breaking down the deterministic cost estimate for the project into different categories, as shown in Figure 1. This initial estimate follows the same cost categories used for most construction projects, including *materials, labor, equipment, subcontracts,* and *miscellaneous expenses.* After the deterministic estimate has been completed, the base cost variability for each category is determined. The base cost variability is defined as an *eventless uncertainty* (Cretu, 2009), which assumes that the project is completed in an environment free of risk events. The variability ($V_i$) of each category ($i$) is modeled using a symmetric PERT-Beta curve (Davis, 2008), in which the deterministic estimate for that category is used as the most likely ($ML_i$) value, and the lowest ($L_i$) and highest ($H_i$) values are determined by adding or subtracting the variability to or from the most likely value as shown below:

$$H_i = ML_i *(1+ V_i/100) \qquad (1)$$

$$L_i = ML_i *(1- V_i/100) \qquad (2)$$

These three variables ($L_i$, $ML_i$, and $H_i$) define the symmetrical PERT-Beta distributions that determine cost fluctuations for each cost category. The use of symmetric PERT-Beta distributions ensures that the effect of variability is *cost neutral* and that there is a higher probability that the cost for each category will be close to its most likely value.

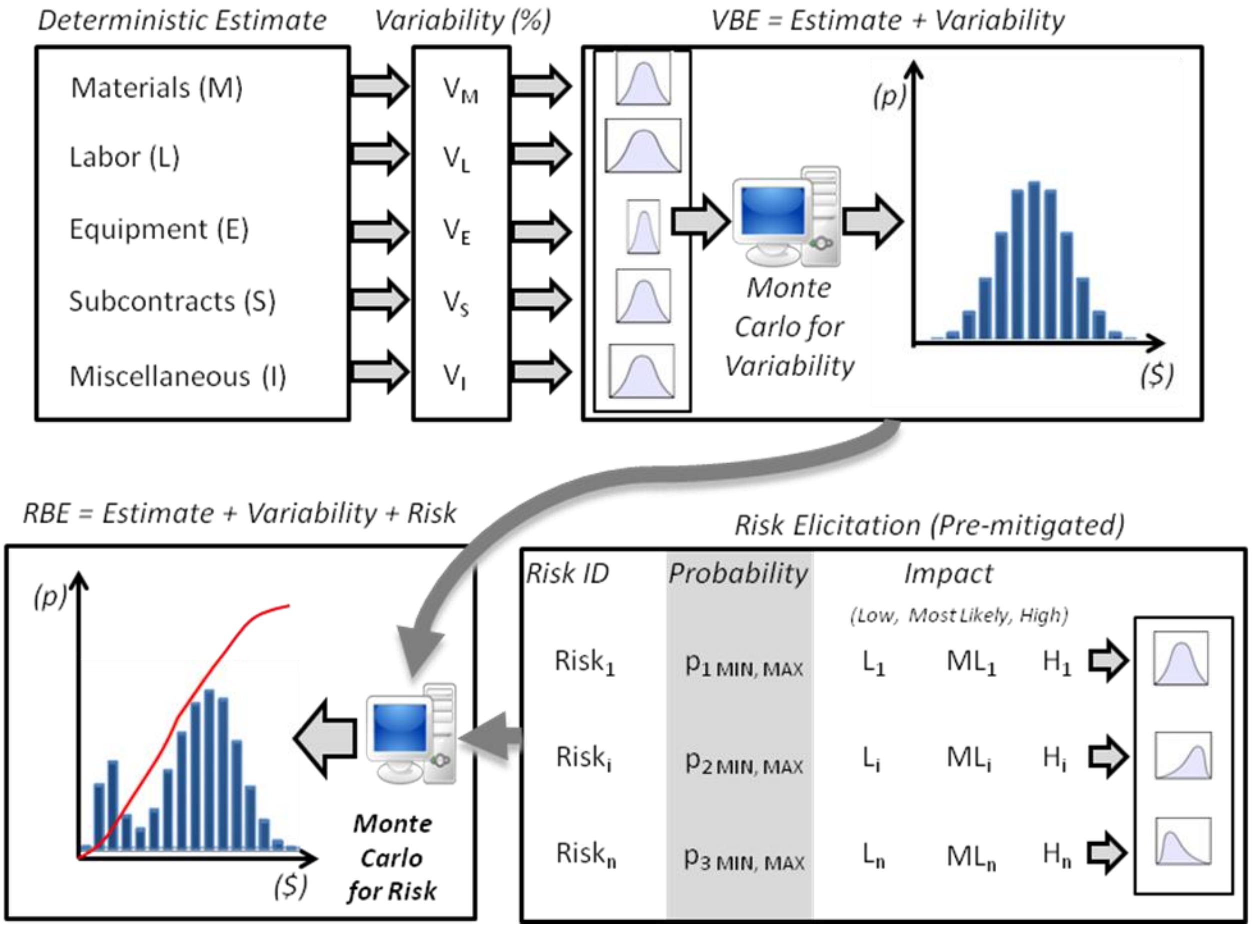


**FIGURE 1. RISK ANALYSIS AND MITIGATION METHODOLOGY**

As shown in Figure 1, each cost category is not defined by one single value, but is instead described by one symmetric PERT-Beta distribution. These distributions are the inputs for the *Monte Carlo simulation for variability*, which uses different sets of random numbers to calculate possible results, which in turn generate an output distribution. After the Monte Carlo simulation has been completed (10,000 iterations), the *variability based estimate (VBE)* is obtained. The VBE is a statistical distribution that combines the deterministic estimate and the variability, as shown in Figure 1. This distribution represents the inherent variability in the cost of the project produced by the standard variation in cost of materials, labor, equipment, subcontractors, and miscellaneous items without considering any potential risk events in the project. Previous research (Cretu, 2009) has demonstrated the importance of keeping the variability risk neutral to accurately identify the true effect of risks on the outcomes of the project.

The next step in the process is risk elicitation, which consists of identifying and describing each potential risk, classifying it, assessing its probability of occurrence, and defining its potential cost impact on the project. As shown by recent research by Samani and Shahbodaghlou (2012), the risks must be broken down into different categories (i.e., financial, operational, political, and strategic) to maximize the likelihood of properly identifying all risks in a project. Small risk elicitation groups should be created to cover different stages (i.e., pre-construction, construction, and post-construction) and functions (i.e., sales, procurement, finance, operations, and service departments) in the project. The collected information and categorization of each risk should be logged and kept throughout the project. This categorization and sub-categorization improves the risk identification and mitigation process and helps provide better analysis and assignment of risks.

The probability of occurrence for an elicited risk is defined by a high ($P_{max}$) and low ($P_{min}$) probability of occurrence. This definition, using a range, assumes a uniform probability distribution of occurrence and is useful for scenarios in which the probability of occurrence is not clearly known or there is a lack of agreement among the elicitors. Moreover, if the elicitors agree on one probability of occurrence, then $P = P_{max} = P_{min}$.

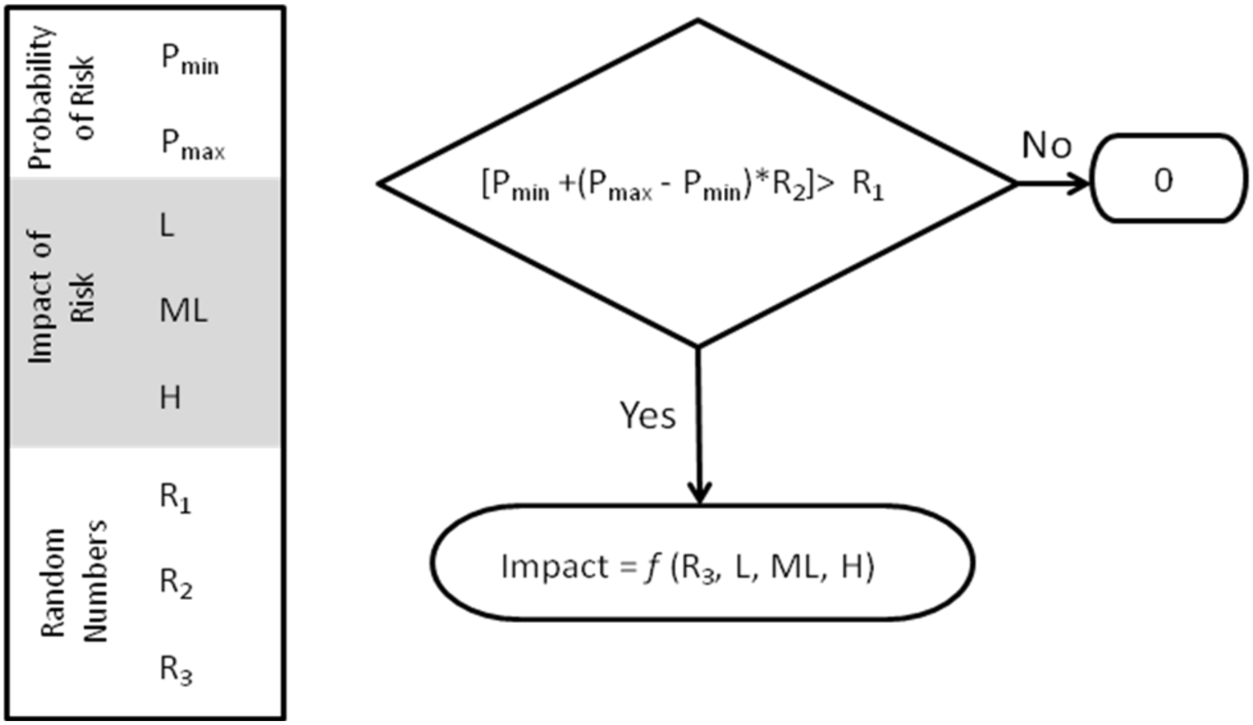


**FIGURE 2. RISK IMPACT CALCULATION ALGORITHM**

The algorithm shown in Figure 2 is used to evaluate the occurrence or non-occurrence of a risk in a given Monte Carlo iteration. First, the *random probability of occurrence* (i.e., $[P_{min} + (P_{max} - P_{min}) * R_2]$) is calculated by using a random number ($R_2$) plus the high ($P_{max}$) and low ($P_{min}$) probability of occurrence as shown below:

$$\text{Random probability of occurrence} = P_{min} + (P_{max} - P_{min}) * R_2 \qquad (3)$$

The random probability of occurrence defines a probability that can have any value between the elicited $P_{min}$ and $P_{max}$ for a given risk.

As shown below, if the *random probability of occurrence* (i.e. $[P_{min} + (P_{max} - P_{min}) * R_2]$ ) is greater than the first random number ($R_1$), then it can be assumed that the identified risk has occurred, and its cost impact is calculated. If the described condition is false, then the risk did not occur and its impact is zero.

$$[P_{min} + (P_{max} - P_{min}) * R_2] > R_1 \begin{cases} \text{TRUE} \rightarrow \text{Risk occurs} \rightarrow \text{cost impact} \\ \\ \text{FALSE} \rightarrow \text{Risk does not occur} \\ \rightarrow \text{zero impact} \end{cases} \qquad (4)$$

The impact of a risk is established during the elicitation process by defining the lowest ($L$), most likely ($ML$), and highest ($H$) cost that it could have on the project. These three variables are used to define a PERT-Beta distribution, which is not necessarily symmetric (i.e., if elicitors determine that the most likely cost is closer to the highest cost or vice-versa). Finally, if the risk does occur based on the decision algorithm defined in Figure 2, then its impact on the cost is calculated using a PERT-Beta function (Davis, 2008). The inputs for the PERT-Beta function are a third random number ($R_3$) and the elicited lowest ($L$), most likely ($ML$), and highest ($H$) impact, as shown below:

$$Impact = f_{PERT\text{-}Beta}\,(R_3, L, ML, H) \qquad (5)$$

A second Monte Carlo simulation is performed to assess the combined effects of variability and elicited risks on the project estimate. This assessment is achieved by adding the effects of the risks using the algorithm in Figure 2 to the variability-based estimate (VBE), as shown in Figure 1. A risk-based estimate (RBE) is achieved after 10,000 cases (i.e., iterations) of the second Monte Carlo simulation have been completed. The RBE is a statistical distribution that combines the effects of the deterministic estimate, the variability, and the elicited project risks.

The RBE distribution provides insightful information that can be used to accurately assess the adequacy of contingencies in a project proposal. As shown in Figure 3, the cumulative probability distribution of the RBE can be used to assess the probability of breaking even on a project. If the contingencies in the cost proposal are insufficient, then the probability of breaking even becomes lower, consuming the profit and potentially even creating losses for the general contractor.

A second relevant application of the RBE is the evaluation of risk mitigation strategies, which consists of holding post-elicitation meetings to discuss ways to reduce the impact of different risks on the project. Once such strategies are identified, a new RBE can be calculated based on the new probability and impact of the mitigated risks. This post-mitigated RBE can be compared to the original RBE to identify the most cost-efficient strategies to reduce the risks.

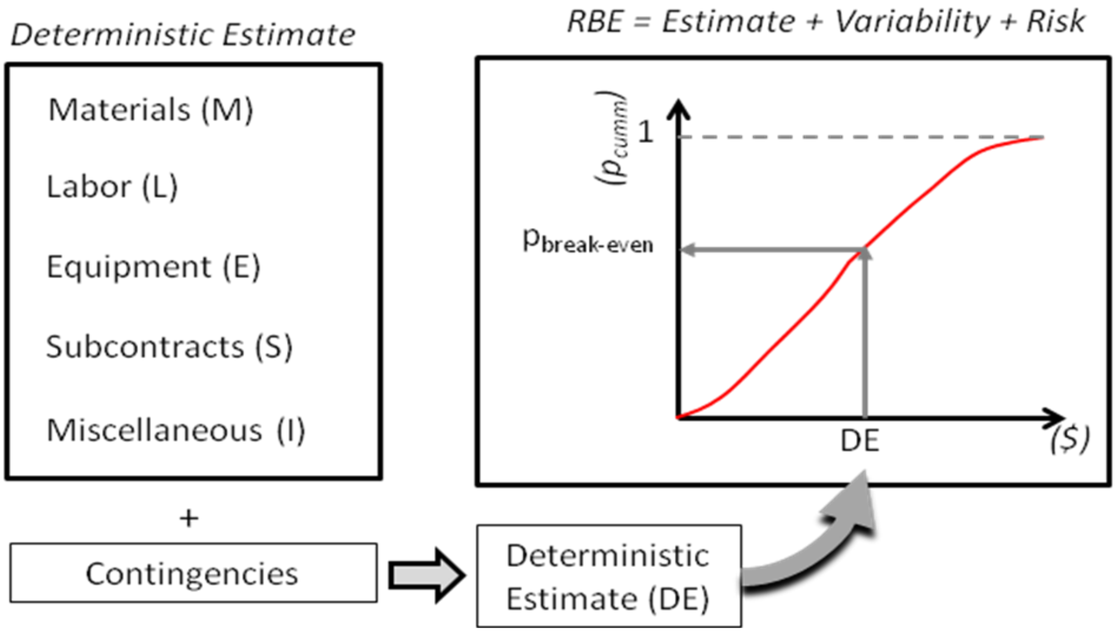


FIGURE 3. ASSESSING THE RISK OF THE DETERMINISTIC ESTIMATE

TABLE 1. EXAMPLE OF RISKS IN CONSTRUCTION PROJECTS

| | **Financial** | **Operational** | **Political** | **Strategic** |
|---|---|---|---|---|
| **Pre-Construction** | Non-awarded project cost | Asphalt Repair/EPA issues | Permitting and zoning issues | Negative cash flow |
| **Construction** | Liquidated damages for signage in the right of way | Schedule slip due to technology skill of field | In-fighting with trades | Schedule delays, cost overruns, safety issues |
| **Post-Construction** | Retention final payment at closeout | Construction warranty repairs | Final Inspection and commissioning | Hand over process and project closeout |

## V. RISK ASSESSMENT AND MITIGATION STRATEGIES

Risk identification involves the project teams and appropriate stakeholders. It includes the assessment of contractual, environmental, organizational factors and the project plan including scope, schedule, quality, and cost. This assessment should be conducted throughout the life of the project, with risk categorized as pre-construction, construction, and post-construction and subcategorized as financial, operational, political, and strategic.

Risk should be categorized as: (1) pre-construction, which includes all risks prior to the construction of the project, (2) construction, which includes all risks associated with the actual construction of the project, and (3) post-construction, which includes all risks associated with the final acceptance of the project. Risk should then be subcategorized in each category as: (a) financial, which includes all monetary or margin risk including credit, liquidity, market, etc., (b) operational, which includes all risk associated with processes, technical failure, human error, or external events, (c) political, which includes all risk associated with government action leading to changes in regulations, and (d) strategic, which includes all risk associated with incorrect business decisions, poor decision implementation, and inability to adapt to changes.

The probability and impact of occurrence for each identified risk should be assessed by the risk eliciting teams and reviewed by the project management team. All identified risks should have a risk response strategy and be reviewed at regularly set time intervals. All risks should have an assigned risk owner for monitoring and controlling. The mitigation plan should emphasize how the risk response will be implemented. For example, if the risk of a project delay has the potential of being caused by a subcontractor, then the subcontractor should be assigned as the owner of that risk. The contract will define the extent of responsibility for the subcontractor, in case such delay occurs. Table 1 shows examples of typical construction project risks classified by category and subcategory:

## VI. METHODOLOGY IMPLEMENTATION AND CASE STUDY

The proposed methodology was implemented on an infrastructure project in Northern California. The project scope was to: (1) furnish and install ramp meter signals at on-ramps of interchanges within a highway corridor, (2) place asphalt overlay, (3) install overhead extinguishable message signs, some of which were on elevated sections of on-ramps, and (4) install state-furnished control hardware and software including platforms for cellular phone communications.

The project was awarded to the general contractor (referred to as GC to maintain his anonymity) for $10,841,045. The GC had estimated a cost of $7,696,013 and was expecting a 29% profit based on his deterministic estimate. The actual cost of the project at completion was $10,166,391.60, yielding an actual profit of 6.2%, which was far below the GC's expectations. The implementation of the proposed methodology to this case assesses the project risk faced by the GC based on the proposal submitted.

### 6.1. Deterministic Estimate

The deterministic estimate included materials, labor, equipment, subcontracts, and miscellaneous expenses. The direct cost for each category is presented in Table 2. Each category included an overhead to cover indirect costs. As shown in Table 2, the total deterministic cost of the project was $7,696,013.

**TABLE 2. DETERMINISTIC BASE ESTIMATE**

| Category | Subtotal |
|---|---|
| Materials | $ 1,061,737 |
| Labor | $ 1,551,829 |
| Equipment | $ 224,160 |
| Subcontractors | $ 4,604,726 |
| Miscellaneous | $ 253,561 |
| **Total Cost** | **$ 7,696,013** |

**TABLE 3. VARIABILITY FOR EACH ESTIMATE CATEGORY**

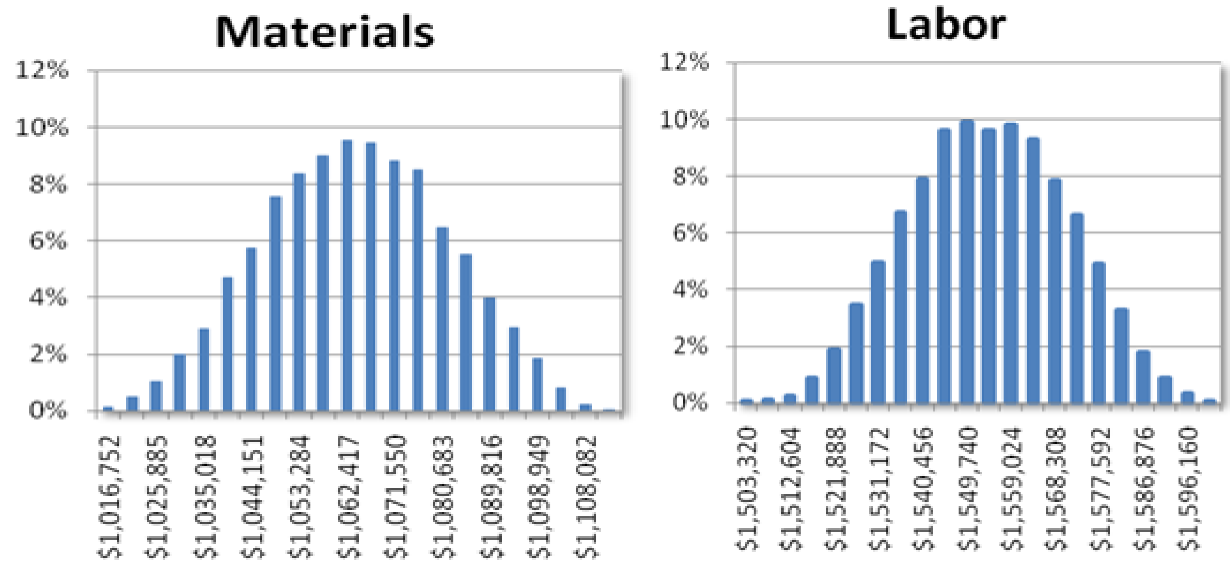
| Category | Variability | Recommended Range |
|---|---|---|
| Materials | 5% | 4% - 6% |
| Labor | 4% | 2% - 10% |
| Equipment | 4% | 3% - 5% |
| Subcontractors | 7% | 5% - 10% |
| Miscellaneous | 3% | 1% - 3% |

## 6.2. Estimate Variability

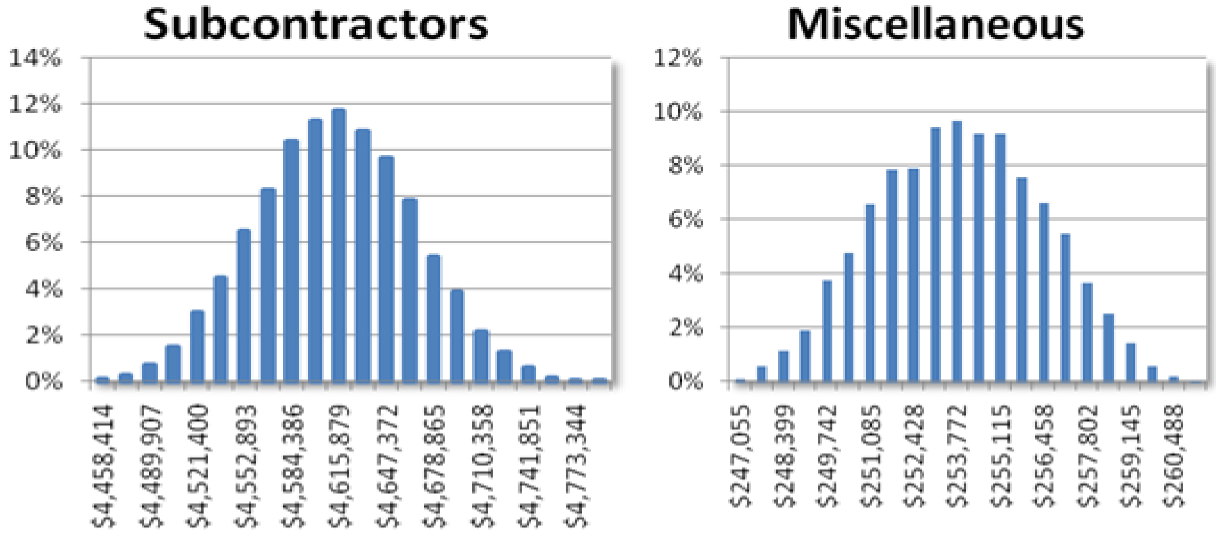
The variability for each estimate category was determined based on the GC’s historical information, as shown in Table 3. This table also includes a recommended range based on the GC’s previous project experience.

The Monte Carlo simulation was run for 10,000 cases to calculate the variability for each of the estimate categories and to analyze the overall cost variability of the project. As shown in Figure 4, the distributions of the material, labor, subcontractor, and miscellaneous costs were all symmetrical as expected. The statistical distribution for the cost of materials ranged from $1,016,752 to $1,108,082. The statistical distribution for the cost of labor ranged from $1,503,320 to $1,596,160, and the statistical distribution for the cost of the subcontractors ranged from $4,458,414 to $4,773,344. The statistical distribution for the cost of miscellaneous items ranged from $246,946 to $260,540.

Finally, the total cost of the project, as shown in Figure 5, had a most likely value of $7,705,949, which is very close to the deterministic estimate of $7,696,013, confirming the initial model assumption of cost neutral variability. The project cost varies between $7,520,474 and $7,857,701, which is approximately +/- 2.3% of the most likely cost.



(a) Materials (b) Labor



(c) Subcontracts (d) Miscellaneous

**FIGURE 4. VARIABILITY OF THE DIFFERENT CATEGORIES IN THE ESTIMATE**

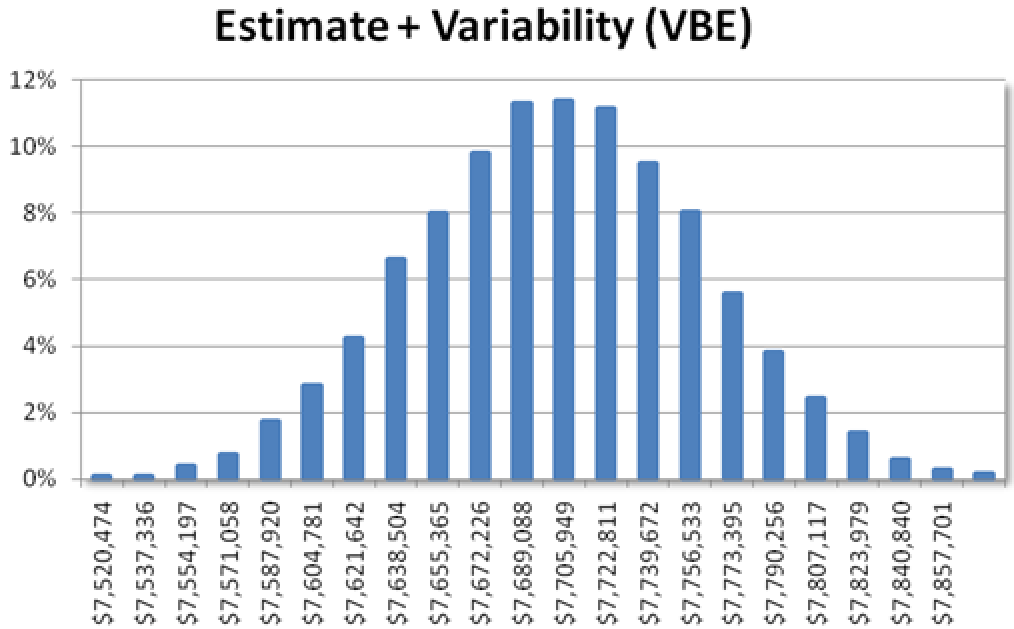


FIGURE 5. OVERALL PROJECT VARIABILITY

## TABLE 4. IDENTIFIED PROJECT RISKS

| Risk ID # | Risk Description | Category | SubCategory | *P* (%) before mitgation | | Cost Impact | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Low | High | ML | L | H |
| 1 | Negative Cashflow | Pre-Construction | Strategic Risk | 20% | 100% | $ 150,000 | $ 1 | $ 500,000 |
| 2 | Asphalt Repair/EPA issues | Pre-Construction | Operational Risk | 0% | 34% | $ 25,000 | $ 25,000 | $ 73,000 |
| 3 | In-fighting with trades | Construction | Political Risk | 30% | 50% | $ 81,000 | $ 81,000 | $ 162,000 |
| 4 | Schedule slip due to technology skill of field | Construction | Operational Risk | 25% | 65% | $ 10,100 | $ 10,100 | $ 54,000 |
| 5 | Stop bars and striping missed in schedule | Construction | Operational Risk | 65% | 100% | $ 90,000 | $ 90,000 | $ 90,000 |
| 6 | Missed Scope and Punchlist rework | Construction | Operational Risk | 65% | 100% | $ 1,500,000 | $ 103,200 | $ 2,500,000 |
| 7 | Additional Lane Closures | Construction | Operational Risk | 75% | 100% | $ 21,000 | $ 21,000 | $ 21,000 |
| 8 | Unresolved change order requests from subcontractors | Construction | Operational Risk | 90% | 100% | $ 30,500 | $ 30,500 | $ 35,500 |
| 9 | Liquidated Damages for utility delay | Construction | Financial Risk | 100% | 100% | $ 669,600 | $ 669,600 | $ 669,600 |
| 10 | Liquidated Damages for signage in the right of way | Construction | Financial Risk | 0% | 10% | $ 502,200 | $ 502,200 | $ 502,200 |

## 6.3. Risk Analysis

### 6.3.1. Identification of Risks

Small-group and one-on-one interviews were held with the project team to identify risks. Table 4 shows the risks that were identified prior to mitigation. The category and subcategory for each risk was selected, and the probability and impact of each risk was elicited. The impact of each risk was defined by its most likely, high, and low cost, as shown in Table 4.

All risks were identified, classified, and prioritized by level of importance based on their probability and impact of occurrence.

### 6.3.2. Risk-Based Estimate (pre-mitigated)

The pre-mitigated RBE graph shown in Figure 6 displays the cost distribution prior to mitigation as calculated by the Monte Carlo simulation after 10,000 iterations. The bars in this figure represent the overall probability distribution of the project cost, while the line represents the cumulative probability distribution. The cumulative probability distribution of the RBE is key to assess the likelihood (y-axis on the right) that the cost of a project will be at or below a value given on the x-axis. For instance, based on the cumulative RBE curve, the deterministic cost estimate of $7,696,013 is below the minimum for the RBE, indicating a near zero probability that the actual cost of the project will fall below this value. This fact should have been a red flag for the management team, as this scenario all but assures that any project risk will reduce the profits or create loss. The project had a likelihood of 96.3% of having a cost equal to or below the sales price of $10,841,045, indicating that the project had a low likelihood of generating actual losses to the contracting company. The final completion cost of $10,166,391 represents a probability of 63% based on the RBE distribution. The results confirm the importance of including risk in the base estimate for a project as no project goes exactly as planned.

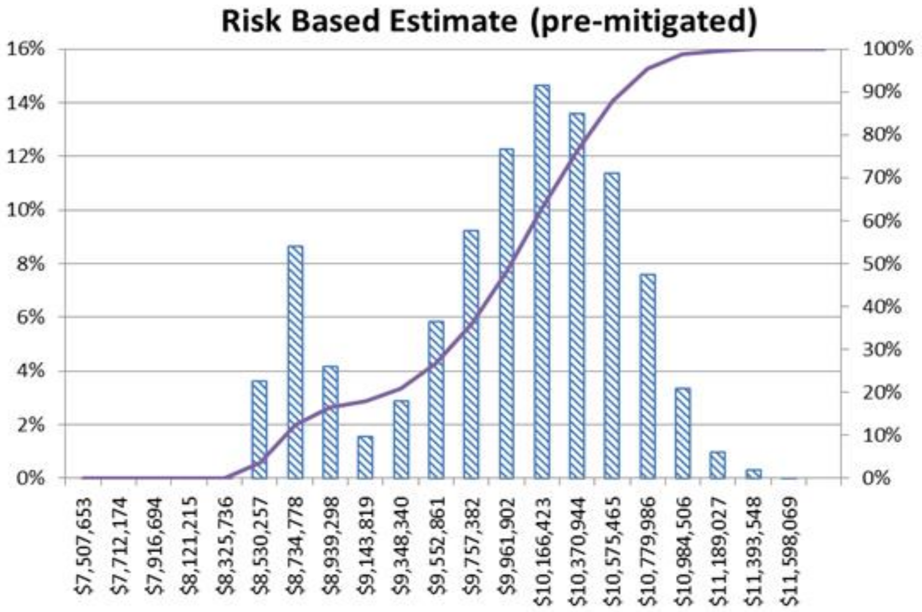


FIGURE 6. RISK BASED ESTIMATE (PRE-MITIGATED)

## TABLE 5. RISK MITIGATION PLAN

| **Risk ID #** | **Risk Description** | **Mitigation Plan** | ***P* (%) after mitgation** | |
|---|---|---|---|---|
| | | | **Low** | **High** |
| 1 | Negative Cashflow | Scheduling of milestones for positive cashflow Plan CF positve SOV with mobiliztion and retention reduction | 0% | 100% |
| 2 | Asphalt Repair/EPA issues | Continue to monitor situation. No notice or directive has been given for corrective action. | 0% | 34% |
| 3 | In-fighting with trades | Follow all contract items and follow up verbal converstaion with written coorespondence | 0% | 10% |
| 4 | Schedule slip due to technology skill of field | Continue to monitor situation and remix labor force if issues can be corrected | 0% | 30% |
| 5 | Stop bars and striping missed in schedule | Quote from subs to determine cost analysis | 0% | 5% |
| 6 | Missed Scope and Punchlist rework | PM and Field to walk with site plan again to see if all work has been complete. | 10% | 100% |
| 7 | Additional Lane Closures | Additional Lane closures from missed scope and slipped schedule | 10% | 25% |
| 8 | Unresolved change order requests from subcontractors | Review change order proposals from subs PM to review adds with field | 10% | 25% |
| 9 | Liquidated Damages for utility delay | Utility delay which was owner caused should see that LD's are removed | 45% | 100% |
| 10 | Liquidated Damages for signage in the right of way | PM to get written approval for maintence agreement for the ROW. | 10% | 55% |

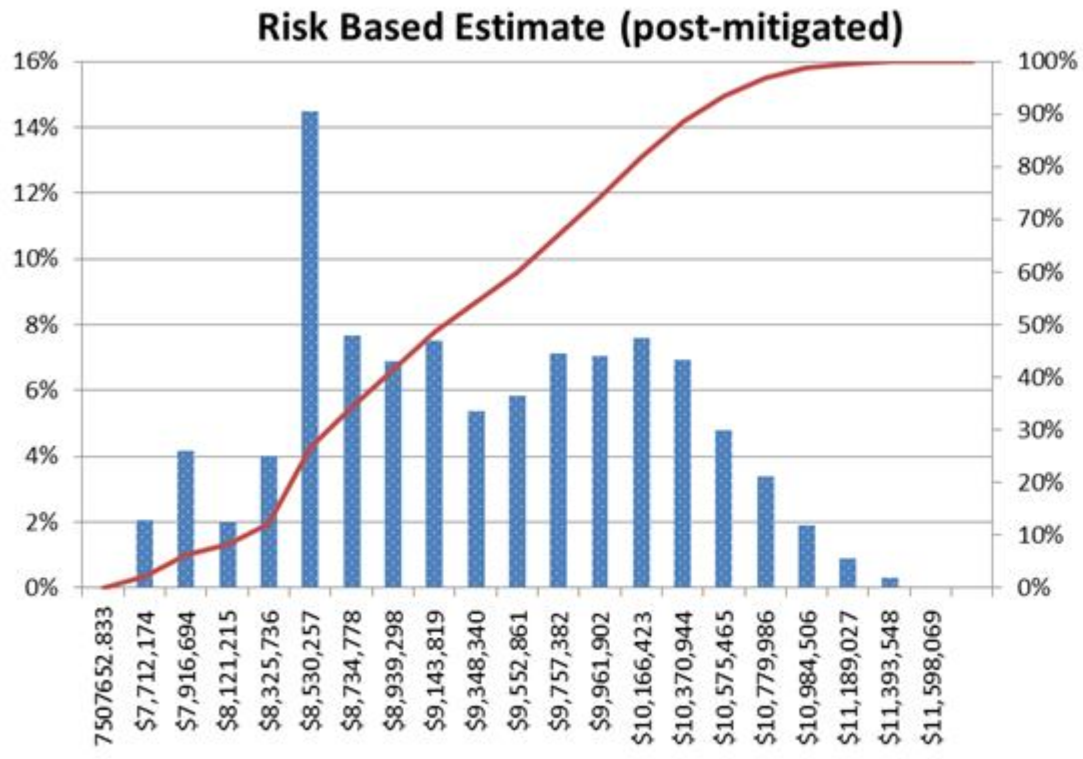


FIGURE 7. RISK BASED ESTIMATE (POST-MITIGATED)

### 6.3.3. Post-Mitigated Risk Based Estimate

The post-mitigation stage is critical for proposing methods of mitigating the effect of risks on the project. This process requires the use of small-group and one-on-one interviews, in which experts and the direct project team are involved. Table 5 shows the proposed risk mitigation plan and each the post mitigation probability of occurrence of each risk. It should be noted that the probability of occurrence for most of the risks significantly decreased after the risk mitigation process.

The post-mitigated RBE, as shown in Figure 7, displays the recalculated probability distribution for the total cost of the project based on a second round of simulation using the new mitigated risk values. Even after risk mitigation, the probability of achieving a project cost equal to or lower than $7,696,013 is only 2.2%. Additionally, the project had a likelihood of 97.7% of having an actual cost equal to or below the sales price of $10,841,045. Essentially, the analysis confirms that, even after risk mitigation, any risk occurrence would consume the profit. This result is consistent with the actual reduction in profit seen by the GC. Overall, the analysis confirms the critical need to assess the project risks before submitting a proposal to the owner.

The pre- and post-mitigated RBEs are compared in Figure 8. They show that implementing a risk mitigation plan can significantly reduce the expected cost of the project at a fixed level of certainty. For instance, at a certainty of 75%, the mitigated cost of the project would be approximately $409K less as compared to the unmitigated project cost. A plan to properly mitigate risks can significantly increase profitability by reducing the overall expected impact of risk on project cost.

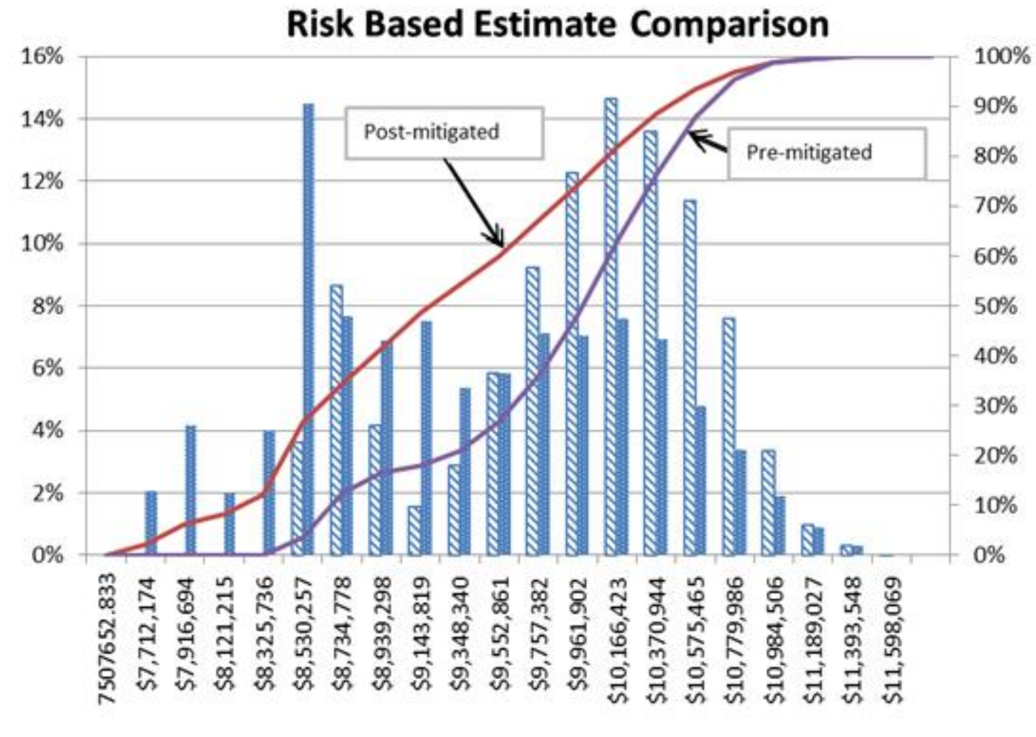


FIGURE 8. RISK BASED ESTIMATE COMPARISON

## VII. CONCLUSIONS

A methodology to assess, evaluate, and mitigate risk in infrastructure projects is proposed. The method is initiated with a conventional deterministic estimate and incorporates the estimate variability and risk through the use of Monte Carlo simulations. The proposed methodology provides practitioners and project managers with a tool to effectively evaluate the impact of risks on a project. Such a framework can facilitate the assignment of risks to the most appropriate parties during the phases of construction and allow for the proper determination of the risk contingency in the project proposal that goes to the owner.

The successful implementation of the proposed methodology on an infrastructure project in Northern California shows that the generated RBE provided insightful information about the project cost that could have been used to reassess the sales price before sending the proposal to the project owner. For instance, the post-mitigated RBE in this case scenario clearly showed that there was only a 2.2% probability that the project cost would be equal to or below the GC's deterministic estimate. This scenario was effectively predicted by the porposed methodology as seen from the RBE but was totally unknown to the GC, who used a deterministic estimate only. In this case scenario, the probability of actual losses for the GC was low, but the likelihood of significant reduction of project profit was high. This is exactly what happened in reality, as seen by the final cost of the project.

This research also highlights the potential benefits of conducting a post-mitigation analysis. As seen at 75% of certainty, mitigating risks could have resulted in $409K of savings, which at 4% of the total project cost represents considerable savings. Furthermore, this research confirms that the newly developed risk assessment methodology provides an added value of risk information that is crucial and can be utilized to evaluate quantitative effects of project risks, schedules, and budgets of *Design-Build* and *CM @ Risk* projects.

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