Development of a Cost and Environmental Impact Estimation Model Based on Monte Carlo Risk Analysis: The Warren Hall Demolition

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Urban construction and deconstruction activities significantly contribute to the deterioration of environmental systems through emissions of greenhouse gases and accumulation of solid wastes. This research develops accurate project estimates based on risk management modeling and life-cycle approaches for sustainable demolition projects. Our model relies on Monte Carlo simulations to effectively assess financial and environmental risks. It allows demolition firms to intelligently allocate allowances to a project based on stochastic results. It also gives the opportunity to establish specific eco-friendly goals in order to comply with applicable regulations, to minimize ecological impacts, and to optimize financial revenues of the project. The findings reveal that a net financial profit can be made while reducing environmental impacts and through using simulated allowances. These results have been validated on the Warren Hall Building demolition project at the California State University, East Bay.

Keywords: Sustainable demolition, Life-cycle Analysis, Monte Carlo simulation, Variability, Risk, Risk Management Process, Allowances, Contingencies.

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I. INTRODUCTION

An increasing degree of attention has been devoted in the construction management industry to the sustainable construction of buildings and infrastructure. Less attention has been placed on the deconstruction of buildings that, for a variety of reasons, are deemed to be at the end of their useful life and have become subject to demolition. Sustainability principles and practices should equally apply to this end-of-life phase, not only in designing new buildings ready to maximize reusability and recyclability and minimize costs and impacts, but also in the destruction of existing buildings. Building deconstruction generates an enormous quantity of solid waste, a significant proportion destined for landfills in many locations due to contamination and the lack of economically viable recycling opportunities. The U.S. Environmental Protection Agency estimated that approximately 136 million tons of building-related construction and demolition (C&D) wastes were generated in 1996 (Yuan, Shen, Jane, Hao, and Lu, 2010) and 143 million metric tons in 2005 (Yuan, Abdol, Lu, and Shen, 2011). A large proportion of this solid waste (48%) was associated with demolition activities. Demolition waste is usually heterogeneous and can include hazardous substances that may pose a significant health risk for local residents and workers. In order to mitigate such effects, both governmental agencies and green building rating systems (e.g., LEED and Green Globes) have implemented measures that promote recycling or down cycling of construction waste, thus minimizing the amount of materials sent to landfills. In California, the authority that enforces current laws that ensure air, clean water, and waste recycling is the California Environmental Protection Agency (Cal/EPA). Title 14 of the California Code of Regulations (Division 7, Chapter 3, Article 5, and Sections 17301 through 17359 - State of California December 23, 2014) explicitly lists all minimum requirements related to solid wastes generation in demolition projects and mandates a significant portion be diverted from the waste stream into reuse and recycling. This is mirrored, to varying degrees, in local ordinances at the municipal level (City of Hayward, 2009).

One of the biggest challenges when managing C&D waste in an environmentally friendly manner is to ensure the proposed solutions are also economically feasible (Banias, Achillas, Vlachokostas, Moussiopoulos, and Tarsenis, 2010). The determination of the optimal financial-environmental balance can be achieved by using cost-benefit analyses. Zhao and Ren (2011) analyzed complex dynamic feedback systems for the waste management chain. They have determined that the profit, unit recycling costs, and potential extra revenues are the three key factors that can contribute to the economic feasibility of recycling. Yuan, Shen, Jane, Hao, and Lu (2010) focused on the minimization of resource consumption and alleviation of environmental pollution. They proved that a higher charging scheme (landfill charges) would lead to increased implementation of sustainable practices. James, Wang, Touran, Christoforou, and Fadlalla (2004) used mass balance principles and integrated waste management processes to evaluate cost-benefit alternatives through various stages of the waste management chain. They confirmed that a realistic model must rely on quantifiable results. In a similar way, Banias, Achillas, Vlachokostas, Moussiopoulos, and Papaioannou (2011) combined environmental and economic factors through multi-criteria assessments to determine the optimum recycling facility location.

While the aforementioned models help optimize the waste management process, they do so only for deterministic scenarios, ignoring the high level of unpredictability associated with the demolition process such as environmental impacts, the increased use of resources to manage the demolition process (increasing life-cycle effects), and financial factors. Gravina and Aloysio (2009) confirmed that uncertainty can be generated by social, political, and economic factors as well as unique local factors (recycling facilities, local businesses, regulations, etc.). For example, the percentage of a specific material type being recycled on a project can vary significantly from another one in a different location due to site-specific issues, local regulations, potential contamination or other unforeseen conditions.

In such unpredictable environments, implementing a risk management process to obtain a risk-based estimate (RBE) is preferable to a conventional deterministic estimate.

The risk-based estimate (RBE) is obtained by completing a risk management process (RMP), which includes four steps: risk identification, risk analysis, risk evaluation, and risk monitoring (Wylie, Gaedicke, Shahbodaghlou, and Ganjeizadeh, 2014; Cretu, Stewart, and Berends, 2011; Tummala and Burchett, 1999). The risk identification and analysis are key steps in the RMP as they provide the inputs (i.e. probability of occurrence; low, most likely, and high impact) to be used in the risk analysis model (Wylie, Gaedicke, Shahbodaghlou, and Ganjeizadeh, 2014; Cretu, Stewart, and Berends, 2011; Cretu, 2009; Smith, Merna, and Jobling, 2006).

Risk-based estimates (RBE) have successfully been used in the construction industry to quantify the effect of risk on a project's actual cost and schedule (Cretu, 2009). Van Dorp and Dufey (1999) used Monte Carlo simulations to model and quantify the statistical dependence between uncertain activities within a project network. Wylie, Gaedicke, Shahbodaghlou, and Ganjeizadeh (2014) developed a Monte Carlo based model to evaluate risk in infrastructure projects. These models use the risk management process in order to structure the assessment of uncertainties in the risk identification phase, analysis phase, evaluation phase, and risk monitoring phase. Smith, Merna, and Jobling (2006) proposed that uncertain and unpredictable events can be organized in the following three groups summarized in Table 1: (a) known risks or variability, (b) known-unknowns, and (c) unknown-unknowns.

Allowances are pools of funds set aside to cover unexpected events that could foreseeably happen due to the particular nature of the project. The allowances are determined by the general contractor as part of the estimate and are determined based on the estimator's experience or using advanced probabilistic methods. An allowance protects the project owner by capping the amount of funds a general contractor can charge for events covered by that given allowance (PMBOK Guide, 2000). Also, the funds are only used if an event covered by the given allowance occurs. In contrast, a *Construction Management (CM) Contingency* is used to manage risks not foreseeable when producing an estimate. These risks (unknown-unknowns) cannot be approximated and they are usually established as a fixed percentage of total direct costs (predetermined by the procurement type, clients, etc.).

Existing risk-based models fail to recognize the dynamic nature of environmental impacts directly related to risks identified. These models insufficiently enhance the ability of a contactor to set clear, achievable, accurate, and realistic ecological goals. They do not facilitate the development of financially profitable estimates combined with optimum eco-friendly solutions. Furthermore, these methods do not provide adequate monitoring and tracking tools that could be useful throughout the execution phase of demolition projects.

The objective of this research is to propose and verify a method to evaluate and mitigate the financial and environmental risks associated with the demolition of infrastructure and buildings. In particular, the proposed method aims to objectively use the risk assessment to estimate the project allowances while facilitating strategic decisions that jointly optimize financial profits and sustainable practices, then helping practitioners target cleaner practices in unpredictable environments.

The implementation of the proposed method will help answer a key question in the demolition industry, which is how to determine accurate allowances in a sustainable demolition estimate. This question will be answered by comparing the probabilistic estimate for allowances delivered by the model with the estimator's allowances and true final costs in the project. A key contribution of this research project is to provide an assessment system that allows contractors to accurately assign allowances while increasing their competitiveness during the bidding phase, mitigate unpredictable events associated with environmental factors, and help contractors deal with risks inherent in a demolition project.

TABLE 1. RISK GROUPS.

Risk Group	**Description**	**Impact on Budget**
Known risks or variability	Small variations that occur in all projects especially due to slight changes in material costs or quantities.	Variations associated with market conditions and present in all projects.
Known-unknowns	Identifiable risks with foreseeable probability of occurrence.	Generally addressed in a budget by "**allowances"** and paid through change orders. For example, an allowance may be assigned to cover unexpected conditions due to insufficient information, such as missing existing underground utilities drawings details where excavation activities are needed.
Unknown-unknowns	Those risks are difficult to identify and predict during the pre-construction phase. They are neither necessarily foreseeable nor quantifiable when establishing the original estimate.	It is usually calculated as a fixed percentage of direct costs (i.e. 1%-3% of the direct costs in all Construction Management at Risk contracts in the California State University system). The word "**contingency**" is used to cover unforeseeable risks that the contractor has not considered as known unknowns at the time of the estimate. These risks are the sole responsibility of the contractor.

II. MODEL DEVELOPMENT

We constructed a model to evaluate deconstruction projects and to generate risk-based estimates. The outputs of the proposed model are financial and environmental. The financial outputs include the project cost probability curve and the contingencies estimate for a given level of risk. The environmental outputs include probability curves for the following parameters: CO_2 equivalent, CFC equivalent, H_2 equivalent, O_3 equivalent. These four parameters were selected due to their level of significance in overall construction materials evaluated and their well-known adverse effects on the environment (global warming for CO_2, ozone depletion for CFCs, acid rains for H_2, and smog for O_3). The model inputs are the (risk-free) project cost (PC) for the deconstruction project, environmental parameters associated with each deconstruction activity, variability, and elicited risks (ATHENA Institute 2015).

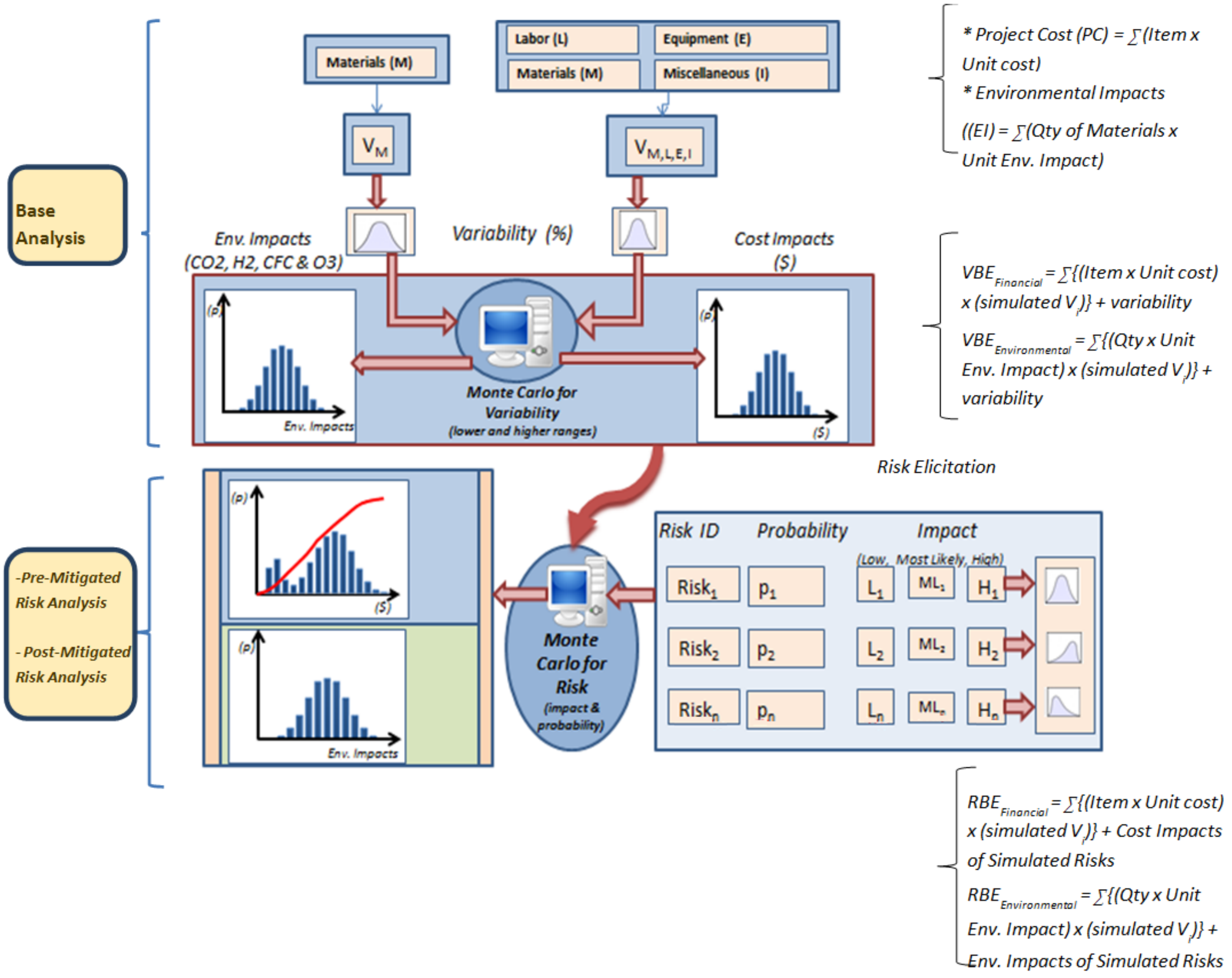
Our model defines the variability and the impacts of each risk by utilizing Beta distribution estimates similar to Program Evaluation and Review Technique (PERT) analyses (Malcolm, Roseboom, Clark, and Fazar, 1959), which are characterized by three key estimates: *optimistic*, *most likely,* and *pessimistic*. These three values are obtained from experts for each risk as part of the risk elicitation process. As illustrated in Figure 1, when analyzing the impact of risks, we associate the optimistic, pessimistic, and most likely scenarios to a low (L_i), most likely (ML_i), and high (H_i) impact. Finally, the Monte Carlo (MC) method is used to analyze the combined effect of the statistical distributions and other stochastic components in the model. The MC method has been previously used in risk analysis due to its simplicity, reliability, and capacity for accounting for and computing a large number of risks (Wylie, Gaedicke, Shahbodaghlou, and Ganjeizadeh, 2014; Cretu, Stewart, and Berends, 2011; Cretu, 2009; Wei, Ya-nan, Wei-Dong, and Dan, 2009; Van Dorp and Dufey, 1999).

The model uses Microsoft Excel due to its wide availability and straightforward interface, which easily allows model updates by a user if desired. Cretu, Stewart, and Berends (2011) compared the results generated by a Monte Carlo simulation on Microsoft Excel (5,000 iterations) with those produced by dedicated simulation software, yet did not find a significant difference.

The overall structure of our proposed Sustainable Demolition Risk Analysis Simulator (SDRS) model is presented in Figure 1. As shown, the SDRS is divided into three major modules: (a) Base Analysis, (b) Pre-Mitigated Risk Analysis, and (c) Post-Mitigated Risk Analysis.

2.1. Base Analysis

The first input for the SDRS is the project cost (PC) determined by the contractor, which includes the following items: materials (M), labor (L), equipment (E), and other fixed costs (I) associated with the project based on quantities and unit prices. These costs do not include effects of variability, project risk, or profit. The project cost (PC) is different than the *Contractor's Estimate (CE)*, which usually includes additional reserve funds to consider both fluctuations associated with market conditions and unpredictable events that may be associated with the project (PMBOK Guide, 2000). These cost items can sometimes be denoted as *Allowances* included in the original cost baselines or *Contingencies* included in the budget but not the overall cost baseline.



*Project Cost (PC) = $\sum$(Item x Unit cost)

*Environmental Impacts ((EI) = $\sum$(Qty of Materials x Unit Env. Impact)

$VBE_{Financial} = \sum\{(\text{Item x Unit cost}) \text{ x } (\text{simulated } V_i)\} + \text{variability}$

$VBE_{Environmental} = \sum\{(\text{Qty x Unit Env. Impact}) \text{ x } (\text{simulated } V_i)\} + \text{variability}$

$RBE_{Financial} = \sum\{(\text{Item x Unit cost}) \text{ x } (\text{simulated } V_i)\} + \text{Cost Impacts of Simulated Risks}$

$RBE_{Environmental} = \sum\{(\text{Qty x Unit Env. Impact}) \text{ x } (\text{simulated } V_i)\} + \text{Env. Impacts of Simulated Risks}$

FIGURE 1. THE SUSTAINABLE DEMOLITION RISK ANALYSIS SIMULATOR.

The second input in the model is the environmental impact (EI) associated with each unit of material or assembly (including labor). The unit impact values are widely reported in the literature; for example, see the ATHENA impact estimator (ATHENA Institute 2015), the Building for Environmental and Economic Sustainability software tool (NIST 2015), the EPA inventory of U.S. greenhouse gas emissions and sinks (U.S. EPA 2013), and the review by Cucek, Klemes, and Kravanja (2012) of footprint analysis tools for monitoring impacts on sustainability. The overall impacts are computed by multiplying the unit impact values (e.g. tons of CO_2 equivalent generated for each ton of concrete) by the total quantities of items associated with each impact on the project (e.g. total amount of concrete in tons). The sum of each environmental impact multiplied by its respective quantity gives the Environmental Deterministic Estimate (EDE).

After the cost and environmental impact estimates are completed, a variability (*Vi*) is assigned to each item (*i*) to produce variability-based estimates (VBE) of the project cost (PC) and environmental impact (EI) (i.e. global warming potential, ozone depletion, acidification potential, and smog factor). It is important to keep in mind that the variability consists only of normal variations in quantity associated with a given activity or material, assuming a base scenario where everything is happening as expected. Therefore, variability tends to be symmetrical and relatively small compared to each items' quantity. A symmetric PERT-BETA distribution is used to simulate the variability through the most likely value (*MLi*), the lower value (*Li*), and upper value (*Hi*) as described in Wylie, Gaedicke, Shahbodaghlou, and Ganjeizadeh (2014). The use of such an approach is consistent with research by Bianchini and Hewage (2012), which suggested that the use of probabilistic analyses to assess EIs can play a key role in cost-benefit analyses. Finally, a Monte Carlo simulation is run to obtain the VBE, which is a set of statistical distributions representing the PC and each environmental factor, respectively.

2.2. Pre-Mitigated Risk Analysis

Risk Elicitation: Identification and Categorization

The identification and elicitation of risks is the step that follows the calculation of the VBE. This step is crucial to obtain all inputs that are necessary to generate the Risk Based Estimate (RBE). Each elicited risk is categorized by *phase, responsibility, status,* and *type*, which allows the development of adequate strategies to manage and mitigate the risk impacts as suggested by Samani and Shahbodaghlou (2012). Quantitatively, each risk will be represented by a *probability of occurrence* and impact, defined by its *most likely (MLi), optimistic (Li),* and *pessimistic* value (*Hi*) estimates using the PERT-Beta distribution as discussed previously (Davis, 2008).

First, each risk is identified and quantified. Risks are then classified and grouped based on their type. Such classification has a significant importance especially when it comes to tracking their cost impacts throughout the entire project's execution. Managers can easily anticipate and develop work plans with appropriate sources of funds that could be used to take a specific action regarding a risk (avoiding, mitigating, accepting, or transferring).

Risk Based Estimate, Allowances, and Contingencies

After the identification and categorization phases, each elicited risk will be defined by its probability of occurrence (P) and impact (L, ML, H). The model will only assign an impact to a risk that has occurred using the following algorithm, where R_1 and R_2 are random numbers:
If $P>R_1$, then the risk is materialized on the particular iteration and the impact is a PERT function of a second random number (R_2), the lowest (L), highest (H), and most likely (ML) impact values.

The RBE combines the distributions for the variability-based estimates and each elicited risk. Depending on the risk, impacts could be financial, environmental, or a combination of both. The RBE probability curves for financial and environmental impacts are obtained after generating 10,000 iterations.

As shown in Figure 3 and the risk elicitation section of Figure 1, the probability curve for the impact of the risks can be used to determine the simulated allowances given a certain risk tolerance. These simulated allowances can be compared to the values given in a contactor's estimate. This procedure eliminates the guesswork from the allowance determination process while capturing the effect of unknown costs that might be hidden in the base estimate unit costs.

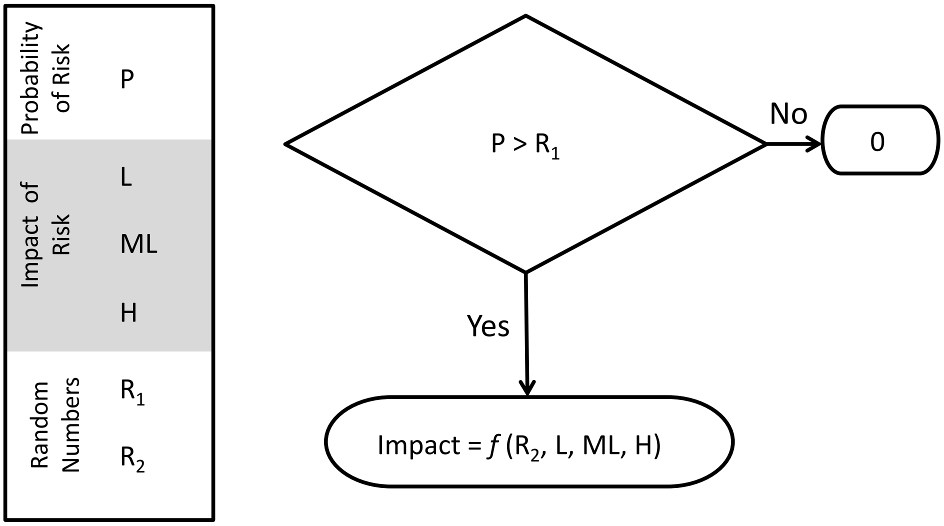


FIGURE 2. RISK ASSESSMENT ALGORITHM.

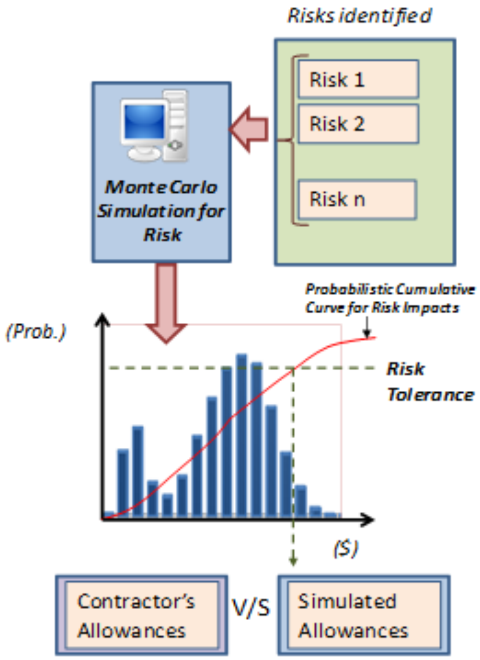


FIGURE 3. RISK ANALYSIS ALGORITHM – ESTIMATION OF ALLOWANCES

2.3. Post-Mitigated Risk Analysis

Risks are identified, assessed, and quantified during the pre-mitigated risk analysis. The post-mitigated risk analysis provides tools to adequately monitor and control all unpredictable events listed during the pre-mitigated risk analysis process. During the post-mitigated risk analysis, mitigation plans and risk response strategies are developed to properly manage and respond to risks. Common risk response strategies are to avoid, reduce, accept, or transfer a risk. The post-mitigated risk analysis allows responding to specific risks listed and assessed during the pre-mitigated risk analysis phase. The nature of the response is crucial to the risk management process. It has the capability to significantly improve project management practices and effectively monitor PCs and EIs.

The algorithm for the post-mitigated risk process is very similar to the way pre-mitigated risk response strategies and risk triggers (when to apply the response strategy) are established to control and mitigate the effects of unpredictable scenarios. Response strategies and risk triggers must be well communicated to the entire project team. The success of the risk management process simultaneously relies on both the risk elicitation process and the ability of the team to adequately respond to risks (Cretu, 2009). The SDRS facilitates the evaluation of the efficiency of a particular response plan by comparing the cost and environmental impact curves of the post-mitigated risk analysis to the pre-mitigated risk analysis and deterministic estimate.

III. MODEL VALIDATION

3.1. Case Study - Warren Hall Demolition Project and Contractor's Estimate

The Warren Hall building was constructed on the California State University, East Bay campus in 1973. It had been a landmark in the Hayward area for about 40 years. This thirteen-story reinforced concrete building, located near the Hayward fault, had a significant likelihood of suffering considerable damage or failure from an earthquake with a magnitude equal to or greater than 7.0 on the Richter scale. After evaluation of multiple alternatives, the total deconstruction of this structure and a new replacement building (different site) was determined to be the most economical decision.

The Warren Hall building was directly connected to the existing Library building by a two story pedestrian bridge (directly over one of the campus's main road, West Loop road), adding more challenges to the deconstruction project. The demolition of this 145,000 square feet building anticipated generating about 11,000 tons of debris to be hauled off site. Each floor had an average area of 12,000 square feet. In addition, supplementary evaluations concluded that there were high risks of encountering hazardous materials such as unexpected asbestos and PCB's becoming a significant threat to both the student community and workers if not correctly abated.

Due to the unknowns associated with the demolition of Warren Hall and overall nature of the project, a Design-Build contract was selected as the most suitable procurement method. The contractor was then responsible for undertaking abatement works, demolition, and any potential design required while being accountable for all means and methods. The scope of work included civil, architectural, mechanical (mainly HVAC), plumbing, electrical, hazardous materials, and fire protection works. When necessary, a fixed amount, specific allowance, was attributed to major groups or phases (e.g. allowances for abatement works, mechanical, electrical etc.). These fees were determined by experienced estimators based on past experience and existing building conditions (existing documentation and preliminary surveys). These allowances were part of the contractor's direct costs and they were initially agreed upon by both the contractor and the client. The estimate given by the contractor is summarized in Table 2.

FIGURE 4. WARREN HALL BUILDING – BEFORE AND AFTER IMPLOSION.

TABLE 2. CONTRACTOR'S ESTIMATE (CE).

Project Cost (Materials, equipment, and labor)	$6,051,913
Allowances (Included in direct costs)	$1,999,478
Total Direct Costs	**$8,051,391**
Contingencies (2% of total direct costs)	$160,795
***Total**	$8,212,186

**Note*: The values presented in this table do not include the contractor's profit and construction management fees (*CSU East Bay, Department of Construction, unpublished construction estimate, 2013*).*

The CE earmarks funds to the project allowances to mitigate the risk of unknown events that could occur due to a known issue or concern. For example, the known fact that part of the project specifications were missing could generate an unknown event such as unexpected hazardous materials in the building. The cost of removing such unexpected hazardous materials would be covered by the allowances. As is common in the demolition industry, in this project, the allowances were established by the general contractor based on the estimator's experience, without the use of advanced modeling procedures and risk management concepts. This situation generally leads to allowances being either too low or high.

In the following sections, we will compare the allowances determined by the contractor to allowances calculated based on risk analysis and the SDRS model.

3.2. Risk Based Analysis

Data Collection and Risk Elicitation

A multi-disciplinary team periodically met to discuss waste management practices throughout the project's execution. This team consisted of the general contractor, demolition contractor, and owner's representatives. The owner was represented by a risk management professional, an environmental health and safety professional, director of construction, and a graduate research student. Data was collected on a weekly basis from January 2013 (beginning of the project) till January 2014 (5 months after the building implosion). Results were analyzed and entered into the SDRS model to evaluate risks and environmental impacts associated with the project. Complementary information on potential project risks came from demolition companies in the San Francisco Bay Area and other inputs from local construction professionals. Particular attention was directed to how allowances were allocated in demolition projects and how traditional demolition procedures could be turned into a sustainable process.

Project managers, project directors, professors, and vice-presidents/presidents from other demolition firms were interviewed. The purpose of this process was to capture variable costs impacts of all of identified risks and their probability of occurrence based on their experience. The information was gathered and averaged before being used in the model (e.g. recycling unit costs, probabilities of occurrence etc.). The amount of materials recycled and hazardous materials were provided by the California State University East Bay – Department of Construction and Planning. The relationships established and findings are detailed in the Methodology and Results sections.

The allowances used in the original budget represented approximately 5 to 10% of each group of items costs (mechanical, plumbing, electrical, interior work, etc.). These values were agreed between owner and contractor based on studies conducted during the pre-deconstruction phase. These fixed reserves were established to cover the high level of uncertainty associated with hazardous materials (asbestos, PCB, lead, etc.), missing as-built documentation (blueprints and specifications) and other foreseeable challenges.

Table 3 summarizes the risks identified throughout the project execution related to allowances.

As part of the risk management process, each risk needs to have a given owner responsible to accurately track its effect, to understand response strategies, and to be able to successfully close all related issues accordingly. This ensures that all managers involved in the construction or execution phase will clearly understand the risks identified and the goals of risk ownership. We recommend color-coded systems (red, yellow, and green), risk scales (1 – 100), and impact levels (critical, severe, moderate, and minimal) to visually track and communicate the importance of every single risk throughout the project. Relevant data was collected and used to determine the reliability of this model just as recommended by James, Wang, Touran, Christoforou, and Fadlalla (2004). The SDRS shows the effect of the variability and compares the impacts of known-unknowns risks calculated as allowances (paid with change orders) and any other unforeseen conditions. The level of confidence has a direct impact on the overall results (costs and environmental factors). This finding was also predicted and confirmed by Smith, Merna, and Jobling (2006).

TABLE 3. LIST OF RISKS: PROBABILITY OF OCCURRENCE AND FINANCIAL IMPACTS.

Risks	Descriptions	Min Cost ($)	Max Cost ($)	Most Likely Cost ($)	Probability of occurrence (%)
1	Insufficient information related to the curtain wall installation to existing Library	120,000	150,000	135,000	75%
2	Possible contaminated fire-proofing materials in steel framing.	20,000	25,000	23,000	60%
3	Missing interiors drawings details.	20,000	40,000	30,000	15%
4	Engineering for Library roof drains and jetting of existing library roof drains – potential unforeseen issues.	11,000	16,000	14,500	70%
5	Electrical acceleration and relocation of repeater. Possible issue with annunciator panel not relocated.	19,200	23,000	21,000	45%
6	Unforeseen conditions related to demo/abatement of AHU-1, salvage flag pole, removal of cellular equipment, and existing beam repair.	210,000	231,450	216,000	78%
7	Abatement works – potential issues with furniture to be moved, contaminated PCB curbs remediation and ACM on window system.	241,000	255,000	248,000	64%
8	Possible grading needed after the building's implosion	450,000	490,000	470,000	15%
9	Potential damages of landscaping surrounding the building.	520,000	560,000	532,000	93%
10	Additional protection maybe needed after demolishing the east wall. Acoustical wall might be needed.	50,000	100,000	78,000	50%
11	Concrete panel removal – details missing	7,800	11,200	10,000	60%
12	Potential misses and scope gaps not covered by the owner	50,000	100,000	75,000	75%
13	Shortage of manpower due to high season for demolition projects	100,000	125,000	110,000	25%

Simulations

Base Analysis: the project cost (PC) including labor, equipment, and materials was determined by the contractor to be $6,051,913. This cost does not include the effect of variability, nor does it include the effect of the project risks.

Variability Analysis: In order to account for the PC variation, a ±2.5% variability was applied to all unit costs (including materials and labor). The same variability was used for simulated environmental impacts. These figures are in line with previous research data (Wylie, Gaedicke, Shahbodaghlou, and Ganjeizadeh, 2014). The PERT-Beta formula was used to simulate the variability. The effect of simulated variability was combined with each unit cost and environmental impact unit in order to generate probabilistic distributions.

The variability-based estimate (VBE) for the project combines the PC and effect of variability. As shown in Figure 5, the probabilistic distribution of the total cost varied between $5,929,102 and $6,116,943.

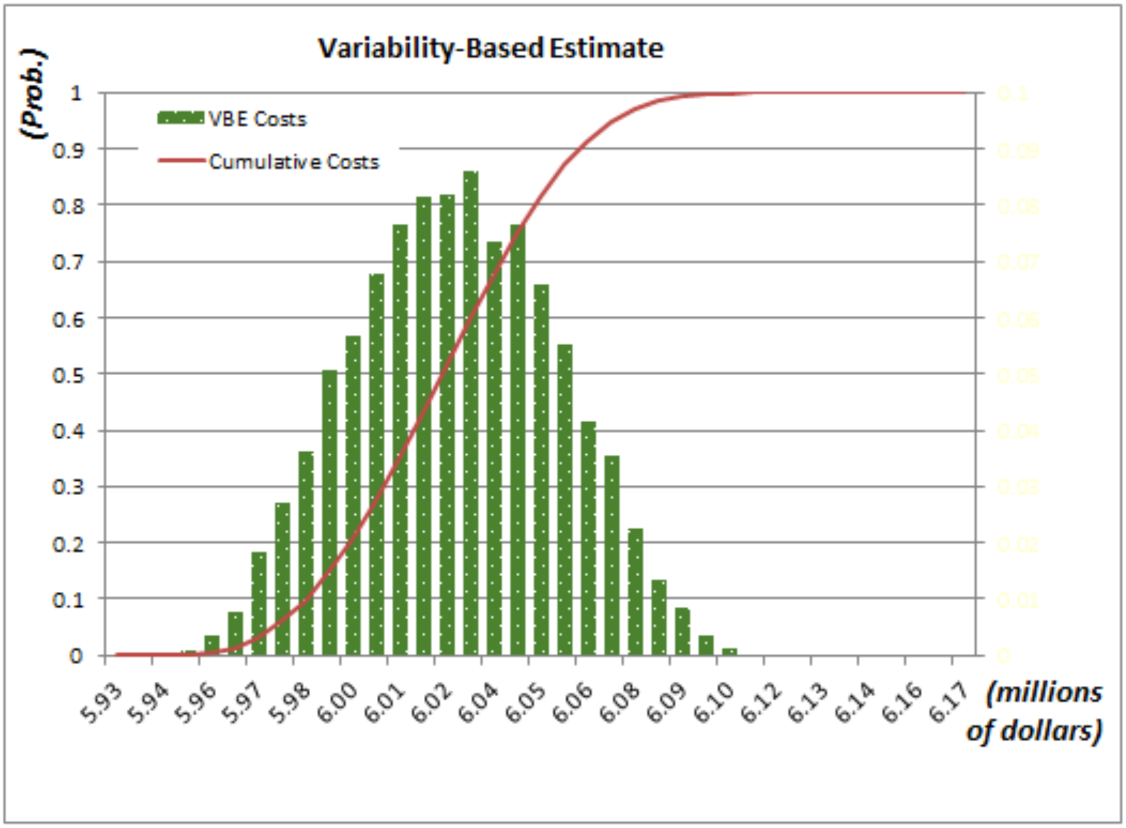


FIGURE 5. TOTAL COST DISTRIBUTION (VBE).

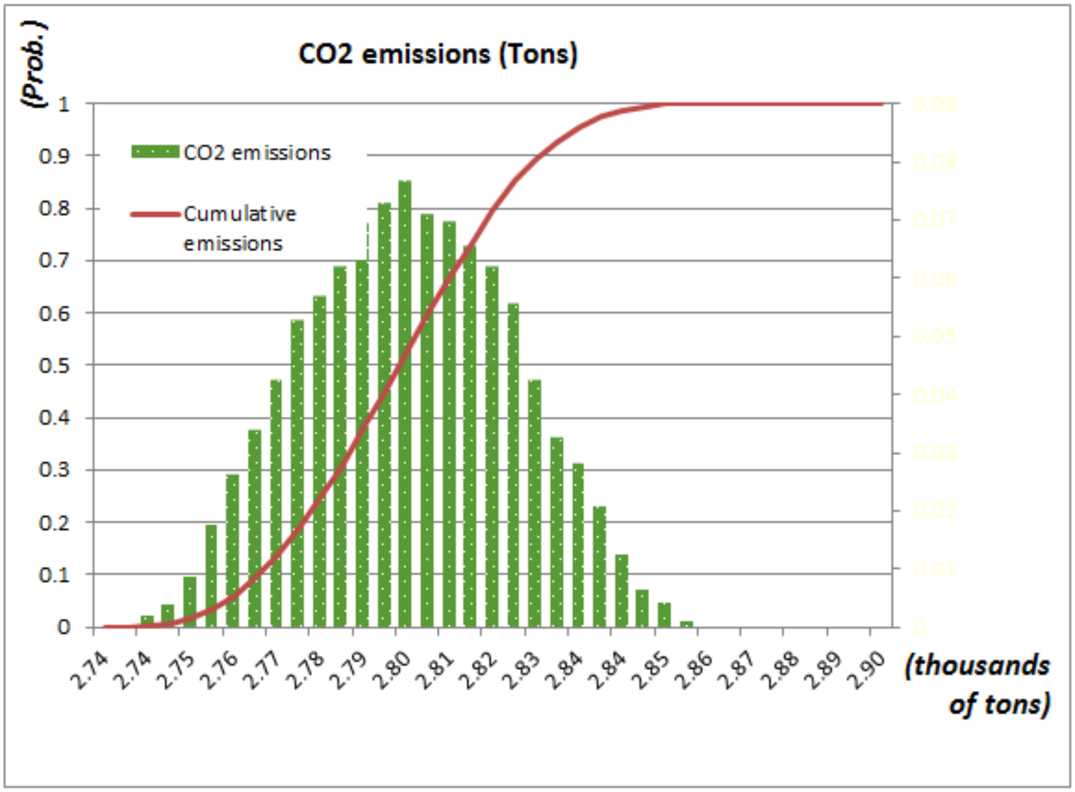


FIGURE 6. CO_2 EMISSIONS GENERATED.

As represented in Figure 6, the environmental impact analysis of the demolition process simulated with the same +/-2.5% variability through the VBE shows that the generated carbon dioxide associated with the demolition process varied between 2,737 tons and 2,858 tons (emissions associated with the building's lifecycle, from extraction and construction to the end of life). Results obtained can be very useful when it comes to running sensitivity analyses (i.e. desired diversion rate, maximum CO_2 emissions, etc.) and comparing multiple scenarios.

Pre-Mitigated Risk Analysis:

Costs and variability were used as inputs to simulate the financial and environmental RBEs for elicited risks indicated in Table 3. As shown in Figure 7, the simulated total cost of the project can be represented by a cost histogram and cumulative probability curve. As shown in this figure, the RBE cost at 95% certainty was $7,368,095. This cost is 8.49% lower than the *total direct costs* in the Contractor's Estimate (CE). Based on the risk analysis, the likelihood of the actual project cost's being above the contractor's total direct cost of $8,051,391 is below 0.1%.

The real costs incurred by the contractor after completion of the project were $7,240,367, which equals an 86% probability on the simulated cumulative curve. These results confirm that the model was able to predict the actual project costs. It should be noted that an enhanced risk elicitation process might have identified additional risks, which could have slightly increased costs and shifted the histogram to the right. In this case, the likelihood associated with the real project costs might have been closer to 50%.

An important aspect of the RBE is the capability of generating probabilistic estimates for the allowances. The combined effect of risks 1 to 13 (see Table 3) was simulated to obtain the probabilistic curve for project allowances. As shown in Figure 8, the histogram indicates that such risks could have an effect on the cost of the project that ranges from $72,977 to $1,820,457. This distribution could be used by the lead estimator to objectively determine the funds assigned to the project allowances. In this particular case, at a cumulative probability equal to 95%, the cost of the allowances would be $1,334,191. The allowance obtained in the pre-mitigated risk analysis is 33.27% lower than the one established by the contractor ($1,999,478 as shown in Table 2). However, this happened because the contractor overestimated the occurrence of events that were proven not applicable to the project. While the overestimation of the allowances did not hurt the contractor in this particular case, it could have caused the owner to choose a different contractor with a competing bid; therefore the overestimation of allowances is not free of negative consequences. This example emphasizes the importance of objectively assessing the allowances and using a risk based model such as SDRS for a thorough analysis before delivering the final estimate.

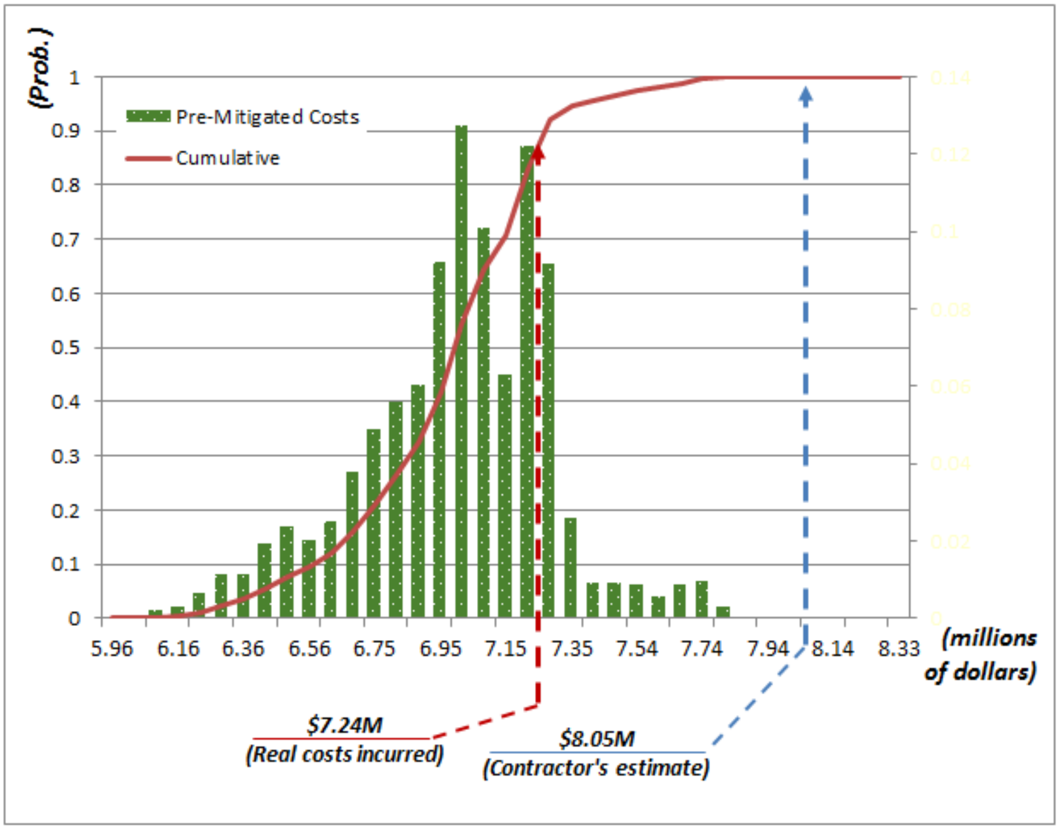


FIGURE 7. PRE-MITIGATED COST ESTIMATE (TOTAL DIRECT COSTS).

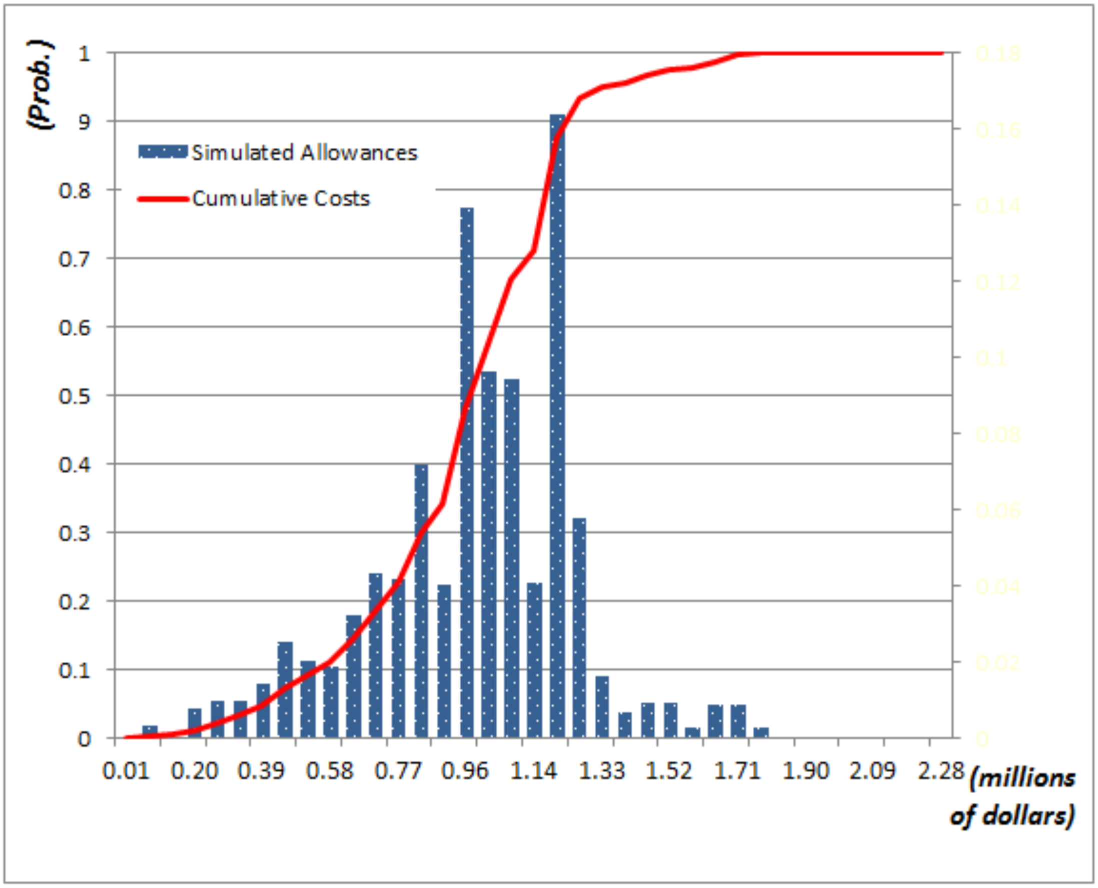


FIGURE 8. SIMULATED ALLOWANCES.

The RBE simulation can also be used to assess the EI generated by risks. As shown in Figure 10, the simulated CO_2 emissions are higher than those calculated in the VBE. This difference is tied to the fact that risks 1, 4, 7, and 8 in Table 3 have an impact in terms of extra CO_2 emissions upon occurrence (added materials). For instance, there is a 95% probability that the CO_2 emissions in this project are 2,834 tons or less. Such predictions are especially useful when dealing with emissions that are regulated and have fines or penalties associated with passing a set threshold.

Post-Mitigated Risk Analysis:

The post-mitigated analysis is the most important step after identifying risks on a project, as it provides the opportunity to reduce the risk probability and impact. In this project, the impacts of eight risks were reevaluated after the post-mitigated analysis. The response strategies and updated impact and probability are summarized in Table 4.

The histograms for both post-mitigated and pre-mitigated costs are represented in Figure 10. This figure shows that the most likely total cost after the post-mitigation risk analysis occurs before the one with the pre-mitigated risk analysis. At a 95% confidence level, the post-mitigated risk analysis simulated a total cost of $7,169,047, which is $199,048 less than the pre-mitigated risk analysis ($7,368,095). The real costs incurred by the contractor after completion of the project ($7,240,367) falls between the pre- and post-mitigated simulated cost (95% probability), which indicates that the contractor could have further increased his profit by engaging in a systematic risk mitigation process.

Therefore, implementing a risk mitigation plan can significantly reduce the expected cost of the project at a fixed level of certainty. A plan to properly mitigate unpredictable events can significantly increase profitability by reducing the overall expected impact of risk on project cost.

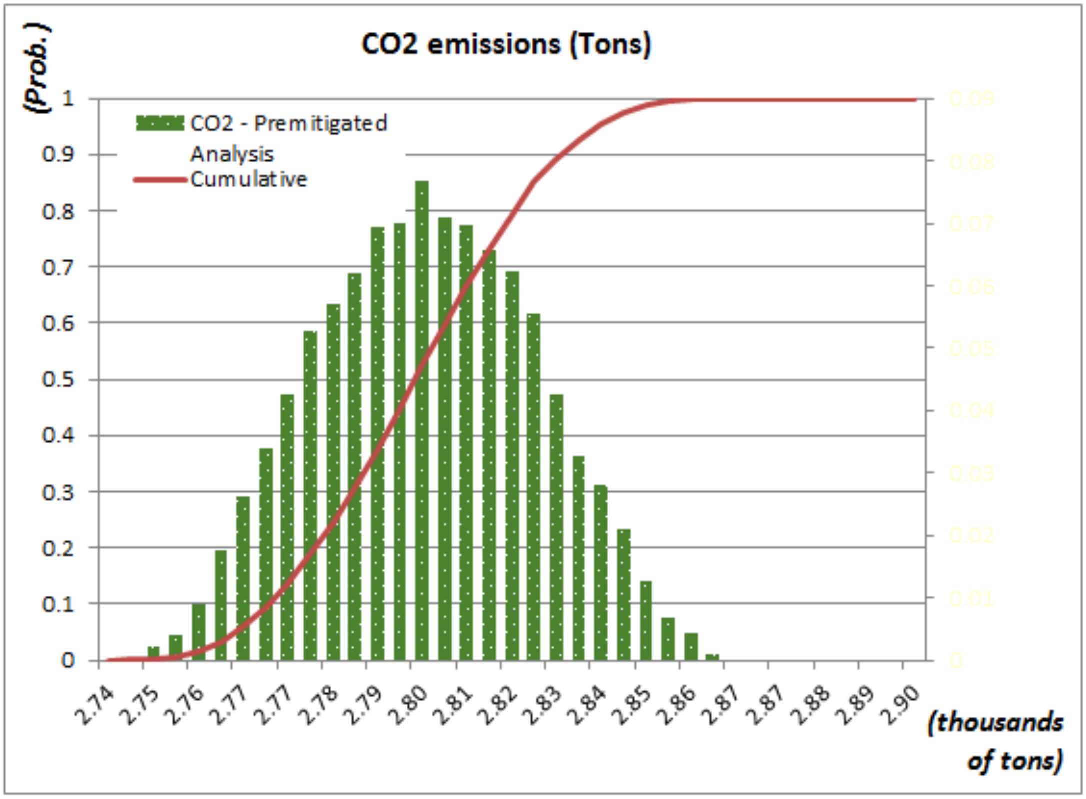


FIGURE 9. CO_2 GENERATED AFTER PRE-MITIGATION.

TABLE 4. RISK RESPONSE STRATEGIES DEVELOPED DURING THE POST-MITIGATED RISK ANALYSIS.

Allowances Risks	**Risks Description**	**Response Strategies**	**Min Cost ($)**	**Max Cost ($)**	**ML Cost ($)**	**Probability of occurrence (%)**
1	Insufficient information related to the curtain wall installation to existing Library	Engineering of curtain wall connection details from early stages. Identification of potential issues that may possibly compromise the installation based on existing conditions – on-going discussions.	120,000	150,000	135,000	55%
2	Possible contaminated fire-proofing materials in steel framing.	Revision of drawings and collaboration with design team. Identification of potential contaminated areas in early phases communicated to all trades – follow-up coordination meeting.	10,000	15,000	12,000	42%
4	Engineering for Library roof drains and jetting of existing library roof drains – potential unforeseen issues.	New alternative suggested (value engineering). Using thin concrete slab or grouts for slopes in lieu of demolition roofing system in place.	5,000	6,000	5,500	70%
6	Unforeseen conditions related to demo/abatement of AHU-1, salvage flag pole, removal of cellular equipment, and existing beam repair.	Hire a consulting firm to conduct a new asbestos evaluation using previous data (from Huntsman Group) and original drawings.	190,000	225,450	208,000	56%
7	Abatement works – potential issues with furniture to be moved, contaminated PCB curbs remediation and ACM on window system.	Third-party hired entity to test all areas that may potentially contained asbestos and other hazardous materials.	220,000	240,000	228,000	64%
9	Potential damages of landscaping surrounding the building.	Plan to optimize the protection of existing landscape during demolition process. Establishment of clear and concise work plans.	450,000	500,000	485,000	75%
10	Additional protection maybe needed after demolishing the east wall.	Weekly coordination meeting to be scheduled. Continuous discussions.	20,000	100,000	67,000	50%
13	Shortage of manpower due to high season for demolition projects	Strong baseline schedule established to keep a consistent demolition work flow.	100,000	125,000	110,000	5%

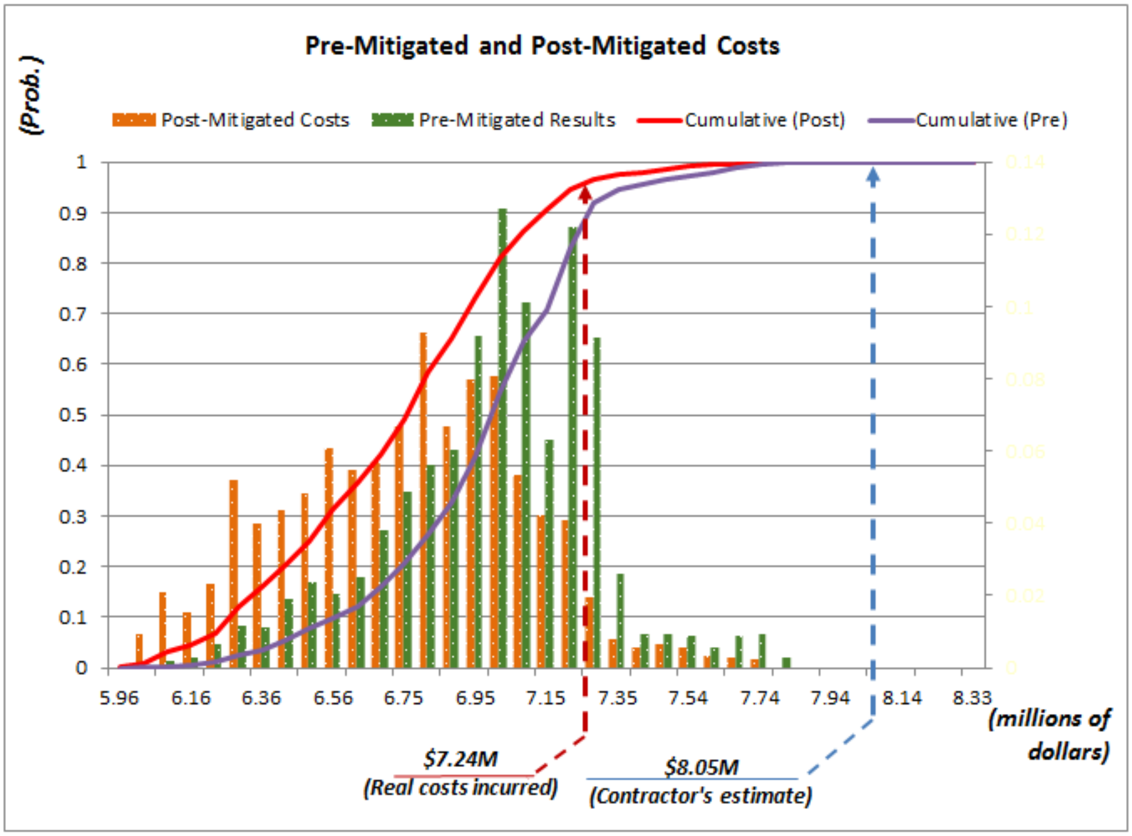


FIGURE 10. PRE-MITIGATED AND POST-MITIGATED COST ESTIMATE.

IV. SUMMARY

The amount of allowances assigned to demolition projects is usually high due to the number of uncertainties characterizing them. The developed model demonstrates that PERT-Beta distributions and Monte Carlo simulations can be successfully used to estimate allowances associated with risks affecting a project. The verification of the model confirmed that the risk-based simulation process can effectively predict actual project costs. Using this tool, contractors can choose to use the simulated risk results to predict profits and reduce the environmental impacts of a demolition project.

The Warren Hall case study shows that the proposed risk-based model can effectively be used to estimate the allowances in a demolition project. Depending on the procurement method, risk impacts can be part of separate allocated funds (allowances) or directly readjusted through unit cost values of the original estimates.

The overall nature of projects is becoming more complex due to new environmental regulations and a very tight economy with limited resources. Construction and demolition firms should act accordingly in order to stay competitive and make a profit. Proceeding with systematic risk management analysis with environmental and financial considerations will help both owners and contractors to achieve common goals.

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