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Standard Practice for
Measuring Cost Risk of Buildings and Building Systems and Other Constructed Projects[1]

This standard is issued under the fixed designation E1946; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers a procedure for measuring cost risk for buildings and building systems and other constructed projects, using the Monte Carlo simulation technique as described in Guide E1369.

1.2 A computer program is required for the Monte Carlo simulation. This can be one of the commercially available software programs for cost risk analysis, or one constructed by the user.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E631 Terminology of Building Constructions

E833 Terminology of Building Economics

E1369 Guide for Selecting Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Buildings and Building Systems

E1557 Classification for Building Elements and Related Sitework—UNIFORMAT II

E2103 Classification for Bridge Elements—UNIFORMAT II

E2168 Classification for Allowance, Contingency, and Reserve Sums in Building Construction Estimating

3. Terminology

3.1 *Definitions*—For definitions of general terms used in this guide, refer to Terminology E631; and for general terms related to building economics, refer to Terminology E833.

4. Summary of Practice

4.1 The procedure for calculating building cost risk consists of the following steps:

4.1.1 Identify critical cost elements.

4.1.2 Eliminate interdependencies between critical elements.

4.1.3 Select Probability Density Function.

4.1.4 Quantify risk in critical elements.

4.1.5 Create a cost model.

4.1.6 Conduct a Monte Carlo simulation.

4.1.7 Interpret the results.

4.1.8 Conduct a sensitivity analysis.

5. Significance and Use

5.1 Measuring cost risk enables owners of buildings and other constructed projects, architects, engineers, and contractors to measure and evaluate the cost risk exposures of their construction projects.[3] Specifically, cost risk analysis (CRA) helps answer the following questions:

5.1.1 What are the probabilities for the construction contract to be bid above or below the estimated value?

5.1.2 How low or high can the total project cost be?

5.1.3 What is the appropriate amount of contingency to use?

5.1.4 What cost elements have the greatest impact on the project's cost risk exposure?

5.2 CRA can be applied to a project's contract cost, construction cost (contract cost plus construction change orders), and project cost (construction cost plus owner's cost), depending on the users' perspectives and needs. This practice shall refer to these different terms generally as "project cost."

6. Procedure

6.1 *Identify Critical Cost Elements:*

6.1.1 A project cost estimate consists of many variables. Even though each variable contributes to the total project cost risk, not every variable makes a significant enough contribution to warrant inclusion in the cost model. Identify the critical elements in order to simplify the cost risk model.

6.1.2 A critical element is one which varies up or down enough to cause the total project cost to vary by an amount greater than the total project cost's critical variation, and one

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[1] This practice is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.81 on Building Economics.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] This practice is based, in part, on the article, "Measuring Cost Risk of Building Projects," by D.N. Mitten and B. Kwong, Project Management Services, Inc., Rockville, MD, 1996.

which is not composed of any other element which qualifies as a critical element. This criterion is expressed as:

$$IF\ V_Y > V_{CRIT} \quad (1)$$

$$\text{AND Y contains no other element X where } V_X > V_{CRIT}$$

$$\text{THEN Y is a critical element}$$

where:

$$V_Y = \quad (2)$$

$$\frac{(\text{Max. percentage variation of the element Y})*(\text{Y's anticipated cost})}{\text{Total Project Cost}}$$

V_{CRIT} = Critical Variation of the Project Cost.

6.1.3 A typical value for the total project cost's critical variation is 0.5 %.[4] By experience this limits the number of critical elements to about 20. A larger V_{CRIT} will lead to fewer critical elements and a smaller V_{CRIT} will yield more. A risk analysis with too few elements is over-simplistic. Too many elements makes the analysis more detailed and difficult to interpret. A CRA with about 20 critical elements provides an appropriate level of detail. Review the critical variation used and the number of critical elements for a CRA against the unique requirements for each project and the design stage. A higher critical variance resulting in fewer critical elements, is more appropriate at the earlier stages of design.

6.1.4 Arrange the cost estimate in a hierarchical structure such as UNIFORMAT II (Classification E1557 for Buildings or Classification E2103 for Bridges). Table 1 shows a sample project cost model based on a UNIFORMAT II Levels 2 and 3 cost breakdown for a building. The UNIFORMAT II structure of the cost estimate facilitates the search of critical elements for the risk analysis. One does not need to examine every element in the cost estimate in order to identify those which are critical.

6.1.5 Starting at the top of the cost estimate hierarchy (that is, the Group Element level), identify critical elements in a downward search through the branches of the hierarchy. Conduct this search by repeatedly asking the question: Is it possible that this element could vary enough to cause the total building cost to vary, up or down, by more than its critical variation? Terminate the search at the branch when a negative answer is encountered. Examine the next branch until all branches are exhausted and the list of critical elements established (denoted by asterisks in the last column of Table 1). Table 1 and Fig. 1 show the identification of critical elements in the sample project using the hierarchical search technique.

6.1.6 In the sample project, Group Element B10 Superstructure has an estimated cost of $915 000 with an estimated maximum variation of $275 000, which is more than $50 000, or 0.5 % of the estimated total building cost. It is therefore a candidate for a critical element. However, when we examine the Individual Elements that make up Superstructure, we discover that Floor Construction has a estimated maximum variation of $244 500, qualifying as a critical element; whereas Roof Construction could only vary as much as $40 000, and does not qualify. Since Floor Construction is now a critical element, we would eliminate Superstructure, its parent, as a critical element.

6.1.7 Include overhead cost elements in the cost model, such as general conditions, profits, and escalation, and check for criticality as with the other cost elements. Consider time risk factors, such as long lead time or dock strikes for imported material, when evaluating escalation cost.

6.1.8 Allowance and contingency, as commonly used in the construction cost estimates, include both the change element and the risk element. The change element in allowance covers the additional cost due to incomplete design (design allowance). The change element in contingency covers the additional cost due to construction change orders (construction contingency). The risk element in contingency covers the additional cost required to reduce the risk that the actual cost would be higher than the estimated cost. However, the risk element in allowance and contingency is rarely identified separately and usually included in either design allowance or construction contingency. When conducting CRA, do not include the risk element in allowance or contingency cost since that will be an output of the risk analysis. Include design allowance only to the extent that the design documents are incomplete. Include construction contingency, which represents the anticipated increase in the project cost for change orders beyond the signed contract value, if total construction cost, instead of contract cost, is used. See Classification E2168 for information on which costs are properly included under allowance and contingency.

6.1.9 The sample project represents a CRA conducted from the owner's perspective to estimate the construction contract value at final design. General conditions, profits, and escalation are identified as critical elements. Since the design documents are 100 % complete, there is no design allowance. The contingency in the cost element represents the risk element and is therefore eliminated from the cost model. There is no construction contingency in the model since this model estimates construction contract cost only. If total project cost is desired, add other project cost items to the cost model, such as construction contingency, design fees, and project management fees.

6.2 *Eliminate Interdependencies Between Critical Elements:*

6.2.1 The CRA tool works best when there are no strong interdependencies between the critical elements identified. Highly interdependent variables used separately will exaggerate the risk in the total construction cost. Combine the highly dependent elements or extract the common component as a separate variable. For example, the cost for ductwork and the cost of duct insulation are interdependent since both depend on the quantity of ducts, which is a highly uncertain variable in most estimates. Combine these two elements as one critical element even though they both might qualify as individual critical elements. As another example, if a major source of risk is labor rate variance, then identify labor rate as a separate critical element and remove the cost variation associated with labor rates from all other cost elements.

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[4] Curran, M.W., "Range Estimating—Measuring Uncertainty and Reasoning With Risk," *Cost Engineering*, Vol 31, No. 3, March 1989.

TABLE 1 Sample UNIFORMAT II Cost Model

ITEM	GROUP ELEMENT	INDIVIDUAL ELEMENT	GROUP ELEMENT COST	INDIVIDUAL ELEMENT COST	EST MAX/ VARIATION	
A10	FOUNDATIONS		$150 000		$45 000	
A1010		Standard Foundations		$100 000		
A1030		Slab on Grade		$50 000		
A20	BASEMENT CONSTRUCTION		$70 000		$30 000	
A2010		Basement Excavation		$20 000		
A2020		Basement Walls		$50 000		
B10	SUPERSTRUCTURE		$915 000		$275 000	
B1010		Floor Construction		$815 000	$244 500	*
B1020		Roof Construction		$100 000	40 000	
B20	EXTERIOR ENCLOSURE		$800 000		$250 000	
B2010		Exterior Walls		$576 000	$172 800	*
B2020		Exterior Windows		$204 000	$102 000	*
B2030		Exterior Doors		$20 000	$8 000	
B30	ROOFING		$54 000		$20 000	
B3010		Roof Coverings		$54 000		
C10	INTERIOR CONSTRUCTION		$240 000		$72 000	*
C1010		Partitions		$132 000	$45 000	
C1020		Interior Doors		$108 000	$30 000	
C20	STAIRS		$95 000		$40 000	
C2010		Stair Construction		$75 000		
C2020		Stair Finishes		$20 000		
C30	INTERIOR FINISHES		$916 000		$300 000	
C3010		Wall Finshes		$148 000	$45 000	
C3020		Floor Finishes		$445 000	$178 000	*
C3030		Ceiling Finishes		$323 000	$129 200	*
D10	CONVEYING		$380 000			
D1010		Elevators & Lifts		$380 000	$228 000	*
D20	PLUMBING		$142 000		$45 000	
D2010		Plumbing Fxtures		$70 000		
D2020		Domestic Water Distribution		$30 000		
D2030		Sanitary Waste		$22 000		
D2040		Rain Water Drainage		$20 000		
D30	HVAC		$1 057 000		$550 000	
D3010		Energy Supply		$20 000	$8 000	
D3020		Heat Generating Systems		$80 000	$30 000	
D3030		Cooling Generating Systems		$275 000	$137 500	*
D3040		Distribution Systems		$500 000	$300 000	*
D3050		Terminal & Package Units		$60 000	$30 000	
D3060		Controls and Instrumentation		$217 000	$130 200	*
D3070		System Testing & Balancing		$20 000	$10 000	
D40	FIRE PROTECTION		$270 000		$100 000	
D4010		Sprinklers		$220 000	$88 000	*
D4020		Standpipes		$50 000	$15 000	
D50	ELECTRICAL		$985 000		$500 000	
D5010		Electrical Service & Distribution		$180 000	$108 000	*
D5020		Lighting & Branch Wiring		$685 000	$411 000	*
D5030		Communication & Security		$120 000	$45 000	
G10	SITE PREPARATION		$120 000		$45 000	
G1030		Site Earthwork		$120 000		
G20	SITE IMPROVEMENT		$800 000		$450 000	
G2030		Pedestrian Paving		$420 000	$252 000	*
G2050		Landscaping		$380 000	$228 000	*
G30	SITE MECHANICAL UTILITIES		$420 000		$126 000	*
G3010		Water Supply		$120 000	$40 000	
G3020		Sanitary Sewer		$120 000	$42 000	
G3030		Storm Sewer		$140 000	$46 000	
G3060		Fuel Distribution		$40 000	$20 000	
G40	SITE ELECTRICAL UTILITIES		$200 000		$100 000	*
G4010		Electrical Distribution		$100 000	$45 000	
G4020		Site Lighting		$25 000	$15 000	
G4030		Site Communications & Security		$75 000	$42 000	
	SUBTOTAL			$7 729 000		
		GENERAL CONDITIONS		$823 000	$411 500	*
	SUBTOTAL			$8 552 000		
		PROFIT (10 %)		$855 200	$427 600	*
	SUBTOTAL			$9 407 200		
		ESCALATION (5 %)		$470 360	$188 144	*
	SUBTOTAL			$9 877 560		
		CONTINGENCY (5 %)		$493 878		
				$10 371 438		
	TOTAL CONSTRUCTION CONTRACT COST					
		* Meets criteria for critical elements				

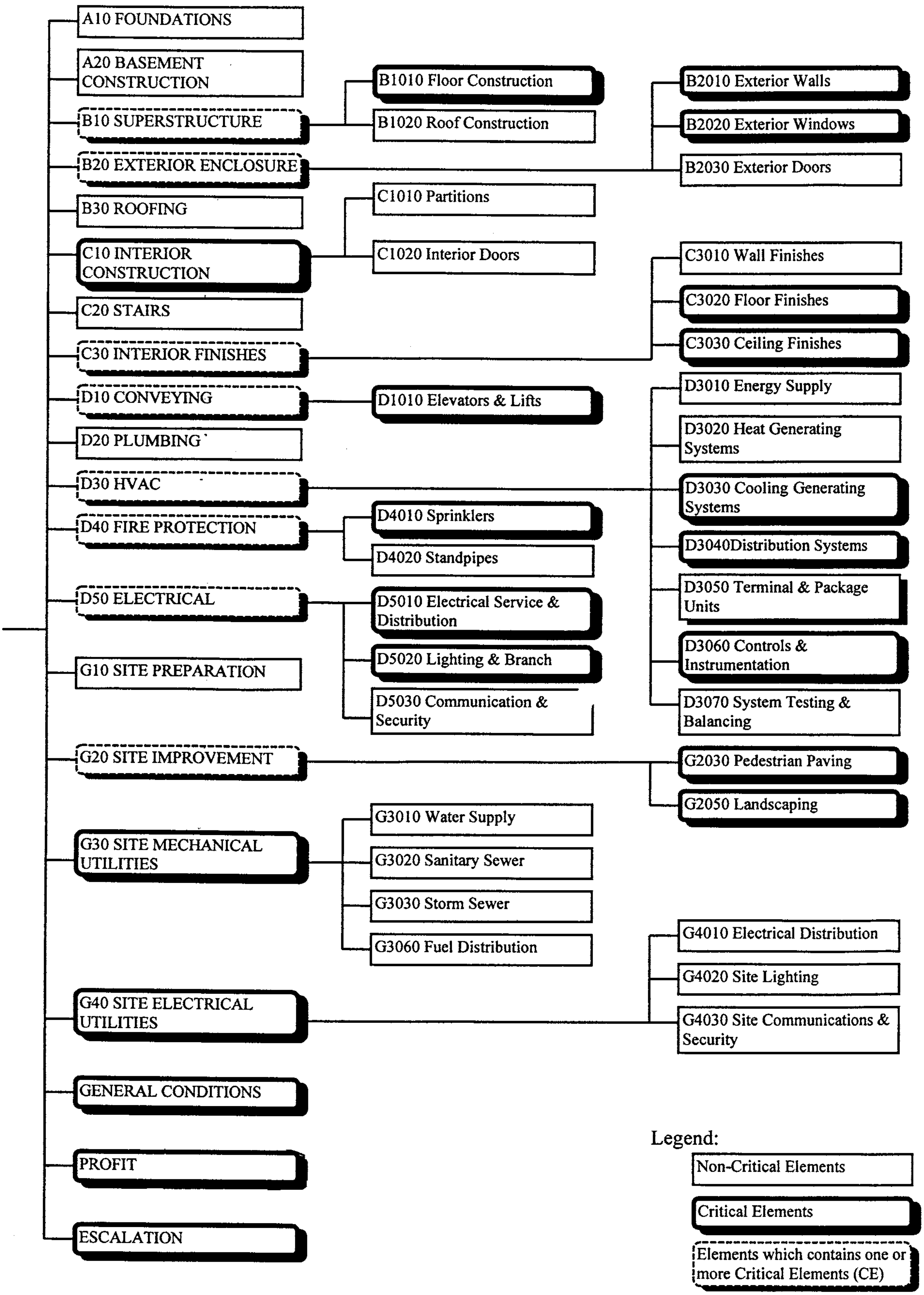

FIG. 1 Identification of Critical Elements in the Sample Project

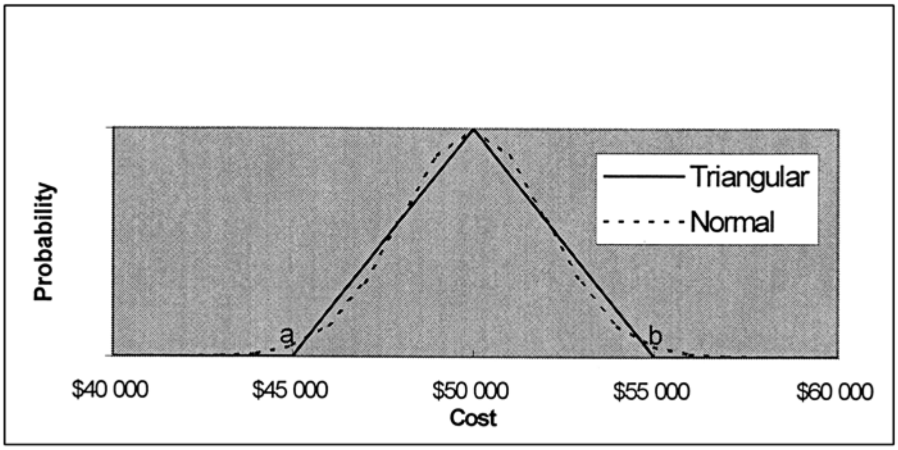

FIG. 2 Comparison of Triangular PDF to Normal Distribution Function

6.2.2 In the sample project, a percentage escalation is treated as a separate cost element, instead of having the escalation embedded in each cost element. The escalations for all cost elements are highly correlated because they all depend on the general escalation rate in material and labor. Therefore the model is more accurate when taking escalation as a separate cost element. Treat escalation as a critical element if it causes the total cost to vary by more than 0.5 %.

6.3 *Select Probability Density Function (PDF):*

6.3.1 Assign a PDF to each critical element to describe the variability of the element. Select the types of PDFs that best describe the data. These include, but are not restricted to, the normal, lognormal, beta, and triangular distributions. In the construction industry, one does not always have sufficient data to specify a particular distribution. In such a case a triangular distribution function has some advantages.[5] It is the simplest to construct and easiest to conceptualize by the team of design and cost experts. The triangular PDF assumes zero probability below the low estimate and above the high estimate, and the highest probability at the most likely estimate. Straight lines connect these three points in a probability density function, forming a triangle, thus giving the name triangular distribution.

6.3.2 Because the triangular distribution function is only an approximation, the low and high estimates do not represent the absolute lowest and highest probable value. As compared to the more realistic "normal distribution," these values represent about the first and 99th percentiles, respectively. In other words, there is a 1 % chance that the value will be lower than the low estimate (point "a" on Fig. 2) and another 1 % chance that it will be higher than the high estimate (point "b" on Fig. 2). The triangular distribution is a reasonably good approximation of the normal distribution except at the extreme high or low ends. However, for construction estimates, there is rarely a requirement for values below the 5th and above the 95th percentile. Therefore, there is no significant loss of model accuracy in using the triangular distribution.

6.4 *Quantify Risks in Critical Elements:*

6.4.1 Quantify the risk for each element by a most likely estimate, a low estimate, and a high estimate. Table 2 shows the list of critical elements identified in the sample project, with the associated three point estimates. As discussed in the previous section, the high and low estimates should capture the middle 98 % of the probable outcome for the element. The most likely estimate, on the other hand, represents value with highest probability of occurrence, and is the peak of the triangular distribution. This may not coincide with the single value cost estimate since the single value is most often interpreted as the mean or median, rather than the mode. On a skewed triangular distribution, the mean (average), median, and mode (most likely) values are all different (Fig. 3).

6.4.2 There may be a tendency to select low estimates that are not low enough, and high estimates that are not high enough. In part this is a result of not being able to envision lowest and highest possible outcomes. It may be helpful to quantify the high and low estimates in a narrower band (for example, 10th and 90th percentiles). Then adjust these estimates to get the two extreme points on the triangular distribution.

$$HE = MLE + (HE' - MLE)*r \tag{3}$$

$$LE = MLE - (MLE - LE')*r \tag{4}$$

where:

MLE = most likely estimate,
HE = high estimate on the triangular distribution,
LE = low estimate on the triangular distribution,
HE' = high estimate given an alternative percentile,
LE' = low estimate given an alternative percentile,
r = adjustment factor which can be calculated using the inverse normal cumulative function, and
r = 1.82 for 10th and 90th percentiles.

6.4.3 The coefficients of variation (standard deviation divided by the mean) for line items in trade estimates range from 13 % to 45 %,[6] with a weighted average of 22 %. These are based on rates on selected items from the lowest bidders of similar projects. Note that the middle 98 % of normal distribution's value occur within ±2.3 standard deviations of the

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[5] Biery, F., Hudak, D., and Gupta, S., "Improving Cost Risk Analysis," *Journal of Cost Analysis*, Spring 1994.

[6] Beeston, D.T., "One Statistician's View of Estimating," Property Services Agency, Department of Environment, London, UK, July 1974.

TABLE 2 Sample Critical Element Input List

	CRITICAL ELEMENT	LOW	MOST LIKELY	HIGH
B1010	Floor Construction	$652 000	$815 000	$1 059 500
B2010	Exterior Walls	$460 800	$576 000	$748 800
B2020	Exterior Windows	$142 800	$204 000	$306 000
C10	Interior Construction	$192 000	$240 000	$312 000
C3020	Floor Finishes	$333 750	$445 000	$623 000
C3030	Ceiling Finishes	$226 100	$323 000	$452 200
D1010	Elevators & Lifts	$228 000	$380 000	$608 000
D3030	Cooling Generating Systems	$192 500	$275 000	$412 500
D3040	Distribution Systems	$300 000	$500 000	$800 000
D3060	Controls & Instrumentation	$108 500	$217 000	$347 200
D4010	Sprinklers	$154 000	$220 000	$308 000
D5010	Electrical Service & Distribution	$108 000	$180 000	$228 000
G5020	Lighting & Branch Wiring	$411 000	$685 000	$1 096 000
G2030	Pedestrian Paving	$210 000	$420 000	$672 000
G2050	Landscaping	$228 000	$380 000	$608 000
G30	Site Mechanical Utilities	$336 000	$420 000	$546 000
G40	Site Electrical Utilities	$140 000	$200 000	$300 000
	General Conditions	$493 800	$823 000	$1 234 500
	Profit	4 %	10 %	15 %
	Escalation	3 %	5 %	7 %

mean. This corresponds to an average range estimate of 2.3 × 22 % = 50 %. Therefore, the typical high estimate should be about 150 % of the most likely estimate; and the low estimate about 50 % of the most likely estimate. This serves as a check on the range estimates.

6.5 *Create a Cost Model:*

6.5.1 The cost model is essentially the hierarchical cost estimate. Treat all non-critical elements as constants. Simplify the cost model by combining constants.

6.5.2 In the sample project, the cost model becomes:

$$\left(\sum \mathrm{COST}_{\mathrm{CE}} + \$1\,249\,000\right)*(1+\mathrm{Profit})*(1+\mathrm{Escalation}) \qquad (5)$$

where:

$\mathrm{COST}_{\mathrm{CE}}$ = variable cost for the critical elements 1 through 18,
$1 249 000 = total cost for all the non-critical elements;
Profit and Escalation = variable percentages.

6.5.3 For triangular PDFs, the random cost of each critical element is calculated by the formula:

$$\mathrm{COST}_{\mathrm{CE}} = \mathrm{LE} + [\mathrm{RV}*(\mathrm{MLE}-\mathrm{LE})*(\mathrm{HE}-\mathrm{LE})]^{0.5} \qquad (6)$$

$$\textit{if } COST_{CE} \leq MLE$$

$$\mathrm{COST}_{\mathrm{CE}} = \mathrm{HE} - [(1-\mathrm{RV})*(\mathrm{HE}-\mathrm{MLE})*(\mathrm{HE}-\mathrm{LE})]^{0.5} \qquad (7)$$

$$\text{if } \mathrm{COST}_{\mathrm{CE}} > \mathrm{MLE}$$

where:

RV = a random variable between 0 and 1.

Use the same random variable for each formula. After calculating both formulas, use the one which satisfies the corresponding condition on the right.

6.5.4 For example, for the critical element Floor Construction, if RV = 0.3, the two equations become:

$$\mathrm{COST}\ (\mathrm{Floor\ Const.}) = \$652\,000 + [0.3*(\$815\,000 - \$652\,000)*(\$1\,059\,500 - \$652\,000)]^{0.5} \qquad (8)$$

$$= \$793\,162, \text{ which satisfies the condition COST} \leq \$815\,000$$

$$\mathrm{COST}\ (\mathrm{Floor\ Const.}) = \$1\,059\,500 - [0.7*(\$1\,059\,500 - \$815\,000)*(\$1\,059\,500 - \$652\,000)]^{0.5} \qquad (9)$$

$$= \$795\,410, \text{ which does not satisfy the condition COST} > \$815\,000$$

The result from Eq 8 will be used since it satisfies the corresponding condition.

6.6 *Conduct a Monte Carlo Simulation:*

6.6.1 Run a Monte Carlo simulation once the risk in the critical elements are quantified and the model set up. The Monte Carlo method builds up a PDF for the bottom line project cost by repeatedly running the model with randomly generated numbers for the critical elements according to the individual PDFs. Each Critical element will use a separate random number for the calculation. Each time the model is run, one point is generated for the total project cost risk PDF. The process is repeated until the total project cost risk PDF "converges" or settles into a final shape, which often requires 1,000 or more iterations. See Guide E1369, Section 7.7, for a more detailed description of the simulation technique.

6.6.2 To implement a CRA, use commercial software programs or write your own simulation software code.

6.7 *Interpret the Results:*

6.7.1 By inspecting the converged PDF for the bottom line construction cost and its corresponding Cumulative Distribution Function (CDF), obtain the following information:

6.7.1.1 Expected (mean) total cost, which is the average of all the data points generated by the simulation.

6.7.1.2 Standard deviation on the total cost, which is the standard deviation of all the data points generated by the simulation.

6.7.1.3 The confidence level, which is the cumulative percentage corresponding to those data points generated by the simulation which are less than or equal to the estimated amount on the CDF. Fig. 2 illustrates the concept of a confidence level. Denote the low estimate as point "a" and the high estimate as point "b." Because point a corresponds to the 1st percentile of the normal distribution, only 1 % of all occurrences of actual costs will fall below point a. The confidence level associated with point a is therefore 1 %. Similarly, point b corresponds to the 99th percentile of the normal distribution, which implies that 99 % of all occurrence of the actual cost will fall below point "b." The confidence level associated with point "b" is therefore 99 %.

6.7.1.4 Cost estimate for a given confidence level, which is the total cost estimate corresponding to the desired confidence level on the CDF. This cost estimate is designated as COST(CL), where CL indicates the confidence level (for example, 10 %).

6.7.1.5 Contingency is the difference between the total cost estimate for the desired confidence level and the base cost estimate. The contingency is designated as CONT(CL).

6.7.2 Fig. 4 and Fig. 5 show the PDF and CDF for the sample project, respectively. The Monte Carlo simulation generated 4000 data points using a computer spreadsheet. The results are as follows:

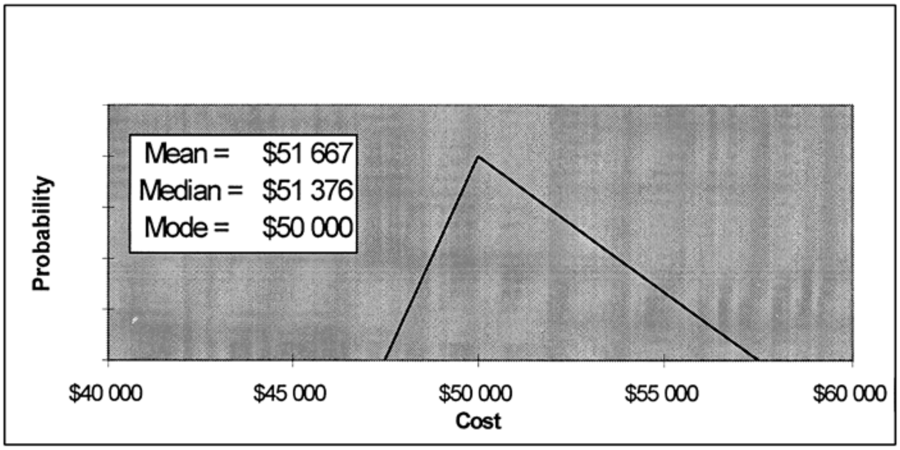

FIG. 3 Skewed Triangular Probability Distribution Function

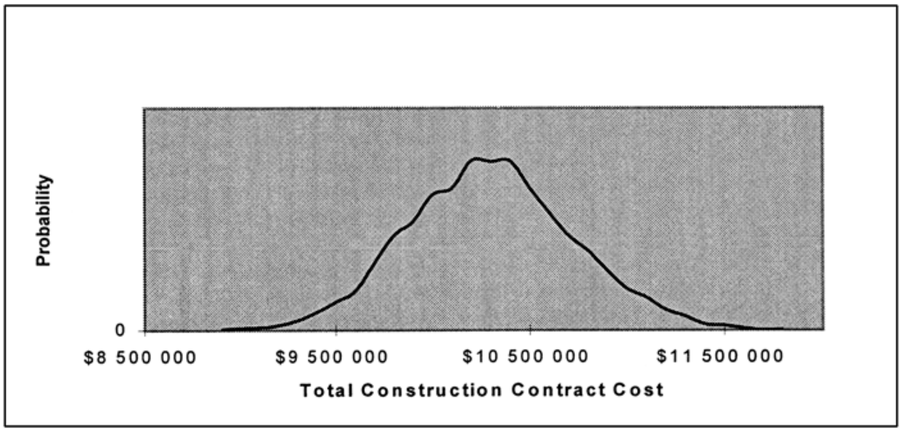

FIG. 4 Sample Probability Density Function Resulting from Monte Carlo Simulation

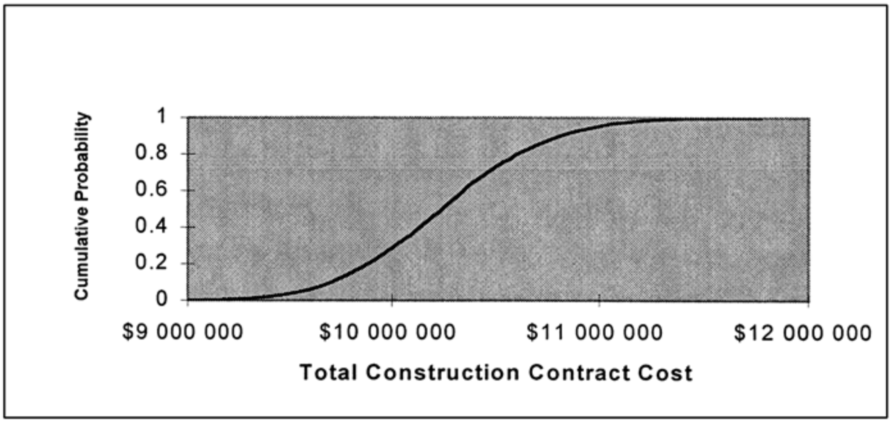

FIG. 5 Sample Cumulative Distribution function Resulting from Monte Carlo Simulation

6.7.2.1 The expected (mean) total contract cost is $10 246 000, which is higher than the deterministic cost estimate of $9 877 560.

6.7.2.2 The standard deviation of the sample of total contract cost is $430 000, or 4.19 % of the mean.

6.7.2.3 The contingency used in the deterministic cost estimate (that is, $493 878) corresponds to a confidence level of 63.0 % (that is, COST(63 %) – $9 877 560 = $493 878).

6.7.2.4 The total cost estimate for each confidence level is:

COST(10 %) = $9 706 000
COST(25 %) = $9 951 000
COST(50 %) = $10 240 000
COST(75 %) = $10 526 000
COST(90 %) = $10 809 000
COST(95 %) = $10 983 000

TABLE 3 SAMPLE SENSITIVITY ANALYSIS

ITEM	CRITICAL ELEMENT	LOW	MOST LIKELY	HIGH	MEAN	VARIANCE	VARIANCE CONTRIBUTION	% OF TOTAL VARIANCE
B1010	Floor Construction	$652 000	$815 000	$1 059 500	$842 167	7.01E+09	9.35E+09	5 %
B2010	Exterior Walls	$460 800	$576 000	$748 800	$595 200	3.50E+09	4.67E+09	3 %
B2020	Exterior Windows	$142 800	$204 000	$306 000	$217 600	1.13E+09	1.51E+09	1 %
C10	Interior Construction	$192 000	$240 000	$312 000	$248 000	6.08E+089	8.11E+08	0 %
C3020	Floor Finishes	$333 750	$445 000	$623 000	$467 250	3.55E+09	4.73E+09	3 %
C3030	Ceiling Finishes	$226 100	$323 000	$452 200	$333 767	2.14E+09	2.86E+09	2 %
C1010	Elevators & Lifts	$228 000	$380 000	$608 000	$405 333	6.10E_09	8.13E+09	4 %
D3030	Cooling Generating Systems	$192 500	$275 000	$412 500	$293 333	2.06E+09	2.75E+09	2 %
D3040	Distribution Systems	$300 000	$500 000	$800 000	$533 333	1.06E+10	1.41E+10	8 %
D3060	Controls & Instrumentation	$108 500	$217 000	$347 200	$224 233	2.38E+09	3.18E+09	2 %
D4010	Sprinklers	$154 000	$220 000	$308 000	$227 333	9.95E+08	1.33E+09	1 %
D5010	Electrical Service & Distribution	$108 000	$108 000	$288 000	$192 000	1.37E+09	1.82E+09	1 %
G5020	Lighting & Branch Wiring	$411 000	$685 000	$1 096 000	$730 667	1.98E+10	2.64E+10	14 %
G2030	Pedestrian Paving	$210 000	$420 000	$672 000	$434 000	8.92E+09	1.19E+10	7 %
G2050	Landscaping	$228 000	$380 000	$608 000	$405 333	6.10E+09	8.13E+09	4 %
G30	Site Mechanical Utilities	$336 000	$420 000	$546 000	$434 000	1.86E+09	2.48E+09	1 %
G40	Site Electrical Utilities	$140 000	$200 000	$300 000	$213 333	1.09E+09	1.45E+09	1 %
	General Conditions	$493 800	$823 000	$1 234 500	$850 433	2.30E+10	3.06E+10	17 %
	Profit	4 %	10 %	15 %	9.67 %	5.06E-04	4.08E+10	22 %
	Escalation	3 %	5 %	7 %	5.00 %	6.67E-05	5.90E-09	3 %
	TOTAL		$7 303 000		$7 647 317		1.83E+11	

6.7.2.5 Given the deterministic cost estimate in Table 1, the contingencies by confidence level are as follows:

CONT(50 %) = $362 000 (3.7 %)
CONT(75 %) = $648 000 (6.6 %)
CONT(90 %) = $931 000 (9.4 %)
CONT(95 %) = $1 105 000 (11.2 %)

6.8 *Conduct a Sensitivity Analysis:*

6.8.1 Use sensitivity analysis to determine the relative contribution of each critical element to the total building cost risk.

6.8.2 The mean and variance for the triangular distribution are:

$$\text{Mean} = (\text{HE}+\text{MLE}+\text{LE})/3 \tag{10}$$

$$\text{Variance} = (\text{HE}^2+\text{MLE}^2+\text{LE}^2 - \text{HE}*\text{LE} - \text{MLE}*\text{LE} - \text{MLE}*\text{HE})/18 \tag{11}$$

See Eq 3 and Eq 4 for the variable definitions. The arithmetic for variance of a function of independent random variables are:

$$\text{VAR}(\text{A}+\text{B}) = \text{VAR}(\text{A})+\text{VAR}(\text{B}) \tag{12}$$

$$\text{VAR}(\text{A}+\text{c}) = \text{VAR}\ (\text{A}) \tag{13}$$

$$\text{VAR}(\text{c}*\text{A}) = \text{c}^2*\text{VAR}(\text{A}) \tag{14}$$

where:

VAR = variance,
A, B = function of independent random variables,
c = constant.

6.8.3 Calculate the contribution of each critical element to the total variance by holding all other variables constant. Multiply the variance of that element by the square of the multiplication factors. In the sample project, the variance contributed by the critical elements is calculated with the following formulas and the results for the sample project are tabulated in Table 3.

$$\text{VAR}_{\text{TBC}}(\text{COST}_{\text{CE}}) = \text{VAR}(\text{COST}_{\text{CE}})*[(1+\text{Profit})*(1+\text{Escalation})]^2 \tag{15}$$

$$\text{VAR}_{\text{TBC}}\ (\text{Profit}) = \text{VAR}(\text{Profit})*[(\textstyle\sum \text{COST}_{\text{CE}}+\$1\,249\,000)*(1+\text{Escalation})]^2 \tag{16}$$

$$\text{VAR}_{\text{TBC}}\ (\text{Escalation}) = \text{VAR}\ (\text{Escalation})*[(\textstyle\sum \text{COST}_{\text{CE}}+\$1\,249\,000)*(1+\text{Profit})]^2 \tag{17}$$

where:

VAR_{TBC} = contribution to the Total Building Cost Variance.

6.8.4 In the sample project, for Floor Construction:

$$\begin{aligned}\text{VAR}(\text{Floor Construction}) &= (1\,059\,500^2+815\,000^2+652{,}000^2 \\ &\quad -1\,059\,500*652\,000 - 815\,500*652\,000 - 815\,000*1\,059\,500)/18 \\ &= 7\,010\,000\,000\end{aligned} \tag{18}$$

$$\text{VAR}_{\text{TBC}}(\text{Floor Construction}) = 7\,010\,000\,000*[(1.10)*(1.05)]^2 = 9\,350\,000\,000$$

And for profits:

$$\begin{aligned}\text{VAR}(\text{Profit}) &= (0.15^2+0.10^2+0.04^2 - 0.15*0.04- \\ &\quad 0.10*0.04 - 0.10*0.15)/18 \\ &= 0.000506\end{aligned} \tag{19}$$

$$\text{VAR}_{\text{TBC}}(\text{Profit}) = 0.000506*[\$8\,552\,000*1.05]^2 = 40\,800\,000\,000$$

The sum of all VAR_{TBC} are 1.85×10^{11}. The percentage of total variance are:

$$\%\mathrm{VAR}(\text{Floor Construction}) = 9.35 \times 10^{9}/1.83 \times 10^{11} = 5\ \% \quad (20)$$

$$\%\mathrm{VAR}(\text{Profits}) = 4.08 \times 10^{10}/1.83 \times 10^{11} = 22\ \%$$

6.8.5 Note that there is no simple expression for VAR (A * B). The variance contribution for the variables that are multiplied together (for example, escalation and profit in the example) is therefore not additive and the sum of all $\mathrm{VAR}_{\mathrm{TBC}}$ will exceed 100 %. However, the individual $\mathrm{VAR}_{\mathrm{TBC}}$ provides a good relative measure of cost risk.

6.8.6 Table 3 shows that the major contributors of cost variance are Profits (22 %), General Conditions (17 %), Lighting and Branch Wiring (14 %), and HVAC Distribution System (8 %). These are the items that should be investigated if reduction in contract cost risk is desired.

7. Applications

7.1 *Budgetary Control*—CRA allows an owner to examine the cost risk exposure of the project starting from the planning phase. Instead of a single value of project cost, the owner has the range and probability of possible project cost and uses this information for contingency planning.

7.2 *Alternative Evaluation*—CRA allows the owner and the architect/engineer to evaluate the project alternatives based on cost risk exposures as well as construction cost. An alternative with a higher cost but lower cost risk exposure than another will be preferable to some owners since the likely amount of cost overrun will be lower. An example is a stalemate in the labor negotiation with the local sheetmetal workers union, which has a potential impact on the cost and availability for the labor to install HVAC distribution systems during the project. The owner/project manager reduces cost risk by using factory preformed ductwork, which has a higher material cost but significantly lower field labor requirement.

7.3 *Competitive Bidding*—Contractors use CRA to identify the acceptable risk exposure on a project and make an informed decision on the bid amount.

7.4 *Negotiation*—CRA informs the negotiating parties of a construction contract on the magnitude of cost risk and helps them allocate risk between the owner and the contractor as appropriate.

7.5 *Project Management*—CRA helps the project manager pinpoint the source of cost risk, monitor the remaining cost risk exposure, and reduce total project cost risk. The options are to accept or mitigate the risks. If the risks are acceptable, no further action needs to be taken, except to assure sufficient funding to cover the required contingency. If the risks are unacceptably high, then explore alternative design or construction methods, or both, to reduce the risk. In the sample project, an investigation shows that the main light fixture type is a historical replication and therefore a custom item, with a high cost risk. To manage the risk, the owner/project manager changes the requirements so that off-the-shelf fixtures are acceptable.

8. Keywords

8.1 cost model; cost risk analysis; Monte Carlo simulation; sensitivity analysis; UNIFORMAT II