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

This standard is issued under the fixed designation E 1946; 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 establishes a procedure for measuring cost risk for buildings and building systems, using the Monte Carlo simulation technique as described in Guide E 1369.

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:*

E 833 Terminology of Building Economics[2]

E 1369 Guide for Selecting Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Buildings and Building Systems[2]

E 1557 Classification for Building Elements and Related Sitework - UNIFORMAT II[2]

3. Terminology

3.1 *Definitions*—For definition of terms used in this guide, refer to Terminology E 833.

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 Building cost risk analysis (BCRA) provides a tool for building owners, architects, engineers, and contractors to measure and evaluate the cost risk exposures of their building construction projects.[3] Specifically, BCRA 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 building's cost risk exposure?

5.2 BCRA can be applied to a building 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 "building cost."

6. Procedure

6.1 *Identify Critical Cost Elements*:

6.1.1 A building cost estimate consists of many variables. Even though each variable contributes to the total building 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 building cost to vary by an amount greater than the total building cost's critical variation, and one which is not composed of any other element which qualifies as a critical element. This criterion is expressed as:

$$IF\ V_Y > V_{CRIT} \tag{1}$$

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

THEN Y is a critical element

where:

$$V_Y = \frac{\text{(Max. percentage variation of the element Y) * (Y's anticipated cost)}}{\text{Total Building cost}} \tag{2}$$

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

6.1.3 A typical value for the total building 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

[1] This practice is under the jurisdiction of ASTM Committee E-6 on Performance of Buildings and is the direct responsibility of Subcommittee E06.81 on Building Economics.

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[2] *Annual Book of ASTM Standards*, Vol 04.11.

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

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

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 BCRA with about 20 critical elements provides an appropriate level of detail. Review the critical variation used and the number of critical elements for a BCRA 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 E 1557). Table 1 shows a sample project cost model based on a UNIFORMAT II Levels 2 and 3 cost breakdown. 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. 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 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 Contingency, as commonly used in the building cost estimates, includes both the change element and the risk element. The change element in contingency covers the additional cost due to incomplete design (design contingency) or 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 contingency is rarely identified separately and usually included in either design or construction contingencies. When conducting BCRA, do not include the risk element in contingency cost since that will be an output of the risk analysis. Include design contingency 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.

6.1.9 The sample project represents a BCRA 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 contingency. 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 BCRA 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.

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

[5] Biery, Fred, Hudak, David, Gupta, Shishu, "Improving Cost Risk Analysis," *Journal of Cost Analysis*, Spring 1994.

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		
		PROFITS (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				

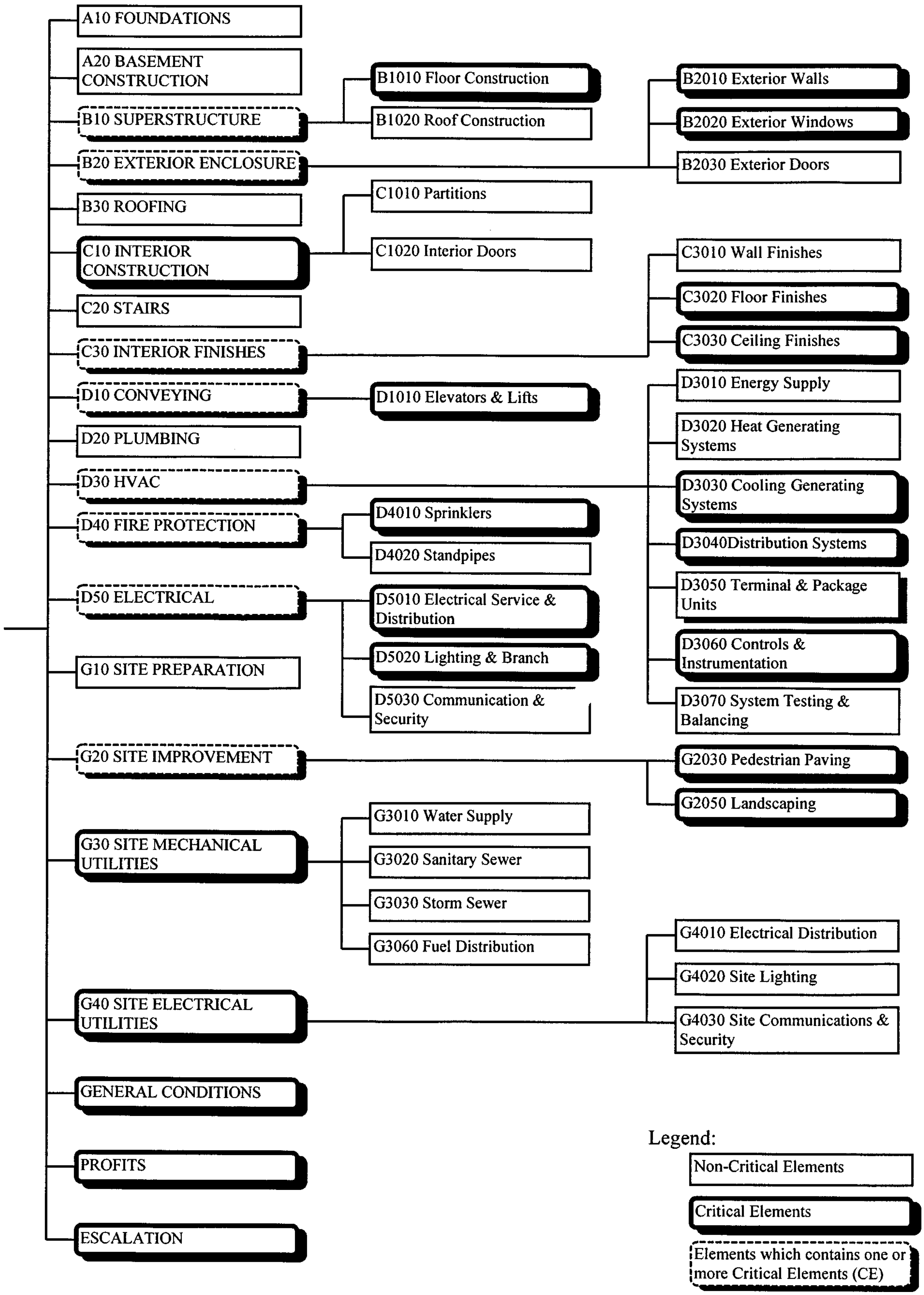

FIG. 1 Identification of Critical Elements in the Sample Project

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 building 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.

$$HE = MLE + (HE' - MLE) * r \quad (3)$$

$$LE = MLE - (MLE - LE') * r \quad (4)$$

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 mean. This corresponds to an average range estimate of 2.3

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
	Profits	4 %	10 %	15 %
	Escalation	3 %	5 %	7 %

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

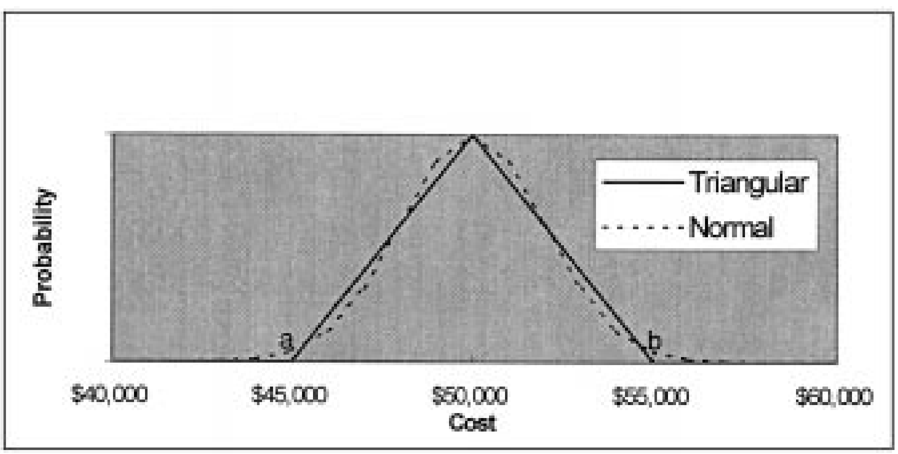

FIG. 2 Comparison of Triangular PDF to Normal Distribution Function

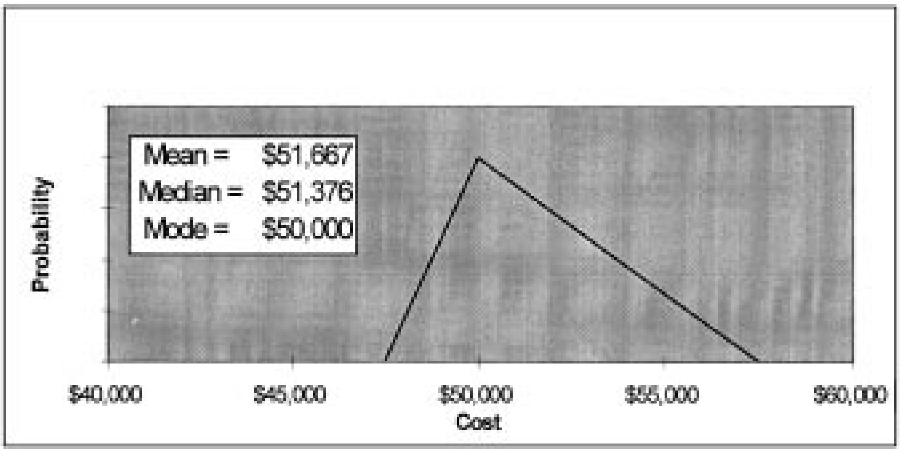

FIG. 3 Skewed Triangular Probability Distribution Function

× 22 % = 50 %. Therefore, the typical high estimate shoud 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:

$$(\Sigma \text{ COST}_{CE} + \$1{,}249{,}000) * (1 + \text{Profit}) * (1 + \text{Escalation}) \quad (5)$$

where:

$COST_{CE}$ = 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:

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

$$\text{if COST}_{CE} \leq \text{MLE}$$

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

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

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:

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

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

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

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

The result from the first equation 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 building 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 building cost risk PDF. The process is repeated until the total building cost risk PDF "converges" or settles into a final shape, which often requires 1,000 or more iterations. See Guide E 1369, section 7.7, for a more detailed description of the simulation technique.

6.6.2 To implement a BCRA, 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, which 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 4,000 data points using a computer spreadsheet. The results are as follows:

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).

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

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:

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

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

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

$$VAR(A + B) = VAR(A) + VAR(B) \quad (12)$$

$$VAR(A + c) = VAR(A) \quad (13)$$

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

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.

$$VAR_{TBC}(COST_{CE}) = VAR(COST_{CE}) * [(1 + Profit) * (1 + Escalation)]^2 \quad (15)$$

$$VAR_{TBC}(Profit) = VAR(Profit) * [(\Sigma\, COST_{CE} + \$1,249,000) * (1 + Escalation)]^2 \quad (16)$$

$$VAR_{TBC}(Escalation) = VAR(Escalation) * [(\Sigma\, COST_{CE} + \$1,249,000) * (1 + Profit)]^2 \quad (17)$$

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

6.8.4 In the sample project, for Floor Construction:

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

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

And for profits:

$$VAR(Profit) = (0.15^2 + 0.10^2 + 0.04^2 - 0.15{*}0.04 - 0.10{*}0.04 - 0.10{*}0.15) / 18 = 0.000506 \quad (19)$$

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

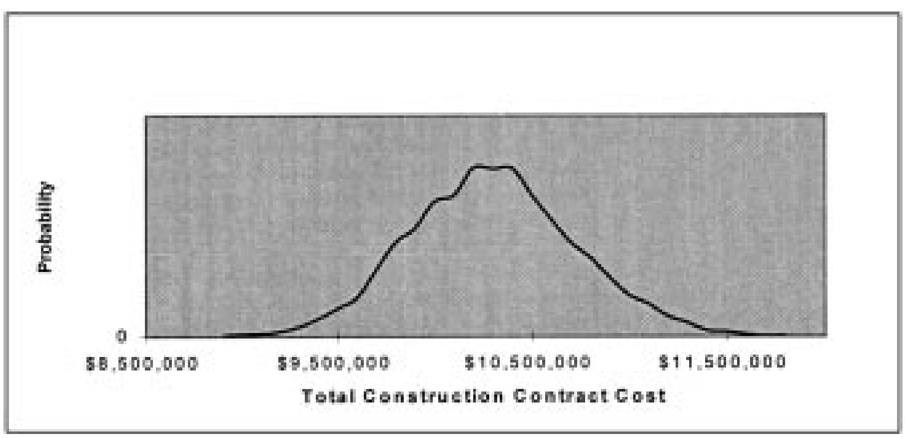

FIG. 4 Sample Probability Density Function Resulting from Monte Carlo Simulation

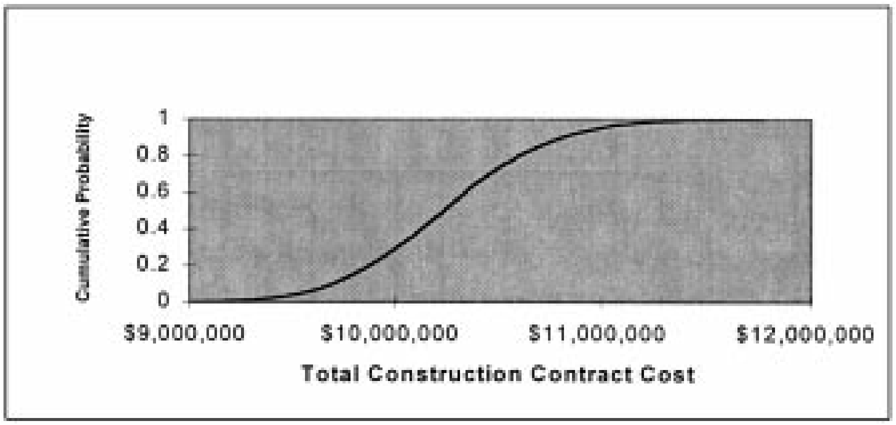

FIG. 5 Sample Cumulative Distribution function Resulting from Monte Carlo Simulation

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 %
	Profits	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	

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

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

$$\%VAR(\text{Profits}) = 4.08 \times 10^{10}/\ 1.83 \times 10^{11} = 22\ \% \quad (20)$$

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 VAR_{TBC} will exceed 100 %. However, the individual VAR_{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*—BCRA allows an owner to examine the cost risk exposure of the project starting from the planning phase. Instead of a single value of building cost, the owner has the range and probability of possible building cost and uses this information for contingency planning.

7.2 *Alternative Evaluation*—BCRA allows the owner and the architect/engineer to evaluate the project alternatives based on cost risk exposures as well as building 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 BCRA to identify the acceptable risk exposure on a project and make an informed decision on the bid amount.

7.4 *Negotiation*—BCRA 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*—BCRA helps the project manager pinpoint the source of cost risk, monitor the remaining cost risk exposure, and reduce total building 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.