Managing Construction Projects Using the Advanced Programmatic Risk Analysis and Management Model

William Imbeah, A.M.ASCE[1]; and Seth Guikema[2]

Abstract: Risk management is an important part of construction management, yet the risk-based decision support tools available to construction managers fail to adequately address risks relating to cost, schedule, and quality together in a coherent framework. This paper demonstrates the usefulness of the Advanced Programmatic Risk Analysis and Management Model (APRAM) originally developed for the aerospace industry, for managing schedule, cost, and quality risks in the construction industry. The usefulness of APRAM for construction projects is demonstrated by implementing APRAM for an example based on an actual building construction project and comparing the results with other risk analysis techniques. The results show that APRAM simultaneously addresses cost, schedule, and quality risk together in a coherent, probabilistic framework that provides the information needed to support decision making in allocating scarce project resources.

DOI: 10.1061/(ASCE)0733-9364(2009)135:8(772)

CE Database subject headings: Risk management; Construction management; Resource management.

Introduction

A successful construction project is typically regarded as one that produces a quality facility that meets or exceeds the expectations of the project sponsor on time and within budget (Wideman 1986; Halpin and Woodhead 1998, p. 12; Hendrickson and Au 2000). Like many other industries, the construction industry has substantial risk built into its profit structure (Mustafa and Al-Bahar 1991; Akintoye and MacLeod 1997). Due to the nature of the different activities involved, construction projects can be complicated and involve a number of uncertainties such as uncertainties about material delivery times and costs, task completion times and costs, and the quality of work completed by subcontractors. These uncertainties can lead to project risks and can be the cause of a construction project's failure to achieve predefined objectives. These objectives are traditionally assumed to be based on project cost and schedule together with facility quality (Laufer and Tucker 1987; Halpin and Woodhead 1998, p. 12; Hendrickson and Au 2000). Although other factors may also influence the perception of project success (e.g., Chan and Chan 2004), these factors can be project specific. This paper focuses on cost, schedule, and quality as the main criteria by which construction projects would be judged a success.

In addition to the above-mentioned factors, managers of construction projects are faced with the challenge of ensuring the appropriate allocation of scarce project resources including financial, material, and human resources during the lifetimes of projects in order to minimize the risks of project failures. In their attempts to appropriately allocate scarce project resources, project managers are again faced with the challenge of balancing technical and managerial failure risks, where technical risks refer to failure to provide a product that conforms to specifications or perform as required, and managerial risks refer to the inability to complete a project within a specified budget and within a specified duration. Such situations require trade-offs between technical and managerial failure risks, and it is essential that managers are furnished with decision-support tools that would help them make valuable decisions. The Advanced Programmatic Risk Analysis and Management Model (APRAM) is an example of a decision-support framework that can be useful for the management of the risk of project failures (Dillon and Paté-Cornell 2001; Dillon et al. 2003). This paper first describes the APRAM model. Then the objectives and goals of this paper are given, followed by an overview of other approaches for risk management in construction. Next, the usefulness of APRAM in the construction industry is demonstrated by applying it to an example based on an actual construction project. A discussion of the strengths and limitations of APRAM is presented, followed by a summary of the paper.

[1]Graduate Civil Engineer, Environmental Chemical Corporation (ECC), 1240 Bayshore Highway, Burlingame, CA; formerly, Graduate Student, Dept. of Civil Engineering, Texas A&M Univ., College Station, TX.

[2]Assistant Professor, Dept. of Geography and Environmental Engineering, Johns Hopkins Univ., Baltimore, MD 21218; formerly, Zachry Dept. of Civil Engineering, Texas A&M Univ., College Station, TX.

Note. This manuscript was submitted on May 8, 2007; approved on March 30, 2009; published online on July 15, 2009. Discussion period open until January 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 135, No. 8, August 1, 2009. ©ASCE, ISSN 0733-9364/2009/8-772–781/$25.00.

Advanced Programmatic Risk Analysis and Management Model

APRAM was developed for the aerospace industry, particularly the management of NASA's "Faster, Better-Cheaper" unmanned space missions (Dillon and Paté-Cornell 2001; Dillon et al. 2003). These missions are characterized by an attempt to produce a quality system faster and at a reduced cost relative to traditional approaches. Many new construction management approaches share similar goals. APRAM involves eight main steps as shown in

J. Constr. Eng. Manage., 2009, 135(8): 772-781

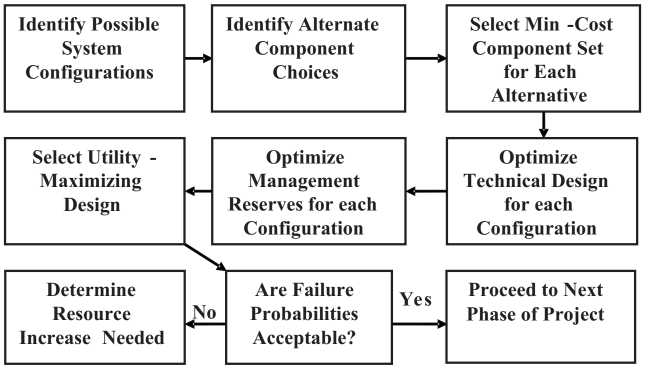

Fig. 1. APRAM process

Fig. 1. The first step in APRAM is to identify the possible alternatives for the design of the system. For example, for a building construction project, one could consider a building based on a number of different structural materials such as precast concrete, steel, or wood. The second step in APRAM, as shown in Fig. 1, involves specifying the possible components for the major portions ("subsystems") of the building such as the roof, the cladding, the foundation, etc. This step also involves conducting the preliminary cost estimate for each of the possible components for each of the subsystems of the building. The third step consists of identifying the minimum cost set of alternatives for each design configuration. For example, the minimum cost precast concrete building design would be identified, where minimum cost is based on the set of components that would just meet the minimum technical specifications for the facility. The difference between the minimum cost design for each system configuration (identified in Step 1) and the total budget is the available budget reserve for each of the system configurations. Each configuration may have a different budget reserve.

The fourth through sixth steps of APRAM, shown in Fig. 1, involve optimizing the allocation of the budget reserve for each system configuration and then choosing the optimal overall configuration and design. The process starts in the fourth step by analyzing the possibility of improving the technical aspect of the facility by spending money from the reserves. First, this is done for technical reinforcement independently of managerial reserves (Step 4). A nonlinear optimization problem is solved for a given fraction (e.g., 75%) of the reserves that is to be spent on technical reinforcement. This optimization returns the optimal set of upgrades to components of the building given the assumed allocation from reserves. For example, the optimization may suggest that the roofing material be upgraded for increased durability but that the cladding be left at the minimum-cost level. The optimization problem is repeated for all possible allocations from the reserves from 0 up to 100%, typically discretized into 5 or 10% increments. The fifth step is similar, except that the optimization is solved for allocating money to avoid schedule and budget problems. Again, the optimization problem is solved for managerial allocations of 0 up to 100% of the total reserves. Then, in the sixth step, the technical and managerial optimizations are combined to choose the overall allocation of reserves that achieves the maximum value for each of the system configurations. Each configuration may have a different portion of the overall reserves being allocated to avoiding technical problems. With a choice of design and budget allocation made, project managers have to determine whether the level of risk for the selected alternative and budget is acceptable, and, if it is not acceptable, how much the budget needs to be increased to reduce the risk to an acceptable level. This is the final step in APRAM (Dillon et al. 2003).

Problem Statement and Objective of Study

The collapse of the Tacoma Narrows Bridge in the 1940s and the collapse of the Kansas City Hyatt Regency walkway in the 1980s are only two of the many examples of cases where constructed facilities have either failed to serve the purposes for which they were constructed or failed because of improper design or construction. In the aftermath of these and failures of other constructed facilities, there has been an increasing awareness of the need for a thorough and effective risk analysis for all constructed projects. The main purpose of this study was to evaluate the effectiveness of APRAM for construction projects. That is, this study was aimed at determining whether APRAM can be useful and practical to the extent that it can be used in making useful decisions (i.e., decisions that add value) in construction. Certain modifications were made to the APRAM model in order to obtain a practical decision support tool that managers of construction projects can use to allocate project resources to improve the chances of project success.

Examples of Risk Analysis Techniques for Construction Management

As summarized in Table 1, various techniques have been developed for use in the management of risks in construction. However, these techniques are limited to addressing risks relating to only cost, schedule, or technical performance individually or at best a combination of cost and schedule risks. The exceptions to this general conclusion are approaches based on Failure Modes and Effects Analysis (FMEA). FMEA addresses budget, schedule, and technical risk together, but it does so based on ordinal, rather than cardinal, scales. That is, the different possible failure events are ranked, but the differences between the rankings for any two possible failure events are not proportional to their risk. For example, the risk due to a potential failure event given a FMEA score of 10 (on the standard 1–10 scale) is not necessarily twice as high as the risk from a potential failure event given a score of 5. Without a cardinal scale, that is a scale in which scores are proportional to risk, FMEA does not provide a sound basis for allocating resources to manage risk. For example, if there are sufficient funds to address either a potential failure event given a score of 10 or two potential failure events each with a score of 5, which should be addressed? FMEA cannot answer this question because ordinal scales do not provide a sound basis for optimizing the use of scarce resources to best manage project risk. Next, an overview of selected construction risk management techniques is provided, focusing on approaches that do provide cardinal scales and a basis for resource allocation decisions for at least one of schedule, budget, and technical risk.

Judgmental Risk Analysis Process (JRAP), Program Evaluation and Review Technique (PERT), Schedule Risk System (SRS), and Estimating using Risk Analysis (ERA) are examples of existing risk analysis techniques that have been used for construction projects. JRAP, SRS, and PERT are all schedule risk analysis methods, whereas ERA can be used to address budget risk. JRAP involves first determining the critical risks that may affect a project's duration. The risks are assigned probability distributions using either historical data (if available), previous ex-

J. Constr. Eng. Manage., 2009, 135(8): 772-781

Table 1. Some Risk Analysis Techniques and Risks Addressed

Risk analysis technique	Addresses schedule risk	Addresses budget risk	Addresses technical risks (quality)
Computer Aided Simulation for Project Appraisal and Review—CASPAR (Willmer 1991)	Yes	Yes	No
Schedule Risk System (Mulholland and Christian 1999)	Yes	No	No
Judgmental Risk Analysis Process—JRAP (Öztaş and Ökmen 2005)	Yes	No	No
Estimating Project and Activity Duration Using Network Analysis (Dawood 1998)	Yes	No	No
Data-Driven Analysis of Corporate Risk Using Historical Cost-Control Data (Minato and Ashley 1998)	No	Yes	No
Estimating Using Risk Analysis—ERA (Mak and Picken 2000)	No	Yes	No
Failure Modes and Effects Analysis—FMEA (Bouti and Kadi 1994)	Yes	Yes	Yes
Utility-Functions in Engineering Performance Assessment (Georgy et al. 2005)	No	No	Yes
Program Evaluation and Review Technique—PERT (Malcom et al. 1959; Kerzner 2003)	Yes	No	No

perience, or engineering judgment. This method requires the determination of the maximum and minimum durations of activities in the schedule network when the probabilities are being assigned. JRAP is considered a pessimistic risk analysis approach because it assumes that the actual duration of a construction activity is greater than the most likely duration more than 50% of the time (Öztas and Ökmen 2005). An activity-risk factor matrix can then be established using the constraint that the total influence of all risk factors on any activity in the schedule network should be 100%. According to Öztas and Ökmen (2005) the activity-risk factor matrix quantifies the varying effect of each risk over each activity. Monte Carlo simulations can then be performed on the schedule network using the activity-risk factor matrix to obtain a list of the critical activities and their durations as well as the total project duration.

PERT was developed for the U.S. Navy in 1958 to tackle uncertainties involved in nonroutine projects (Kerzner 2003; Nasir et al. 2003; Malcolm et al. 1959). PERT requires a logically sequenced network diagram consisting of all events and activities. Using a beta distribution, a probability distribution can be determined for each activity to represent possible durations as a result of project uncertainties. This results in optimistic, most likely, or pessimistic durations for each activity in the network diagram. The mean duration for each path is the sum of the mean durations of each activity along that path. The critical path can be obtained by determining the sequence of activities and events with the maximum duration.

SRS is a tool for quantifying uncertainties in construction schedules. SRS involves risk identification and risk measurement (Mulholland and Christian 1999). A database system of previously experienced schedule risks known as HyperCard serves as an aid in the identification of project risks. The risk measurement phase can be performed by using a spreadsheet to model the effects of the identified risks on the project schedule to obtain the project's schedule risk profile.

ERA is a methodology that can be used to determine the amount of contingency required for a project by identifying uncertainties and determining the effects of the uncertainties on the project budget (Mak and Picken 2000). To use ERA, a risk-free base estimate has to be prepared. Project risks need to be identified and these are classified as either fixed or variable. Fixed risk events are those that either fully occur, or do not occur, whereas variable risk events are events that will definitely occur but whose extent of occurrence cannot be ascertained. An average risk allowance and a maximum risk allowance are then calculated for each risk event. With all risk events identified and the average and maximum risk allowances calculated, the average risk allowances for all events can be summed to obtain the required contingency.

With the exception of FMEA, none of the above-discussed approaches address schedule, budget, and technical risks simultaneously. However, these three key aspects of risk are all interrelated in construction projects. For instance, a schedule slippage can impact the total cost of construction in the event of inflation or escalation of material costs. There is a need therefore for techniques that will address the integration of the different risks of failure involved in construction. In other words, in addition to ensuring that projects are completed on time and under budget, project managers need to simultaneously address issues relating to the technical aspects of their facilities and then make trade-offs between these by optimizing the use of budget reserves. For example, in some cases, projects may slightly slip budget if there is an urgent need to improve technical aspects of the project in order to provide a quality facility that can fully serve the purposes for which it was constructed. This sort of trade-off, however, should be made only when it adds value to project participants.

Research Method and Results

APRAM was applied to an example based on the development of a 323 m^2 meter visitor center in Midland, Tex. to evaluate the effectiveness of APRAM in a construction setting. The project involved the construction of the main visitor center building, a rest stop and picnic areas, as well as roads tying in to existing roads. The actual plans and specifications for the project were used to determine the scope of work. However, APRAM was applied to this project after the facility was completed. This meant that preconstruction assessments of risk from the project management team were not available. Illustrative but realistic risk assessments and were used to demonstrate the usefulness of APRAM.

Determination of Total Budget

A cost estimate was prepared for the project based on converting the detailed plans to a quantity take-off list and using unit pricing

J. Constr. Eng. Manage., 2009, 135(8): 772-781

Table 2. Construction System Configurations

Component	CCS 1	CCS 2	LCS 1	LCS 2
Structural frame	Precast concrete	Cast-in-place concrete	Steel framing (galvanized steel)	Timber framing
Reinforcement steel	Modified steel	Black steel	N/A	N/A
HVAC	Single HVAC zone	Multiple HVAC zones	Single HVAC zone	Multiple HVAC zones
Roofing	Tile roofing	Built up roofing (modified bitumen)	Metal roofing	Slate roofing
Façade	Tiled wall	Concrete wall	Metal cladding	Glass curtain wall
Moisture protection	Damp-proofing	Damp-proofing and waterproofing	Waterproofing	Damp-proofing and waterproofing

based on RSMeans (2007) to determine the initial cost of development as well as the total project budget. The initial cost of development was determined to be approximately $1,200,000 after location adjustment. A total budget of $1,600,000 was suggested as the amount of money the owner intended to spend on the project in order to account for contingency funds.

Identification of Possible System Configurations

APRAM requires the identification of all alternatives that can be used in the development of the facility. In other words, all financially and technically feasible configurations of the completed facility need to be identified to be able to fully apply APRAM. For this study, different options for constructing the facility were selected based on the combination of materials that can be used for building the main elements of the facility. A Conventional Construction System (CCS) and a Lightweight Construction System (LCS) were thus selected. CCS as used in this study refers to the use of masonry, mainly brick and concrete, for the main structural support system. LCS has lightweight steel framing or timber framing as the main structural support system. Once the alternatives have been identified, APRAM further requires the choices of materials and/or components that can be used for CCS and LCS. Two different sets of materials and/or components were identified for each construction system and these are referred to as CCS 1, CCS 2, LCS 1, and LCS 2. These sets of material components are referred to as configurations in this paper. Table 2 provides a summary of some of the materials and/or components for each construction system.

Determination of Residual Budget

The prepared cost estimate was adjusted to obtain the cost of developing the facility with each of the configurations shown in Table 2. Once the development costs were obtained, the residual budget (r) for each configuration was determined by finding the difference between the project budget (T_B) and the total cost of development of the facility ($\mathrm{Dev}_{\mathrm{cost}}$). The residual budget refers to the amount of money available for improving the technical elements of the facility and for management reserves. Table 3 shows the total cost of developing the facility as well as the residual budget for each identified configuration.

Table 3. Development Costs and Residual Budgets for Different Configurations

Configuration	Development cost	Residual budget
CCS 1	$1,250,000	$350,000
CCS 2	$1,300,000	$300,000
LCS 1	$1,255,000	$345,000
LCS 2	$1,350,000	$250,000

Identification of Technical Failures and Managerial Problems

For each configuration, possible technical failures as well as managerial problems that may arise were identified. This was done by considering factors that can result in completing the project behind schedule and over budget. Also, factors that can result in the completed facility performing at a degraded level were considered in identifying technical failures. Because each of the configurations would have different failure modes, the list of technical failures differs across configuration as well. For CCS 1, the failure modes considered were spalling of the concrete, a failure of the tiled wall joints, lack of knowledge of roof installation at the remote job site, an improper design not corrected in the review process, a lack of expertise at the remote job site, and inadequate protection of the concrete from water. For CCS 2, the failure models considered were corrosion of the structural steel, failure of the quality control plan, a shortage of testing or inspection personnel at the remote job site, cracking of the concrete walls, an improper design not corrected during the review process, poor concrete construction practices, and the delivery of low-quality concrete. For LCS 1, the failure modes considered were poor installation practices, using improper design that was not corrected in the review process, chipping of the metal cladding, damage to the metal roof by high winds, difficulty in assuring strength of welds, and a dent in the metal roof. For LCS 2, the failure modes considered were an improper design not corrected in the review process, decay of lumber, excessive exposure of the lumber to moisture, cracking of the curtain wall, and a lack of skilled professionals at the remote job site. In all four cases, these are illustrative failure modes assigned *after* the project had been completed based on the experience of the research team. For an implementation of APRAM, these failure modes would need to be defined early in the project planning process based on interactions with the project management team and the subcontractors conducting critical portions of the work. Probabilities could then be assigned to the different potential failure modes based on expert elicitation of probabilities with the project management team using established elicitation methods (e.g., Spetzler and von Holstein 1975).

The identified technical failures and managerial problems were assigned illustrative probabilities for the purpose of this study. In practice, owners or contractors developing construction projects would need to identify the risks and assign probabilities based on their experience with previous projects and/or data on projects with similar scope from historical databases such as the database system described by Mulholland and Christian (1999).

J. Constr. Eng. Manage., 2009, 135(8): 772-781

In the absence of historical data, expert opinion could be sought to obtain failure probabilities based on the procedures summarized, for example, in Morgan and Henrion (1990) and Spetzler and von Holstein (1975). For the purposes of demonstrating the usefulness of APRAM in the construction industry, the assumed possible failure modes, will be used.

The probabilities of overall technical and managerial project failures (both partial and total) were computed for each configuration based on the probabilities assigned to each possible failure event by using fault tree analysis. Fault tree analysis is a top-down method of analyzing system performance given the probabilities of lower level failure events occurring. This analysis involves the identification of a top event (failure in this case) and sequentially identifying unions and intersections of events that can lead to the occurrence of the top event (Paté-Cornell 1984).

The next step was to relate changes in the failure probabilities to the expenditure of resources for reducing these failure probabilities. Guikema and Paté-Cornell (2002) defined a risk/cost function for modeling systems in which the probabilities of failure of a system decrease exponentially as money is invested to make the system more robust and improve system performance. These exponential curves are only approximations but they work well in many situations. A decreasing exponential curve was thus used for each identified failure state to reflect the expected reduction of the probability of each failure with the allocation of a portion of the residual budget.

Optimization and Determination of Technical Reinforcement Budget

The portion of the residual budget that can be used to reinforce or improve the technical capabilities of the facility is the technical reinforcement budget ($\mathrm{Tech}_{\mathrm{rein}}$) and this can be expressed as

$$\mathrm{Tech}_{\mathrm{rein}} = \alpha r \tag{1}$$

where α represents the fraction of the residual budget that is used to reduce the risks of technical failure and can range from nothing to the entire residual budget (i.e., $0 \leqslant \alpha \leqslant 1$). A nonlinear optimization was performed for all values of α to determine the fraction of the residual budget that will minimize the owner's utility. Utility here refers to the decision-maker's preference, which in this case is assumed to be reducing expected cost of failure (E). Other, more general, criteria based on net present value or expected utility theory could also be used. However, the simple criterion used here serves to demonstrate the approach, and it will likely be a reasonable criterion in many situations. The expected cost of failure for each allocation of technical reinforcement budget ($\mathrm{Tech}_{\mathrm{rein}}$) was obtained using the equation

$$E = \sum_i \left(p(\mathrm{TTF}_i|\mathrm{Tech}_{\mathrm{rein}})C(\mathrm{TTF})\right) + \sum_j \left(p(\mathrm{PTF}_j|\mathrm{Tech}_{\mathrm{rein}})C(\mathrm{PTF})\right) \tag{2}$$

where $p(\mathrm{TTF}_i|\mathrm{Tech}_{\mathrm{rein}})$ = probability of a total technical failure given the amount invested in technical reinforcement. Total technical failure occurs if the facility does not function at all or functions at a degraded level. $p(\mathrm{PTF}_j|\mathrm{Tech}_{\mathrm{rein}})$ = probability of a partial technical failure given the amount invested in technical reinforcement. Partial technical failure occurs if certain aspects of the facility are observed to be defective. $C(\mathrm{TTF})$ = cost of total technical failure. $C(\mathrm{PTF})$ = cost of partial technical failure.

Different optimizations were performed for different values of α for each configuration in order to determine the optimal allocation of the technical reinforcement budget ($\mathrm{Tech}_{\mathrm{rein}}$) among the different failure modes.

Optimization and Determination of Best Response to Managerial Problems

With $\mathrm{Tech}_{\mathrm{rein}}$ allocated to the technical system, the portion of the residual budget left was $(1-\alpha)r$. This is referred to as management reserves ($\mathrm{Mgmt}_{\mathrm{res}}$). Dillon et al. (2003) used decision analysis to determine the optimal level of the management reserves. This approach, however, used sequential decision trees, that is, an action taken to mitigate a managerial problem might be followed by another problem which would require another mitigation action that could then in turn be followed by another problem and so forth. This approach was considered unsuitable for a construction project because construction project development differs from space mission development. The aerospace industry often uses a spiral development process, leading to successive detection and correction of problems as successive versions of the system are developed. In contrast, construction projects tend to be linear in the sense that there are often not successive versions or prototypes of facilities developed. This means that the discovery and correction of problems that occur during construction must occur in a linear, more compressed time scale. This makes the iterative refinement of the use of budget reserves that is implicit in the decision trees used in the original APRAM model less relevant to construction. Instead of decision trees, we modified the original APRAM model to solve a more static optimization problem for allocating managerial reserves. The writers' first attempt at doing this was based on FMEA.

Even though it was possible to assign a fraction of the managerial reserves to each managerial problem with the FMEA based on each risk item's risk priority number, the FMEA did not take into account the probabilities of the different failure states. The FMEA only helps rank potential failure modes and does not provide a sound basis for allocating resources. Therefore, the same nonlinear optimization used for determining the optimal technical reinforcement budget level was used for allocating managerial reserves. The expected cost of failure was again minimized for this optimization. The expected cost of failure for each allocation of management reserves was obtained from

$$E = \sum_i \left(p(\mathrm{TMF}_i|\mathrm{Mgmt}_{\mathrm{res}})C(\mathrm{TMF})\right) + \sum_j \left(p(\mathrm{PMF}_j|\mathrm{Mgmt}_{\mathrm{res}})C(\mathrm{PMF})\right) \tag{3}$$

where $p(\mathrm{TMF}_i|\mathrm{Mgmt}_{\mathrm{res}})$ = probability of a total managerial failure given the amount invested in management reserves. A total managerial failure occurs if the project is canceled due to a substantial budget or schedule overrun. $p(\mathrm{PMF}_j|\mathrm{Mgmt}_{\mathrm{res}})$ = probability of a partial managerial failure given the amount invested in management reserves. A partial managerial failure occurs if the project is behind schedule or over budget but not by enough to lead to project cancellation. $C(\mathrm{TMF})$ = cost of total managerial failure. $C(\mathrm{PMF})$ = cost of partial managerial failure

Optimizations were performed for each value of α for each configuration. Figs. 2–5 show the results of the optimizations of the technical reinforcement budget and management reserve for

J. Constr. Eng. Manage., 2009, 135(8): 772-781

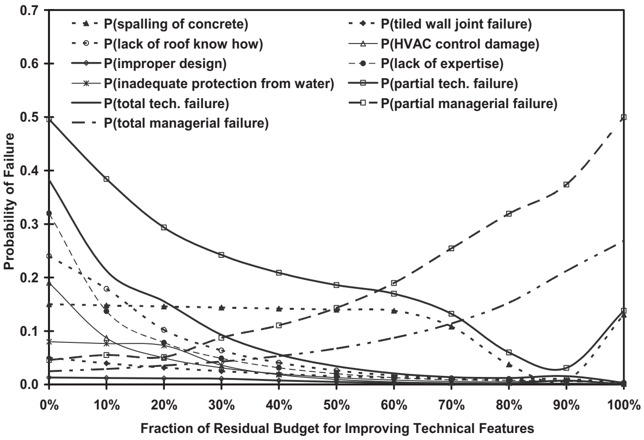

Fig. 2. Probabilities of different failure states versus investment of residual budget (CCS 1)

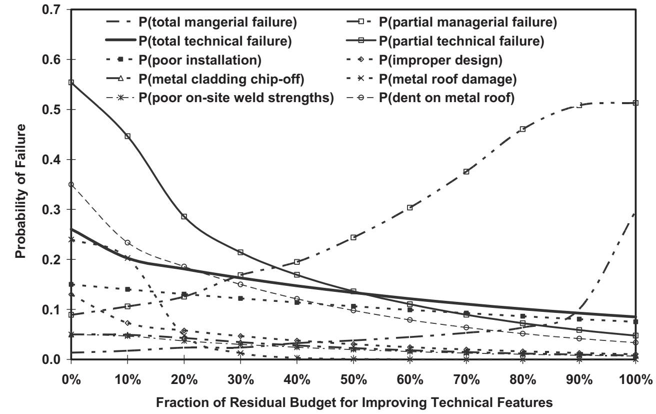

Fig. 4. Probabilities of different failure states versus investment of residual budget (LCS 1)

each configuration. The probabilities of the various managerial problems were left out of the graphs in order to make them more legible.

Figs. 2–5 show the probabilities of the identified failures decreasing as more money (from the residual budget) is invested. It is important to note that the technical elements of the facility need to be reinforced before part of the residual budget can be put aside as management reserves. Figs. 2–5 result from the optimization of the residual budget for technical and managerial reinforcement independently. This information is then combined to yield the overall best allocation of the reserves. For example, for CCS 1, combining the results from the independent technical and managerial optimizations suggests that allocating 50% of the residual budget to improve the technical system and holding the remaining 50% as reserves will overall yield the lowest expected failure cost. Any other allocation will yield a higher failure cost for CCS 1 and would thus be a suboptimal use of resources. Similarly, for CCS 2, the optimal allocation is to spend 70% of the residual budget on improving the technical elements of the facility with the remaining 30% held as reserves for addressing development problems. Also for LCS 1, the optimal allocation is to spend 60% of the residual budget for technical reinforcement and hold 40% of the residual budget as reserves in order to reduce the expected cost of failure. The optimal allocation for the configuration having timber framing (LCS 2) is to spend 80% of the residual budget on improving the technical system and hold 20% of the residual budget as reserves in order to minimize the expected costs of failure. These results show that APRAM gives configuration-specific allocations of the residual budget, allowing risk management practices to be tailored to the type of facility being constructed.

Selection of Optimal Alternative and Allocation of Residual Budget that Minimizes Overall Failure Risk

The final step involved the integration of the two separate optimizations in order to identify the optimal allocation of the residual budget. In other words, this step determined the fraction (α) of the residual budget that maximized the owner's utility. This step also allowed the selection of the best alternative that minimized the expected cost of failure. The order in which failure (both technical and managerial failure) can occur needed to be determined to be able to complete this step. Because a technical failure can be realized only after the facility has been constructed, it is expected that a managerial failure (either partial or total) or no managerial failure will have to occur first. Thus a managerial failure or no managerial failure has to occur before total technical failure, partial technical, or no technical failure can occur. An event tree was used to identify the order in which failure can

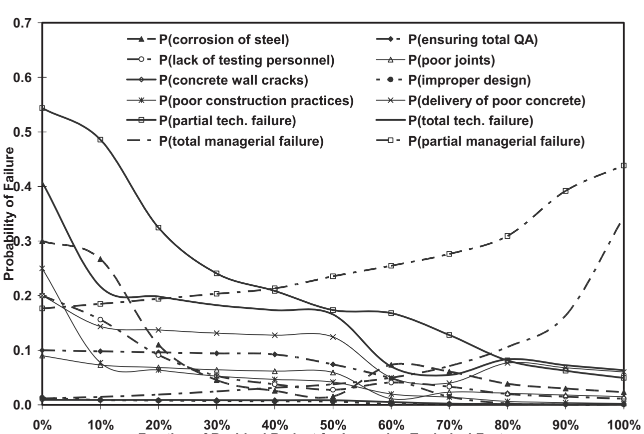

Fig. 3. Probabilities of different failure states versus investment of residual budget (CCS 2)

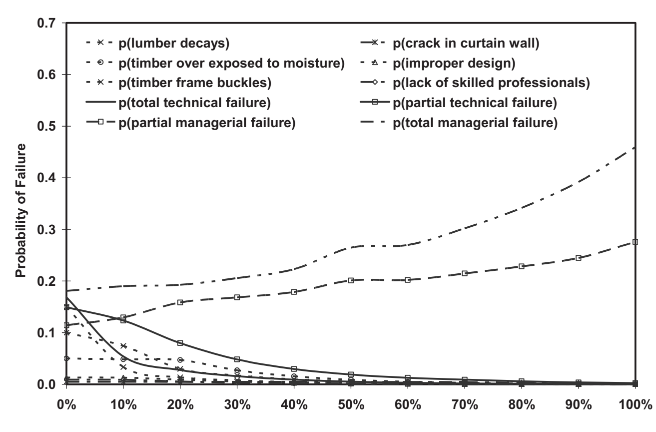

Fig. 5. Probabilities of different failure states versus investment of residual budget (LCS 2)

J. Constr. Eng. Manage., 2009, 135(8): 772-781

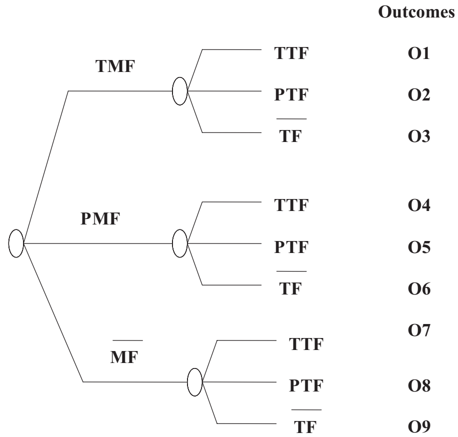

Fig. 6. Event tree showing possible failure outcomes

occur for each alternative. Fig. 6 shows the event tree used for this study. Paté-Cornell (1984) described an event tree as a tree with a finite number of branches that can be used to place events in a chronological order provided the events are known or predictable. O_1-O_9 in Fig. 6 represent the outcomes of the different failure states and they can be obtained from

$$O_1 = C(\text{TMF}) + C(\text{TTF}) \tag{4}$$

$$O_2 = C(\text{TMF}) + C(\text{PTF}) \tag{5}$$

$$O_3 = C(\text{TMF}) + C(\overline{\text{TF}}) \tag{6}$$

$$O_4 = C(\text{PMF}) + C(\text{TTF}) \tag{7}$$

$$O_5 = C(\text{PMF}) + C(\text{PTF}) \tag{8}$$

$$O_6 = C(\text{PMF}) + C(\overline{\text{TF}}) \tag{9}$$

$$O_7 = C(\overline{\text{MF}}) + C(\text{TTF}) \tag{10}$$

$$O_8 = C(\overline{\text{MF}}) + C(\text{PTF}) \tag{11}$$

$$O_9 = C(\overline{\text{MF}}) + C(\overline{\text{TF}}) \tag{12}$$

where $\overline{\text{TF}}$=no technical failure; $\overline{\text{MF}}$=no managerial failure; $C(\overline{\text{TF}})$=cost of no technical failure; and $C(\overline{\text{MF}})$=cost of no managerial failure.

The expected cost of overall project failure for each α (i.e., allocation of the residual budget to technical reinforcement and management reserves) was determined using

$$\begin{aligned} E = {} & (p(\text{TMF})p(\text{TTF})O_1) + (p(\text{TMF})p(\text{PTF})O_2) \\ & + (p(\text{TMF})p(\overline{\text{TF}})O_3) + (p(\text{PMF})p(\text{TTF})O_4) \\ & + (p(\text{PMF})p(\text{PTF})O_5) + (p(\text{PMF})p(\overline{\text{TF}})O_6) \\ & + (p(\overline{\text{MF}})p(\text{TTF})O_7) + (p(\overline{\text{MF}})p(\text{PTF})O_8) + (p(\overline{\text{MF}})p(\overline{\text{TF}})O_9) \end{aligned} \tag{13}$$

Table 4 provides a summary of the optimal allocation of the residual budget for each alternative and the associated probabilities of technical and managerial failures.

The alternative with the least expected cost of failure is LCS 2 and this is the alternative to be selected for the development of the facility. For this alternative, 80% of the residual budget will be included in the initial cost of development of the facility and 20% of the residual budget held as management reserves to serve as contingency for events that can result in completing the project behind schedule and/or over budget. The optimal allocation of the residual budget to improving the technical system is 80% because this provides the owner with the lowest expected cost of failure.

Increasing Total Project Budget to Meet Acceptable Failure Levels

In the event that any of the probabilities of managerial failure and technical failure (both partial and total) for the optimal configuration is greater than the acceptable risk thresholds, the decision maker has to determine by how much the total budget has to be increased in order to achieve the expected levels of risk. In order to do this, an analysis can be performed to determine how sensitive the expected cost of failure is to changes (increases in this case) in the total project budget. In this analysis, the total project budget was first set to $1,500,000 such that the residual budget was $150,000. The different values of α were optimized to reduce the expected costs of failure for both the technical reinforcement budget and the managerial reserve. The total project budget was then increased in increments of $100,000 until the total project budget reached $2,900,000. As an illustration, assume the decision maker's acceptable risk levels for technical failure and managerial failure are 0.05 and 0.2, respectively. It can be inferred from Fig. 7 that the probabilities of both total and partial technical failures for the visitor center project with a project budget of $1,600,000 are below acceptable limits. Partial and total managerial failures are however above acceptable limits. The owner should thus be willing to pay a penalty of $220,000 in order to meet acceptable risk levels.

Table 4. Summary of the Integration of the Different Optimizations

Configuration	Expected costs of failure	α (%)	p(PMF)	p(TMF)	p(PTF)	p(TTF)
Conventional Construction System 1 (CCS 1)	$132,000	50	0.143	0.067	0.186	0.034
Conventional Construction System 2 (CCS 2)	$161,000	70	0.277	0.071	0.128	0.055
Lightweight Construction System 1 (LCS1)	$201,000	60	0.304	0.044	0.110	0.121
Lightweight Construction System 2 (LCS 2)	$36,000	80	0.228	0.342	0.006	0.001

J. Constr. Eng. Manage., 2009, 135(8): 772-781

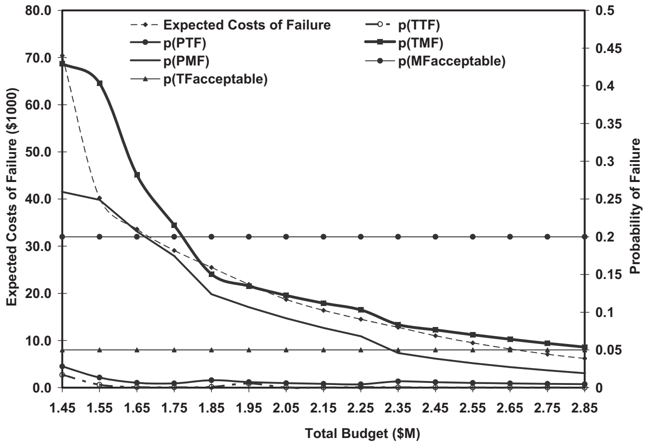

Fig. 7. Expected costs of failure versus total project budget

Table 6. Estimated Expected Failure Costs for All Configurations without APRAM

Configuration	Costs of failure	p(PMF)	p(TMF)	p(PTF)	p(TTF)
Conventional Construction System 1 (CCS 1)	$581,000	0.007	0.012	0.496	0.383
Conventional Construction System 2 (CCS 2)	$658,000	0.132	0.001	0.544	0.408
Lightweight Construction System 1 (LCS1)	$309,000	0.008	0.002	0.554	0.161
Lightweight Construction System 2 (LCS 2)	$267,000	0.089	0.017	0.149	0.169

Comparison with other Methods for Risk Management in Construction

For the purpose of comparison, the overall expected cost of failure was also estimated without the implementation of APRAM. This was performed using the @Risk software to determine contingency funds for the project. To do this, Monte Carlo simulation was used to estimate the mean project cost together with the 95th percentile of the project cost. The difference between the 95th percentile and the mean cost is taken to be the contingency. A triangular distribution was assumed for the total cost of the project. The most likely costs used were the cost obtained from the cost estimate, whereas the high and low costs were based on assuming that the accuracy of the cost estimates was within $\pm 50\%$. Table 5 shows the inputs to @Risk.

A Monte Carlo simulation of the total project cost with 15,000 iterations yielded a mean total project cost of approximately $1,854,700. This cost (i.e., $1,845,700) represents an estimate of the mean project cost, accounting for uncertainties in the cost categories shown in Table 5. The 95% confidence bounds for this estimate are $1,852,606 and $1,855,565. The estimate of the total project cost obtained from the simulation suggested a contingency allowance of 23%, where the contingency is calculated based on the difference between the base estimated cost without cost uncertainty (i.e., $1,500,000, see Table 5) and the mean total project cost from the Monte Carlo simulation. Adjusting the estimate of the total project cost for location yielded approximately $1,440,000 (with 23% contingency) and this was used to determine the overall mean cost of failure for each configuration. Table 6 shows the costs of failure and associated probabilities for all configurations.

Table 6 provides a summary of the expected total cost of failure and associated probabilities using a contingency allowance of 23%. LCS 2 emerged as the configuration that would reduce the expected costs of failure (i.e., LCS 2 has the least expected cost of failure). However, the expected costs of failure using a percentage of the total project cost as contingency, $267,000 is about eight times the cost of failure using APRAM. Using APRAM therefore can enable the decision maker to simultaneously address the schedule, cost, and technical risks that a project may be exposed to and to manage these risks in order to achieve the lowest possible overall cost of failure.

Table 5. Risk Analysis Inputs

Category	Low	Most likely	High
A Direct field costs	$484,000	$968,000	$1,451,000
B Contractor's overhead and profit	$97,000	$193,000	$290,000
C Other project costs	$4,100	$8,300	$12,000
D Permits and insurance	$169,000	$339,000	$508,000
E Total project cost	$750,000	$1,500,000	$2,300,000

Discussion

The analysis performed in this study has shown that APRAM can be used to manage construction project risks of cost, time, and quality simultaneously. APRAM can also be used to determine the expected cost of failure, and it further offers the decision maker/owner the opportunity to lower expected costs through optimal allocations of the residual budget. APRAM also allows the owner or project initiator to explore all possible options for developing a facility. Application of APRAM during construction project development could also offer the opportunity to involve all project participants at an early stage in the project development process if the owner or decision maker decides to include them in the risk identification process.

Comparison with Other Risk Management Approaches

FMEA is the only other risk analysis approach among the techniques mentioned in this study that can simultaneously handle cost, schedule, and quality risk in construction projects. However, FMEA provides ordinal rankings of risk, not cardinal rankings. That is, FMEA can help a construction manager rank-order risks according to their likelihood and severity, assuming FMEA is implemented well and the score levels for severity and likelihood are clearly and logically defined. However, FMEA does not provide information about how much worse one risk is than another. That is, it does not provide cardinal rankings. Having cardinal rankings of risk is critical if the allocation of scarce resources is to be optimized. If a project manager does not know how much worse one risk is than another, he or she does not have a sound basis for deciding how many resources to allocate to reducing each of the risks. FMEA is appropriate for helping to identify risks and ranking risks ordinally but it does not provide a sound basis for allocating resources to optimally manage risk because it does not provide cardinal rankings.

J. Constr. Eng. Manage., 2009, 135(8): 772-781

The other risk analysis techniques discussed in this paper either address only cost or schedule risks or a combination of the two. Also, available construction risk analysis techniques such as JRAP, PERT, and SRS only provide probabilities for project parameters but do not offer any means to reduce the probabilities. The ERA methodology can be used to determine project contingency funds but the project contingency allowance is not meant for improvement of the technical elements of the facility. APRAM thus provides a basis for a more comprehensive decision support tool that construction industry professionals can use to allocate limited resources for managing risk for construction projects when simultaneously accounting for schedule, cost, and technical risk.

Limitations of APRAM

Although APRAM does provide a comprehensive basis for considering and managing schedule, budget, and technical risk in construction projects, it is more useful within certain organizational settings than others. APRAM will work best when there is close integration of design and construction professionals at an early stage in the project development process. In order to realize the full benefits of implementing APRAM for a construction project, the contractor and the designer need to provide inputs during the conceptual design phase of a project. This would help to determine the most cost effective as well as most constructible design, allowing APRAM-based risk management to be integrated into early project decision making. The design–build approach in which one entity is responsible for both design and construction would therefore be a more effective strategy compared to traditional design–bid–build. This can be mainly attributed to the fact that with the traditional design–bid–build approach, the contractor or builder cannot be identified until detailed design is completed removing the opportunity for APRAM to help guide both design and construction management simultaneously. In the case of design–build however, the design–build firm is selected early in the project development process.

As with most quantitative project management tools, the difficulty of implementing ARPAM grows as the size of the project grows. With more tasks, more subsystems of increasing complexity, and more materials and employees involved, the number of potential failure events to consider grows substantially. However, it is exactly these types of problems for which APRAM would be most valuable. For complex projects, managerial intuition may provide a poor basis for risk management, especially for managing the trade-off between technical and managerial (schedule and budget) risks. The original APRAM model was designed for complex space missions with costs on the scale of \$500,000,000, and APRAM should be applicable to large, complex construction projects.

Even though this study has shown that APRAM can be useful for analyzing the risks of construction projects, there are some issues that the model does not address. Among these is the issue of safety during construction projects. Safety could be classified as being a managerial failure because accidents can result in the suspension of a project pending further investigations. This can lead to substantial schedule delays. Severe accidents may also lead to large financial costs for compensation of the victims in some cases. Because accidents can be caused by negligence and carelessness, no amount of investment of the residual budget can ensure that there are no accidents on site. However, such investments may decrease the probability of safety-related accidents in some cases. One way to decrease the probability of accidents during construction projects is to ensure that OSHA regulations and other health and safety measures are strictly enforced on all construction sites. APRAM could be further developed to include safety-related risks by either including the costs of these risks to the project owner or by adding worker safety as an explicit decision criterion, appropriately weighted relative to the other criteria. However, the focus of this paper is on the three main risks usually identified as primary risks in construction—schedule, budget, and quality risks.

APRAM in its current form also focuses on only those risks that can be mitigated through the allocation of fungible resources. In practice, however, not all technical failures and managerial problems can be effectively handled using money. Some technical failures may require the integration of design and construction as a mitigation measure, an effort that depends on the project delivery approach, not specifically the allocation of resources. For example, a more appropriate way of reducing the impact of delays in material delivery on project duration may be integrating vendors into the project planning process and ensuring continuous communication between the project team and vendors.

Finally, APRAM does not address the issues of poor judgment, a lack of knowledge, and inadequate training on the part of the construction manager or other project participants. The model assumes that project team members are competent in their various disciplines. For example, even though APRAM can guide the choice of whether or not to use more durable construction materials like modified steel and corrosion inhibitors during construction, the model does not directly address failure to comply with good construction practices such as adequate consolidation and curing of concrete. Inadequate consolidation and curing of concrete would still result in low quality constructed facilities even though more money has been spent on acquiring durable materials.

Conclusions and Recommendations

Construction managers lack appropriate decision support tools for simultaneously addressing project risks due to cost, schedule, and quality. This paper has shown that APRAM can fill this gap by providing a risk analysis technique that can minimize the expected costs of project failure by integrating project risks of time, budget, and quality through the allocation of resources. APRAM offers a mechanism that can be used to optimally allocate resources available for reducing the probabilities or consequences of the identified potential budget, schedule, and quality failures. APRAM offers the potential to more fully integrate budget, schedule, and quality risk into a coherent risk management framework for construction professionals.

Acknowledgments

The writers wish to acknowledge the helpful advice of David Trejo and Daren Cline at Texas A&M University as well their comments on an early draft of this material. The helpful comments of the anonymous reviewers are also gratefully acknowledged.

J. Constr. Eng. Manage., 2009, 135(8): 772-781

Notation

The following symbols are used in this paper:

Dev_{cost} = total cost of development;
E = expected cost of failure.
$Mgmt_{(res)}$ = management reserve;
r = residual budget;
T_B = total project budget; and
$Tech_{(rein)}$ = technical reinforcement budget.

References

Akintoye, A. S., and MacLeod, M. J. (1997). "Risk analysis and management in construction." *Int. J. Proj. Manage.*, 15(1), 31–38.

Bouti, A., and Kadi, D. A. (1994). "A state-of-art review of FMEA/FMECA." *Int. J. Reliab., Qual., Safety*, 1(4), 515–543.

Chan, A. P. C., and Chan, A. P. L. (2004). "Key performance indicators for measuring construction success." *Benchmarking: Int. J.*, 11(2), 203–221.

Dawood, N. (1998). "Estimating project and activity duration: A risk management approach using network analysis." *Constr. Manage. Econom.*, 16(1), 41–48.

Dillon, R. L., and Paté-Cornell, M. E. (2001). "APRAM: An advanced programmatic risk analysis method." *Int. J. Technol., Policy, Manage.*, 1(1), 47–55.

Dillon, R. L., Paté-Cornell, M. E., and Guikema, S. D. (2003). "Programmatic risk analysis for critical engineering systems under tight resource constraints." *Oper. Res.*, 51(3), 354–370.

Georgy, M. E., Chang, L. M., and Zhang, L. (2005). "Utility-function model for engineering performance assessment." *J. Constr. Eng. Manage.*, 131(5), 558–568.

Guikema, S. D., and Paté-Cornell, M. E. (2002). "Component choice for managing risk in engineered systems with generalized risk/cost functions." *Reliab. Eng. Syst. Saf.*, 78, 227–238.

Halpin, D. W., and Woodhead, R. W. (1998). *Construction management*, 2nd Ed., Wiley, New York.

Hendrickson, C., and Au, T. (2000). *Project management for construction*, 2nd Ed., Carnegie Mellon Univ., Pittsburgh, 33–60.

Kerzner, H. (2003). *Project management: A systems approach to planning, scheduling and controlling*, 8th Ed., Wiley, Hoboken, N.J., 449–458.

Laufer, A., and Tucker, R. L. (1987). "Is construction project planning really doing its job? A critical examination of focus, role and process." *Constr. Manage. Econom.*, 5(3), 243–266.

Mak, S., and Picken, D. (2000). "Using risk analysis to determine construction project contingencies." *J. Constr. Eng. Manage.*, 126(2), 130–136.

Malcolm, D. G., Roseboom, J. H., Clark, C. E., and Fazar, W. (1959). "Application of a technique for research and development program evaluation." *Oper. Res.*, 7(5), 646–669.

Minato, T., and Ashley, D. B. (1998). "Data-driven analysis of corporate risk using historical cost-control-data." *J. Constr. Eng. Manage.*, 124(1), 42–47.

Morgan, G. M., and Henrion, M. (1990). *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis*, Cambridge University Press, New York, 102–168.

Mulholland, B., and Christian, J. (1999). "Risk assessment in construction schedule." *J. Constr. Eng. Manage.*, 125(1), 8–15.

Mustafa, M. A., and Al-Bahar, J. F. (1991). "Project risk assessment using the analytic hierarchy process." *IEEE Trans. Eng. Manage.*, 38(1), 46–50.

Nasir, D., McGabe, B., and Hartono, L. (2003). "Evaluating risk in construction—Schedule model (ERIC-S): Construction schedule risk model." *J. Constr. Eng. Manage.*, 129(5), 518–527.

Öztaş, A., and Ökmen, Ö (2005). "Judgmental risk analysis process development in construction projects." *Build. Environ.*, 40(9), 1244–1254.

Paté-Cornell, M. E. (1984). "Fault trees vs event trees in reliability analysis." *Risk Anal.*, 4(3), 117–185.

RSMeans. (2007). *RS Means building construction cost data*, R.S. Means Company, Kingston, Mass.

Spetzler, C. S., and von Holstein, C. A. S. (1975). "Probability encoding in decision analysis." *Manage. Sci.*, 22(3), 340–354.

Wideman, R. M. (1986). "The PMBOK Report—PMI body of knowledge standard." *Proj. Manage. J.*, 17(3), 15–24.

Willmer, G. (1991). "Time and cost risk analysis." *Comput. Struct.*, 41(6), 1149–1155.

J. Constr. Eng. Manage., 2009, 135(8): 772-781