Designation: E917 – 15

Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems[1]

This standard is issued under the fixed designation E917; 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.

INTRODUCTION

Several methods of economic evaluation are available to measure the economic performance of a building or building system over a specified time period. These methods include, but are not limited to, life-cycle cost (LCC) analysis, the benefit-to-cost ratio, internal rate of return, net benefits, payback, multiattribute decision analysis, risk analysis, and related measures (see Practices E964, E1057, E1074, E1121, E1765, and E1946). These methods differ in their measure and, to some extent, in their applicability to particular types of problems. Guide E1185 directs you to the appropriate method for a particular economic problem. One of these methods, life-cycle cost (LCC) analysis, is the subject of this practice. The LCC method sums, in either present-value or annual-value terms, all relevant costs associated with a building or building system over a specified time period. Alternative (mutually exclusive) designs or systems for a given functional requirement can be compared on the basis of their LCCs to determine which is the least-cost means of satisfying that requirement over a specified study period.

1. Scope

1.1 This practice establishes a procedure for evaluating the life-cycle cost (LCC) of a building or building system and comparing the LCCs of alternative building designs or systems that satisfy the same functional requirements.

1.2 The LCC method measures, in present-value or annual-value terms, the sum of all relevant costs associated with owning and operating a building or building system over a specified time period.

1.3 The basic premise of the LCC method is that to an investor or decision maker all costs arising from an investment decision are potentially important to that decision, including future as well as present costs. Applied to buildings or building systems, the LCC encompasses all relevant costs over a designated study period, including the costs of designing, purchasing/leasing, constructing/installing, operating, maintaining, repairing, replacing, and disposing of a particular building design or system.

1.4 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E631 Terminology of Building Constructions
E833 Terminology of Building Economics
E964 Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems
E1057 Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems
E1074 Practice for Measuring Net Benefits and Net Savings for Investments in Buildings and Building Systems
E1121 Practice for Measuring Payback for Investments in Buildings and Building Systems
E1185 Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems
E1369 Guide for Selecting Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Buildings and Building Systems
E1765 Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments

[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.

Related to Buildings and Building Systems

E1946 Practice for Measuring Cost Risk of Buildings and Building Systems and Other Constructed Projects

E2204 Guide for Summarizing the Economic Impacts of Building-Related Projects

2.2 *Adjuncts:*

Discount Factor Tables Adjunct to Practices E917, E964, E1057, E1074, and E1121[3]

3. Terminology

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

4. Summary of Practice

4.1 This practice outlines the recommended procedures for computing the LCCs associated with a building or building system over a specified time period. It identifies and gives examples of objectives, alternatives, and constraints for an LCC analysis; identifies project data and general assumptions needed for the analysis; and presents alternative approaches for computing LCCs. This practice requires that the LCCs of alternative building designs or systems be compared over a common time period to determine which design or system has the lowest LCC. This practice also states that uncertainty, unquantifiable effects, and funding constraints shall be considered in the final analysis. It identifies the recommended contents of an LCC report, describes proper applications of the LCC method, provides examples of its use, and identifies limitations of the method. A comprehensive example of the LCC method applied to a building economics problem is provided in Appendix X1. A comprehensive example illustrating the treatment of uncertainty within the LCC method is provided in Appendix X2. Appendix X3 provides a detailed example analyzing the life-cycle cost implications resulting from energy efficiency improvements in a high school building. Appendix X4 provides a description of the Adjunct.

5. Significance and Use

5.1 LCC analysis is an economic method for evaluating a project or project alternatives over a designated study period. The method entails computing the LCC for alternative building designs or system specifications having the same purpose and then comparing them to determine which has the lowest LCC over the study period.

5.2 The LCC method is particularly suitable for determining whether the higher initial cost of a building or building system is economically justified by reductions in future costs (for example, operating, maintenance, repair, or replacement costs) when compared with an alternative that has a lower initial cost but higher future costs. If a building design or system specification has both a lower initial cost and lower future costs relative to an alternative, an LCC analysis is not needed to show that the former is the economically preferable choice.

5.3 If an investment project is not essential to the building operation (for example, replacement of existing single-pane windows with new double-pane windows), the project must be compared against the "do nothing" alternative (that is, keeping the single pane windows) in order to determine if it is cost effective. Typically the "do nothing" alternative entails no initial investment cost but has higher future costs than the proposed project.

6. Procedure

6.1 Follow these steps in calculating the LCC for a building or building system:

6.1.1 Identify objectives, alternatives, and constraints (see Section 7).

6.1.2 Establish basic assumptions for the analysis (see 8.1).

6.1.3 Compile cost data (see 8.2).

6.1.4 Compute the LCC for each alternative (see Section 9).

6.1.5 Compare LCCs of each alternative to determine the one with the minimum LCC (see 10.1).

6.1.6 Make final decision, based on LCC results as well as consideration of risk and uncertainty, unquantifiable effects, and funding constraints (if any) (see 10.2, 10.3, 10.4, and 10.5).

7. Objectives, Alternatives, and Constraints

7.1 Specify the design or system objective that is to be accomplished, identify alternative designs or systems that accomplish that objective, and identify any constraints that limit the available options to be considered.

7.2 An example is the selection of a space heating system for a new house. The system must satisfy the thermal comfort requirements of the occupants throughout the heating season. Available alternatives (for example, various gas furnaces, oil furnaces, heat pumps, and electric baseboard heaters) may have different types of fuel usage with different unit costs, different fuel conversion efficiencies, different initial costs and expected maintenance and repair costs, and different lives. System selection will be constrained to those fuel types available at the building site.

8. Data and Assumptions

8.1 *Basic Assumptions*—Establish the uniform assumptions to be made in the economic analysis of all alternatives. These assumptions usually include, but are not limited to, the consistent use of the present-value or annual-value calculation method, the base time and study period, the general inflation rate, the discount rate, the marginal income tax rate (where relevant), the comprehensiveness of the analysis, and the operational profile of the building or system to be evaluated.

8.1.1 *Present-Value Versus Annual-Value Calculations*—The LCCs of project alternatives must be calculated uniformly in present-value or annual-value terms. In the former, all costs are discounted to the base time; in the latter, all costs are converted to a uniform annual amount equivalent to the present value when discounted to the base time.

8.1.2 *Study Period*—The study period appropriate to the LCC analysis may or may not reflect the life of the building or system to be evaluated. The same study period must be used for each alternative when present-value calculations are used. An

[3] Available from ASTM International Headquarters. Order Adjunct No. ADJE091703. Original adjunct produced in 1984. Adjunct last revised in 1985.

annual-value LCC may, under certain restrictive assumptions, be used to compare alternatives with different study periods (see 9.2.3). The following guidelines may be useful for selecting a study period for an LCC analysis:

8.1.2.1 When analyzing a project from an individual investor's standpoint, the study period should reflect the investor's time horizon. For a homeowner, the study period for a house-related investment might be based on the length of time the homeowner expects to reside in the house. For a commercial property owner, the study period might be based on the anticipated holding period of the building. For an owner/occupant of a commercial building, the study period might correspond to the life of the building or building system being evaluated. For a speculative investor, the study period might be based on a relatively short holding period. For investments by government agencies and large institutions, specific internal policies often direct the choice of study period.

8.1.2.2 When LCC analyses of alternative building systems or design practices are performed for general information rather than for a specific application (for example, government or industry research to determine the cost effectiveness of thermal insulation or high-efficiency heating and cooling equipment in typical installations), the study period will often coincide with the service life of the material or system (but be limited to the typical life of the type of building where it is to be installed). When the service life is very long, a more conservative choice for the study period might be used if the uncertainty associated with the long-term forecasting of costs substantially reduces the credibility of the results.

8.1.2.3 Regardless of the type of investor or purpose of the analysis, use the same study period for all categories of costs when calculating the present value of any cost associated with a project. Furthermore, when comparing alternative designs or systems on the basis of their present-value LCCs, use the same study period for each investment alternative.

8.1.2.4 When the study period selected is significantly shorter than the service life of the building or system evaluated, it is important that a realistic assessment of the project's resale (or residual) value at the end of the study period be included in the LCC analysis. Even if the building will not be sold at that time, the resale value will likely have a significant impact on the LCC.

8.1.3 *Inflation*—General price inflation is the reduction in the purchasing power of the dollar from year to year, as measured, for example, by the percent increase in the gross national product (GNP) deflator over a given year. LCC analyses can be calculated in constant-dollar terms (net of general inflation) or in current-dollar terms (including general inflation). If the latter is used, a consistent projection of general price inflation must be used throughout the LCC analysis, including adjustment of the discount rate to incorporate the general inflation rate.

8.1.3.1 When income tax effects are not included in the LCC analysis, as in the case of LCC evaluations of nonprofit buildings and owner-occupied houses (without financing), it is usually easier to express all costs in constant dollars. Price changes for individual cost categories that are higher or lower than the rate of general inflation can be included by using differential rates of price change for those categories.

8.1.3.2 When income tax effects are included in the LCC analysis, it is usually easier to express all costs in current dollars because income taxes are tied to current-dollar cash flows rather than constant-dollar cash flows.

8.1.4 *Discount Rate*—The discount rate selected should reflect the investor's time value of money. That is, the discount rate should reflect the rate of interest that makes the investor indifferent between paying or receiving a dollar now or at some future point in time. The discount rate is used to convert costs occurring at different times to equivalent costs at a common point in time.

8.1.4.1 Select a discount rate equal to the rate of return on the next best available use of funds. Where the discount rate is legislated or mandated for a given institution, that rate takes precedence.

8.1.4.2 A discount rate that includes general price inflation over the study period is referred to as the "nominal" discount rate in this practice. A discount rate expressed in terms net of general price inflation is referred to as the "real" discount rate.

8.1.4.3 A nominal discount rate, i, and its corresponding real discount rate, r, are related as follows:

$$r = \frac{1+i}{1+I} - 1 \text{ or } i = (1+r)(1+I) - 1 \quad (1)$$

where:

I = the rate of general price inflation.

8.1.4.4 Use a real discount rate if estimates of future costs are expressed in constant dollars, that is, if they do not include general inflation.

8.1.4.5 Use a nominal discount rate if estimates of future costs are expressed in current dollars, that is, if they include general inflation.

8.1.4.6 When alternative building or system designs are compared using the LCC method, use the same discount rate in each LCC computation.

8.1.5 *Comprehensiveness*—Different levels of effort can be applied in undertaking an LCC analysis. The appropriate level of comprehensiveness depends upon the degree of complexity of the problem, the intended purpose of the evaluation, the level of monetary and nonmonetary impacts contingent upon the investment decision, the cost of the different levels of comprehensiveness, and the resources available to the investor or decision maker.

8.1.5.1 Some anticipated effects are more difficult to quantify in monetary terms than others. Include effects that are difficult to quantify through the use of multiattribute decision analysis (see Practice E1765). (See 10.4 for more information on unquantifiable effects.) Overlooking or omitting significant factors from an LCC evaluation diminishes the comprehensiveness and usefulness of the evaluation.

8.1.5.2 Comprehensiveness requires that all suitable alternatives be considered when selecting among alternative designs or systems for a particular purpose.

8.1.6 *Income Taxes*—For building investments that are subject to income tax, include in the analysis adjustments of capital costs, expenses, and resale value to reflect income tax effects (see 9.3).

8.2 *Cost Data*—Compile the cost data required to estimate the LCC of each alternative design or system to be evaluated. This includes the timing of each cost as it is expected to occur during the study period.

8.2.1 The measurement of the LCC of a building design or building system requires data on initial investment costs, including the costs of planning, design, engineering, site acquisition and preparation, construction, purchase, and installation; financing costs (if specific to the investment decision); annually and non-annually recurring operating and maintenance costs (including, for example, scheduled and unscheduled maintenance, repairs, energy, water, property taxes, and insurance); capital replacement costs; and resale value (or salvage/disposal costs).

8.2.2 Data will also be needed for functional use costs if these costs are significantly affected by the design or system alternatives considered. These are costs related to the performance of the intended functions within the building, such as salaries, overhead, services, and supplies.

8.2.3 The shorter the study period selected for the LCC analysis relative to the expected useful lifetime of the project being considered, the more important the assessment of resale value becomes, even if the building or system will not be sold at the end of the study period. Where relevant, deduct tax liabilities due to anticipated gains in asset value.

8.2.4 Omit from LCC evaluation costs that are not significantly affected by the design decision or system selection.

8.2.5 To select among design or system alternatives solely on the basis of the lowest LCC presumes that each alternative is at least capable of satisfying the project requirements and that the analyses have been conducted using the same operational profile. When there are performance advantages that favor one alternative over another, make an adjustment to incorporate such differences into the LCC measure. For example, adjustments are needed to reflect higher rental income, higher sales, improved comfort, or improved employee productivity for one design relative to the other. Make this adjustment to the LCC by subtracting the value of any improvement in performance from the corresponding costs of that alternative in each year that such differences occur. However, do not use the LCC method if such improvements are large relative to the cost differences among alternatives (see 13.1).

8.2.6 *Timing of Cash Flows*—In addition to compiling all relevant costs, the timing of each cash flow must be determined. The time of occurrence is needed so that costs incurred at different points in time can be discounted to their time-equivalent values before summation.

8.2.6.1 Cash flows may be single events, such as a one-time replacement cost or a resale value. They may be recurring and relatively constant in nature, such as routine maintenance costs, or they may occur at regular intervals but change over time at some projected rate of increase or decrease, such as energy costs.

8.2.6.2 Cash flows may occur in lump-sum amounts, concentrated at a certain time of the year, such as an annual insurance premium. They may be spread out evenly over the year, such as salaries, or they may occur irregularly during the year. Rather than accounting for the specific pattern of each cash flow, a simplifying model of cash flow is usually adopted for an LCC analysis. In the simplified model, all cash flows in a given year are assumed to occur at the same point in time within the year, usually at the end of the year. This simplifying assumption normally provides sufficient accuracy for the LCC analysis while reducing computational requirements. (The discounting methods outlined in Section 9 are all based on end-of-year cash flows.)

8.2.7 *Current Dollar Analysis*—When all cash flows over the study period are to be denominated in current dollars (that is, when general price inflation is included in projecting all future costs), the following guidelines apply:

8.2.7.1 Future cash flows that are fixed in amount (such as loan payments) should be used without adjustments.

8.2.7.2 Future cash flows that are expected to change at rates significantly different from the general rate of price increase (for example, energy costs) should be estimated on the basis of the specific rate of price change expected, be it faster or slower than the general rate of price inflation.

8.2.7.3 All other future cash flows should be estimated to reflect the rate of general price inflation.

8.2.8 *Constant Dollar Analysis*—When all cash flows over the study period are to be denominated in constant dollars (that is, when general price inflation is excluded in projecting all future costs), the following guidelines apply:

8.2.8.1 Cash flows expected to increase at the same rate as general price inflation require no adjustment. Their values should be stated in base-year dollars.

8.2.8.2 Future costs expected to change faster (slower) than the rate of general price inflation, I, can be estimated in base-year constant dollars by multiplying the base-time value of such costs by the differential rate of price change (see Note 1) for that cost category, as follows:

$$C_t = C_0(1+e)^t \quad (2)$$

where:

e = the differential price escalation rate,
C_t = the constant-dollar value of a cost in year t, and
C_0 = the cost at the beginning of the study period (the base time).

8.2.8.3 The differential rate of price change, e, and the actual rate of price change, E, are related as follows:

$$e = \frac{1+E}{1+I} - 1 \text{ or } E = (1+e)(1+I) - 1 \quad (3)$$

NOTE 1—In Eq 2 and Eq 3, e and I are assumed to be constant over the study period. If e and I are not the same in each time period i, then:

$$C_t = C_0 \ (1+e_1)(1+e_2)\ldots(1+e_t)$$

where:

$$e_i = \frac{1+E_i}{1+I_i} - 1 \text{ or } E_i = (1+e_i)(1+I_i) - 1$$

9. Compute LCC[4]

9.1 To compute the LCC of a building or building system, all relevant cash flows in periods $t = 0$ through $t = N$ are discounted to a common point in time and summed.

9.1.1 Conceptually, the computation of an LCC in present-value terms (PVLCC) can be represented as:

$$\text{PVLCC} = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \quad (4)$$

where:

C_t = the sum of all relevant costs occurring in year t,
N = length of study period, years, and
i = the discount rate.

9.1.2 For example, at the base time ($t = 0$), C_t is typically equal to the initial investment cost; in each subsequent year ($t = 1$ to N), C_t is typically equal to the sum of operating, maintenance, and replacement costs in that year; at the end of the study period ($t = N$), C_t also typically includes a credit for the resale value of the project.

9.2 For ease of computation, the following equivalent approach can be used instead of Eq 4:

9.2.1 Find the present value (PV) of each cost category (for example, initial cost (IC), maintenance and repairs (M), replacements (R), fuel (F), and resale value (S)), using the appropriate discount formula as found in Table 1, or the equivalent discount factor from the adjunct Discount Factor Tables (see 2.2). Then sum these present value amounts to find PVLCC, as shown in Eq 5.

$$\text{PVLCC} = \text{IC} + \text{PVM} + \text{PVR} + \text{PVF} - \text{PVS} \quad (5)$$

Note that resale value, when explicitly expressed as a positive cash flow, is subtracted from the other cost categories in calculating the PVLCC. (If the cost of removal results in a negative cash flow, this should be added to the other cost categories.)

9.2.2 Each of the following patterns of cash flows has a specific type of discounting procedure that can be used to expedite the calculation of the present value for each cost category:

9.2.2.1 Amounts expected to occur at a single point in time (for example, capital replacement costs and resale value) can be discounted to present value by multiplying that amount by the single present value factor for the specified time and discount rate.

9.2.2.2 Amounts expected to occur in approximately the same amount from year to year (for example, operating and maintenance (O and M) costs when expressed in constant dollars) can be discounted to present value by multiplying the annual cost by the uniform present value factor for the specified study period and discount rate.

9.2.2.3 Amounts changing over time at some projected rate (for example, energy costs) can be discounted to present value by multiplying the annual cost, as of the base time, by the modified uniform present value factor for the specified study period and discount rate.

9.2.2.4 Initial investment costs (or any other costs occurring at time $t = 0$) need not be discounted to present value since they are already stated in present-value terms.

9.2.3 The LCC, or any present-value amount, may also be expressed in equivalent annual-value terms (AV) by multiplying the present-value amount by an appropriate uniform capital recovery (UCR) factor, as shown in Table 1. The annual-value LCC may be used, under restrictive assumptions, to compare alternative building systems using different study periods. This approach assumes that all costs for each system are exactly replicated with each replacement for a length of time equal to the lowest common multiple of system lives (that is, the shortest time period into which each of the system lives can be divided with no remainder).

9.2.4 Table 2 illustrates the use of the discount formulas and factors to find present values and annual value equivalents for the set of cost data displayed in Fig. 1 (see Note 2). Fig. 2 illustrates graphically the relationship between these data and their equivalent present values.

NOTE 2—For any given set of cost data and assumptions, the present value of an investment and the annual value of the same investment are time-equivalent values.

9.3 *Income Tax Adjustments*—For investor-owned building facilities, income tax adjustments (including tax credits, if any) may be a significant factor in determining the cost effectiveness of alternative building designs or system selection. Therefore, include them in the analysis.

9.3.1 One method of including income tax effects is to adjust all costs that are tax deductible to their after-tax equivalents before discounting, deduct any tax credits from investment costs, establish a depreciation schedule for capital components and compute the corresponding tax savings in each year, and adjust the resale value (if any) for additional tax liabilities or savings related to capital gains, capital losses, and depreciation recapture, as appropriate. Calculate the present value of each cash flow category and the depreciation tax savings and sum these present values to find the after-tax PVLCC. Note that the present value of the depreciation tax savings is treated as a negative cost and therefore has a negative sign in the PVLCC equation.

9.3.2 An alternative method of including income tax effects is to establish a separate category for all income tax adjustments in each year, calculate these annual amounts and discount them to present value, sum them, and adjust the PVLCC accordingly.

10. Compare LCCs and Make Final Decision

10.1 After computing LCC measures for each alternative design or system to be considered, compare them to determine which alternative has the lowest LCC.

10.1.1 If the overall performance of the alternatives is otherwise equal, or if performance differences have been taken into account in the computation of the LCCs, the alternative with the lowest LCC is preferred on economic grounds.

[4] The NIST Building Life-Cycle Cost (BLCC) Computer Program helps users calculate measures of worth for buildings and building components that are consistent with ASTM standards. The program is downloadable from http://www.eere.energy.gov/femp/information/download_blcc.html.

TABLE 1 Discount Formulas

Equation Name	Schematic Illustration	Application	Algebraic Form[A,B]
Single compound amount (SCA)	[P] → [F?]	to find *F* when *P* is known	$F = P \cdot [(1 + i)^N]$
Single present value (SPV)	[P?] ← [F]	to find *P* when *F* is known	$P = F \cdot \left(\frac{1}{(1+i)^N}\right)$
Uniform sinking fund (USF)	[A?] + [A?] . . . + [A?] ← [F]	to find *A* when *F* is known	$A = F \cdot \left(\frac{i}{(1+i)^N - 1}\right)$
Uniform capital recovery (UCR)	[P] → [A?] + [A?] . . . + [A?]	to find *A* when *P* is known	$A = P \cdot \left(\frac{i(1+i)^N}{(1+i)^N - 1}\right)$
Uniform compound amount (UCA)	[A] + [A] . . . + [A] → [F?]	to find *F* when *A* is known	$F = A \cdot \left(\frac{(1+i)^N - 1}{i}\right)$
Uniform present value (UPV)	[P?] ← [A] + [A] . . . + [A]	to find *P* when *A* is known	$P = A \cdot \left(\frac{(1+i)^N - 1}{i(1+i)^N}\right)$
Modified uniform present value (UPV*)[C]	[P?] ← [A_1] + [A_2] . . . + [A_n]	to find *P* when known A_0 is escalating at rate *e*	$P = A_0 \cdot \left(\frac{1+e}{i-e}\right) \cdot \left[1 - \left(\frac{1+e}{1+i}\right)^N\right]$

where:
P = present sum of money,
F = future sum of money equivalent to *P* at the end of *N* periods of time at *i* interest or discount rate,
A = end-of-period payment (or receipt) in a uniform series of payments (or receipts) over *N* periods at *i* interest or discount rate,
A_0 = initial value of a periodic payment (receipt) evaluated at the beginning of the study period,
$A_t = A_0 \cdot (1 + e)^t$, where $t = 1, \dots, N$,
N = number of interest or discount periods,
i = interest or discount rate, and
e = price escalation rate per period.

[A] Note that the USF, UCR, UCA, and UPV equations yield undefined answers when $i = 0$. The correct algebraic forms for this special case would be as follows: USF formula, $A = F/N$; UCR formula, A = P ⁄ N; UCA formulas, $F = A \cdot N$. The UPV* equation also yields an undefined answer when $e = i$. In this case, P = A_0 ·N.
[B] The terms by which the known values are multiplied in these equations are the formulas for the factors found in Discount Factor Tables. Using acronyms to represent the factor formulas, the discounting equations can also be written as $F = P \cdot$SCA, $P = F \cdot$SPV, $A = F \cdot$USF, $A = P \cdot$UCR, $F = A \cdot$UCA, $P = A \cdot$UPV, and $P = A_0 \cdot$UPV*.
[C] To find *P* when A_t changes from year to year at a different rate each year (either due to a change in price or a change in physical quantity, or both), use the following equation:

$$P = \sum_{t=1}^{N} \frac{A_t}{(1+i)^t}$$

where:
A_t = $A_{t-1} \cdot (1 + e_t)$, and
e_t = the rate of change in *A* for year *t*.

10.1.2 If a proposed project is nonessential to the building operation, compare it against the LCC of the "do-nothing" alternative. Select the alternative with the minimum LCC, other things equal.

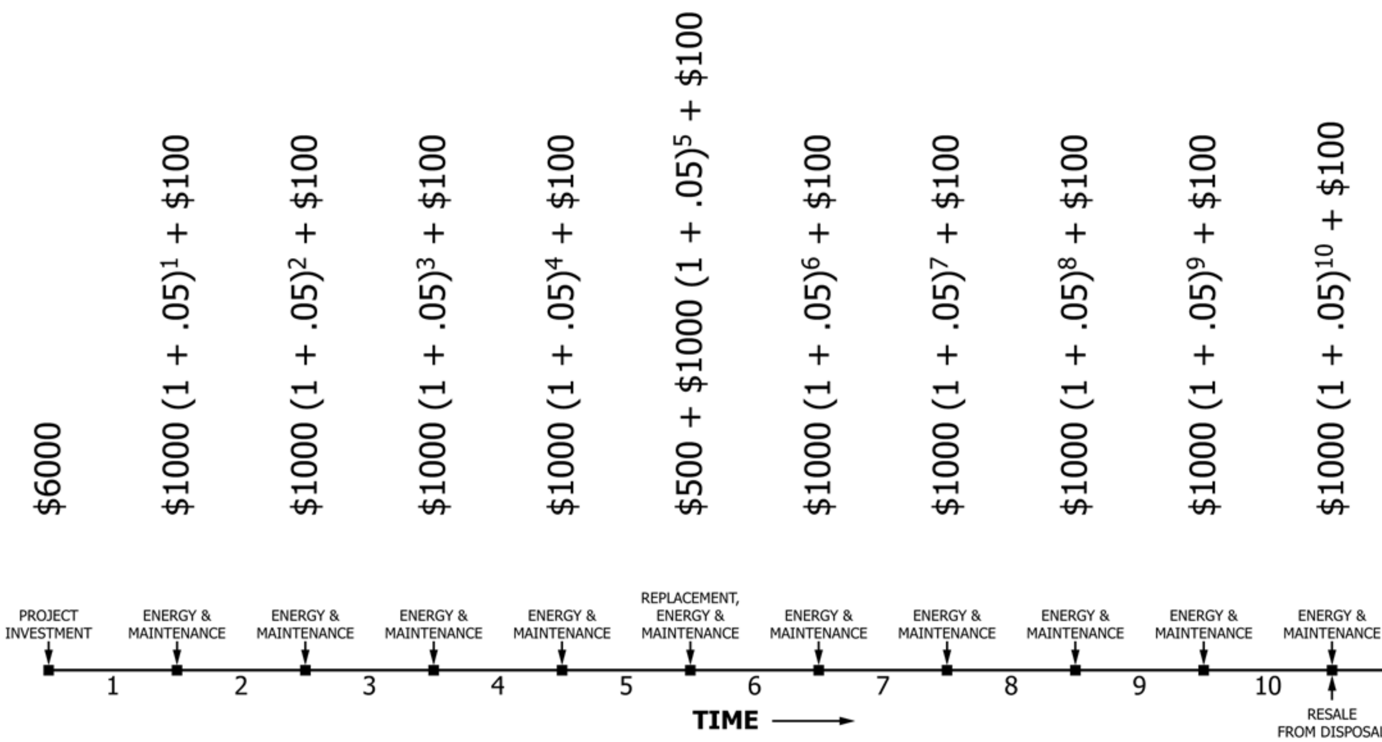
10.2 The decision process for selecting among alternatives includes consideration of not only the comparative LCCs of competing designs, but the risk exposure of each alternative relative to the investor's tolerance for risk, any unquantifiable aspects attributable to the design alternatives, and the availability of funding and other cash-flow constraints.

10.3 *Risk and Uncertainty*—Decision makers typically experience uncertainty about the correct values to use in establishing basic assumptions and in estimating future costs. Guide E1369 recommends techniques for treating uncertainty in input values to an economic analysis of a building investment project. It also recommends techniques for evaluating the risk that a project will have a less favorable economic outcome than what is desired or expected. Practice E1946 establishes a procedure for measuring cost risk for buildings and building

TABLE 2 Illustration of Discounting Cash Flows
(Based on Study Period of 10 Years and Real Discount Rate of 8 %)

Description of Cash Flow (1)	Discounting to Present Value Equivalents			Discounting to Annual Value Equivalents		
	Discount Formula[A] (2)	Corresponding Discount Factor[B] (3)	Present Value, Dollars[C] (4)	Discount Formula (5)	Corresponding Discount Factor (6)	Annual Value, Dollars[D] (7)
Initial investment cost of $6000	n.a.[E]	1	6000	UCR	0.14903	894
Replacement cost in fifth[F] year of $500, constant $	SPV	0.6806	340	UCR	0.14903	51
Yearly (non-energy) O and M cost over 10 years of $100, constant $[F]	UPV	6.710	671	UCR	0.14903	100
Yearly energy cost over 10 years, valued at $1000 at the beginning of the study period, escalating at a differential rate of 5 % per year[F]	UPV*	8.5923	8593	UCR	0.14903	1281
Resale value of $1200 at end of tenth year, constant $	SPV	0.4632	556	UCR	0.14903	83

[A] From Table 1.
[B] From Discount Factor Tables Adjunct.
[C] Column 4 = amount in column 1 × discount factor in column 3.
[D] Column 7 = amount in column 4 × discount factor in column 6.
[E] No discounting necessary.
[F] Payments to occur at the end of the year.



NOTE 1—Arrows above the scale indicate expenditures (cash outflows). Arrows below the scale indicate receipts (cash inflows).

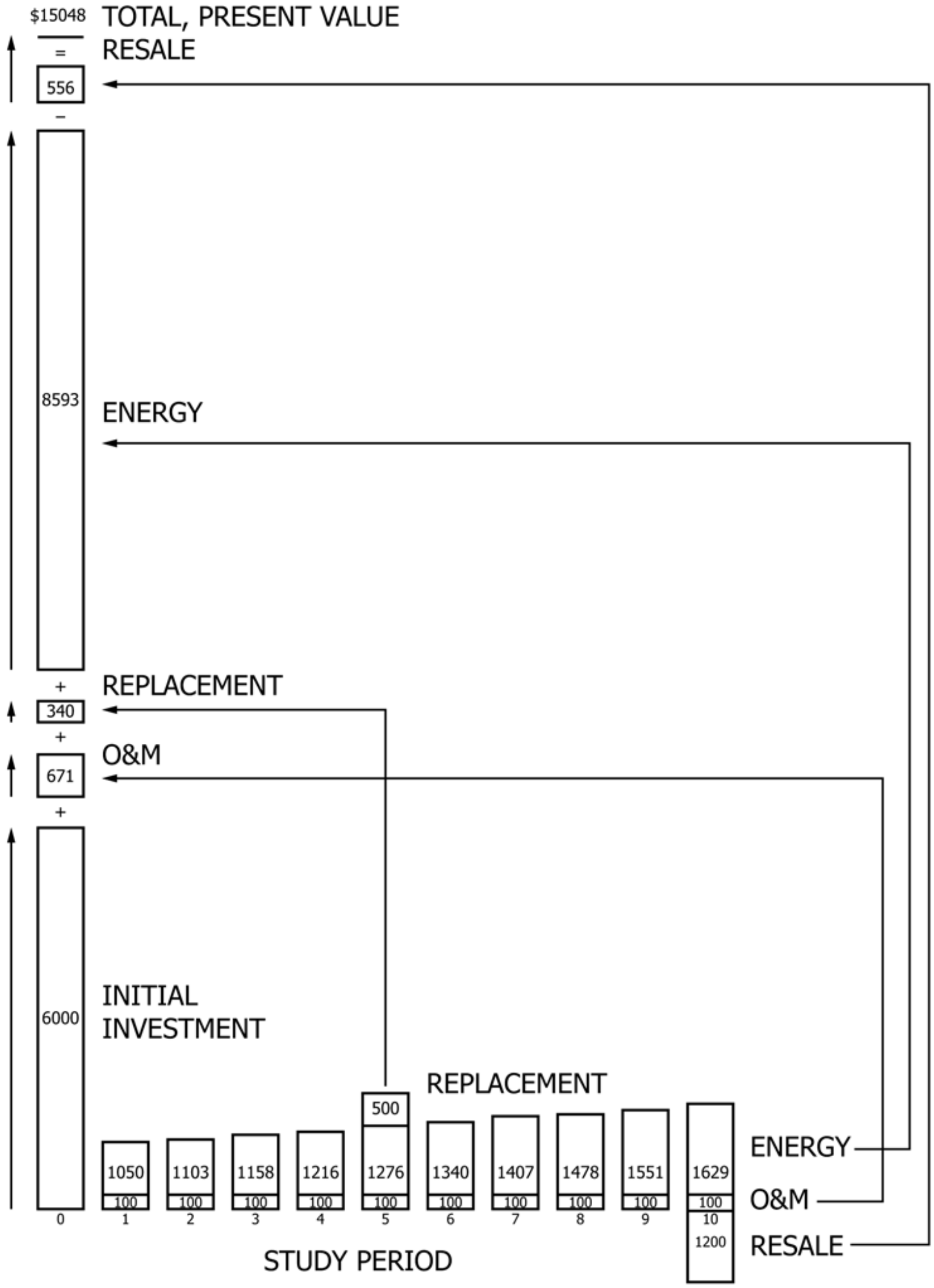
FIG. 1 Illustration of Cash Flow Diagram

systems, using the Monte Carlo simulation technique as described in Guide E1369.

10.3.1 Sensitivity analysis is a test of the outcome of an analysis to alternative values of one or more parameters about which there is uncertainty. It shows decision makers how the economic viability of a project changes as, for example, fuel price escalation, discount rates, study periods, and other critical factors vary.

10.3.1.1 To illustrate, Fig. 3 shows the sensitivity of the present-value of fuel savings to three critical factors: study periods (0 to 25 years), discount rates (0, 5, 10, and 15 %), and energy price escalation rates (0, 5, 10, and 15 %).

10.3.1.2 Note that, other things being equal, present-value savings increase over time, but more slowly with higher discount rates and more quickly with higher price escalation rates. The impact of fuel price escalation is most apparent when comparing the top curve of the graph ($i = 0.10$, $e = 0.15$) with one close to the bottom ($i = 0.10$, $e = 0$). The present value of $1000 of fuel savings per year over 25 years is about $50 000 for a discount rate of 10 % and a fuel price escalation of 15 %,



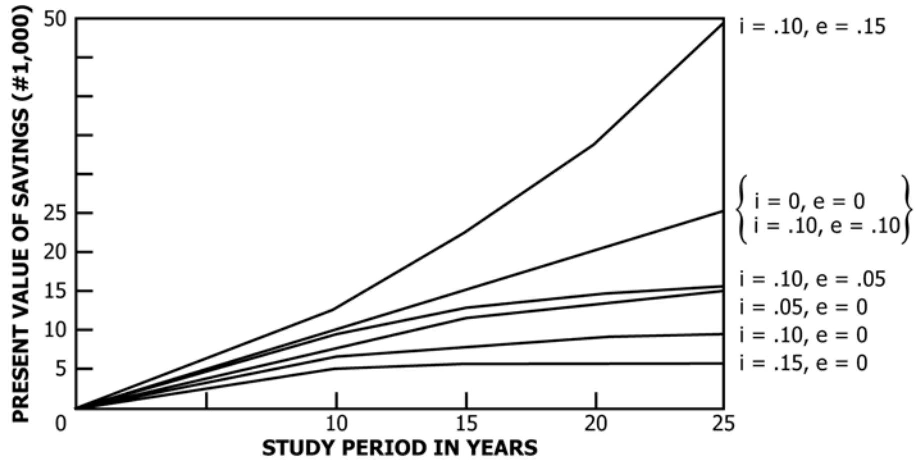
NOTE 1—Cash flows correspond to those given in Fig. 1, and present values correspond to those given in Table 2.

FIG. 2 Illustration of Discounting Cash Flows to Present Value

and only about $9000 for the same discount rate and an escalation rate of 0 %, other things being equal. Whereas the quantity of energy savings and initial prices are the same in all of the cases shown, the present value of the dollar savings varies widely depending on the selection of the escalation rate of fuel prices and the discount rate.

10.3.1.3 Although impact scenarios such as those illustrated in Fig. 3 do not show the analyst what parametric values to choose, they do show decision makers the sensitivity of the results to alternative assumptions. Knowing the consequences of error may help analysts make better decisions about conservation investments with uncertain outcomes.

10.3.2 Probability analysis, sometimes called expected-value analysis, can be used to evaluate the costs and benefits of an event whose expected chance of occurrence can be predicted. Historical data, if available, can be used to generate probability data for existing technologies. Computer simulation is sometimes used to generate data on innovative technologies when historical data are not available.



NOTE 1—i = discount rate, and e = energy escalation rate.

FIG. 3 Sensitivity of Present Value Energy Savings to Study Periods, Discount Rates, and Energy Escalation Rates

10.3.2.1 Table 3 illustrates the application of probability analysis to the problem of estimating the cost of replacing the compressor of a heat pump when the year of replacement is uncertain. The present value of the compressor replacement would differ depending on which year the analyst selects as the likely time of replacement. For example, if year eight were selected, then the present value cost would be $374 ($800·0.467). The expected value of the compressor replacement, on the other hand, as measured in present dollar terms using probability analysis, is shown in Table 3 to be $385. While it is unlikely that the exact cost of replacing the compressor will be predicted using a probabilistic approach, generally, over a large number of applications, the difference between the actual cost and the predicted cost will be less than in the case where a single point estimate is used.

10.3.2.2 Supporting statistical analysis, such as computation of the standard deviation from the expected present value, is useful in assessing the likely variation from predicted results.

10.3.3 Monte Carlo simulation varies a small set of key input variables either singly or in combination according to an experimental design. Associated with each input variable is a probability distribution function from which values are randomly sampled. The major advantage of a Monte Carlo simulation is that it permits the effects of uncertainty to be rigorously analyzed.

TABLE 3 Expected Value of Cost of Compressor Replacement

NOTE 1— Expected Value of Cost = Cost × Probability × SPV.

Year of Replacement	Probability	Cost ($)	SPV 10 % Discount Rate	Expected Present Value Cost ($)
6	0.1	800	0.565	45
7	0.2	800	0.513	82
8	0.6	800	0.467	224
9	0.1	800	0.424	34
Expected value of compressor replacement:				$385

10.3.3.1 In a Monte Carlo simulation, not only the expected value of LCC can be computed but also the variability of that value. In addition, probabilistic levels of significance can be attached to the computed LCC value for each alternative under consideration.

10.3.3.2 Monte Carlo simulation is especially useful when performing economic evaluations of alternatives designed to mitigate the effects of natural or man-made, or both, hazards that occur infrequently but have significant cost consequences. To insure that low-probability, high-consequence outcomes are adequately sampled in the Monte Carlo simulation, do the following. Postulate a probability distribution (for example, uniform or triangular) and a range of values for each of the outcome probabilities having the highest cost consequences. Include these outcome probabilities explicitly as variables in the experimental design, recognizing that for a given hazard, the sum of all outcome probabilities is 1.0. Set the number of iterations for the Monte Carlo simulation high enough to insure adequate sampling of each variable included in the experimental design (Practice E1946 recommends 1000 or more iterations). A comprehensive example on the application of Monte Carlo simulation in combination with the LCC method is provided in Appendix X2.

10.3.3.3 In order to provide a concise summary of the results of the Monte Carlo simulation, report ranges of values or computed statistics for LCC or any other measures of economic performance analyzed in the Monte Carlo simulation.

10.4 *Unquantifiable Effects*—Where the effects of one design relative to another are difficult to quantify but are important to the decision maker, list these in the LCC report, along with guidance as to their relative importance in the final selection. For example, it may be difficult to place a dollar value on the aesthetic appearance of a building facade or a view from a window, but these may be important considerations in selecting among alternative building designs. The unquantifiable effects may either reinforce or offset the quantifiable aspects of the analysis and therefore should not be overlooked in the decision. For a formal method of accounting for unquanifiable effects, see Practice E1765 on multiattribute decision analysis.

10.5 *Funding Constraints*—When insufficient funding is available to finance the project alternative with the lowest LCC, the economic solution may be constrained to an alternative with a lower initial cost but higher future costs. The alternative with the lowest LCC that fits within the funding constraint is the most economical choice under these conditions.

11. Report

11.1 Report the following information:

11.2 A report of an LCC analysis should state the objective, the constraints, the alternatives considered, the key assumptions and data, the present-value or annual-value, or both, of each cost category, and the total present-value or annual-value LCC, or both, of each alternative. Items whose values should be made explicit include the discount rate; the study period; the main categories of cost data, including initial costs, recurring and nonrecurring costs, and resale values; grants; tax deductibles; credits and expenses; and financing terms if integral to the decision-making process. The tax status of the investor should be given. The method of treating inflation should be stated. Assumptions or costs that have a high degree of uncertainty and are likely to have a significant impact on the results of the analysis should be specified and the sensitivity of the results to these assumptions or data described. Any significant effects that remain unquantified should be described in the LCC report.

11.3 A generic format for reporting the results of an LCC analysis is described in Guide E2204. It provides technical persons, analysts, and researchers a tool for communicating results in a condensed format to management and non-technical persons. The generic format calls for a description of the significance of the project, the analysis strategy, a listing of data and assumptions, and a presentation of LCC and any other measures of economic performance. The example presented in Appendix X2 is summarized using the generic format.

12. Applications

12.1 The LCC method is used to determine whether or not a given project that is expected to reduce future costs is economically justified. For example, the replacement of an inefficient heating plant with a new, high-efficiency unit can be evaluated using the LCC method.

12.2 The LCC method is also used to determine the efficient scale of investment when several levels of investment are under consideration. For example, the most economic level of insulation in a roof system is determined by evaluating the alternatives available (for example, R-11, R-19, R-30, R-38, R-49, where the R-value is the measure of thermal resistance, $F \cdot h \cdot ft^2/Btu$ ($K \cdot m^2/W$)) and selecting the level with the lowest LCC.

12.3 Alternative designs or systems for a given purpose are compared on the basis of their LCCs. For example, in a new building, the designer may choose among a number of alternative heating and cooling systems, considering both fuel type and efficiency. The system with the lowest LCC would be the most economical choice, unless unquantifiable effects or riskiness of the technology or fuel availability, or both, weighed against this choice.

12.4 If a number of non-mutually exclusive projects (for example, retrofitting a high-efficiency heating system, a high-efficiency lighting system, and new windows in an existing building) are being considered for a single facility for which a single overall LCC can be calculated, and a limited budget is available to fund those projects, use LCC analysis to allocate that budget efficiently. The combination of projects resulting in the lowest overall LCC for that facility, and whose overall funding requirement fits within the budget constraint, is the most economic combination.

13. Limitations

13.1 LCC analysis is not the method of choice when alternative building designs or systems result in different revenue streams (for example, generate different rental income) or result in other benefits related to the overall performance of the building (for example, more usable space). In these cases economic evaluation methods that pay more explicit attention to benefits should be used. These alternative methods include the net benefits, benefit-to-cost ratio, internal rate of return, and payback methods.

13.2 The LCC method is not suitable for allocating a limited budget among a number of non-mutually exclusive projects (where the acceptance of one does not preclude the acceptance of others), unless all of the projects can be meaningfully combined into the single overall LCC measure. (This can generally be done only when all of the projects are intended to be installed in the same facility (see 12.4).) The savings-to-investment ratio or adjusted internal rate of return measures, which can be used to determine the economic ranking of projects, are more generally applicable to budget allocation problems.

14. Keywords

14.1 building economics; building systems; cost analysis; engineering-economics; life-cycle costs; present-value analysis

APPENDIXES

(Nonmandatory Information)

X1. LIFE-CYCLE COST APPLICATION 1: INDUSTRIAL PLANT CASE STUDY

X1.1 *Investor:* Corporate owner of an existing industrial plant. *Objective:* To provide space heating for the plant at the lowest cost. Alternatives considered: (*1*) Continue use of existing oil-fired furnace using No. 2 fuel oil without modification of the system. (*2*) Purchase and install a waste heat recovery system to the jacket of the plant exhaust stack to supplement the existing space heating furnace and reduce its consumption of fuel oil by 90 %. The data and assumptions to be used in this example are displayed in Table X1.1. The LCC analysis includes income tax savings and a general price inflation rate of 6 % per year.

X1.2 The LCC of each of the two alternatives over the seven-year holding period is calculated and displayed in the series of tables that follow. Tables X1.2-X1.4 give the year-by-year results for Alternative 1; that is, continuing to use the existing oil-fired furnace without modification. Tables X1.5-X1.10 give the results for Alternative 2; that is, supplementing the existing system with a waste heat recovery system. (The LCCs of the alternatives are then compared to determine the lowest cost option.)

X1.3 Table X1.11 provides a direct comparison of the LCC results for Alternatives 1 and 2. As can be seen, the fuel cost reductions from the waste heat recovery system more than offset its after-tax investment and other costs. Therefore, the waste-heat recovery system has the lowest LCC and is the preferred investment alternative on economic grounds.

TABLE X1.1 Sample Investment Problem: Data and Assumptions

Study period (investor's holding period)[A]	7 years
Discount rate	15 %
Inflation rate	6 %
Investment cost data	
Purchase and installation	$35 000
Down payment	$3 500
Loan interest rate	12.5 %
Loan life	7 years
Yearly loan payment	$7 012
Asset life	20 years
Depreciation (straight-line)	$1 750 ⁄year[B]
Loan interest payments	deductible from taxable income
Resale value at end of 7 years[C]	$34 208
Recurring O and M (nonfuel) costs	
Existing furnace[D]	$500/year
Waste heat recovery system	$200/year
O and M costs	deductible from taxable income
Energy costs	
Fuel consumption for space heating without waste heat recovery	1000 MBtu/year (1.056 GJ/year)
Fuel consumption for space heating with waste heat recovery	100 MBtu/year (0.106 GJ/year)
Base year fuel price	$5.69/MBtu ($5.39/GJ)
Annual rate of fuel price increase	8 %
Energy costs	deductible from taxable income
Federal tax rate	28 %
State tax rate	5 %
Combined tax rate[E]	31.6 %

[A] A relatively short study period was selected for this example to facilitate a year-by-year display of costs.
[B] Based on straight-line depreciation, 20-year life, and an original book value of $35 000.
[C] Based on original system cost of $35 000, system deterioration prorated uniformly over 20 years, and appreciation at the rate of general price inflation.
[D] Nonfuel O and M costs for the existing furnace are assumed to be unchanged by addition of the waste-heat recovery system.
[E] To account for the deductability of state tax from federal tax liability, the combined tax rate is 0.28·(1 – 0.05) + 0.05 = 0.316.

TABLE X1.2 Alternative 1: Fuel Costs without Addition of Waste-Heat Recovery System

(1) Year	(2) Base Period Fuel Price, $/MBtu	(3) Annual Fuel Requirement, MBtu	(4) Fuel Price Escalation Multiplier	(5) Annual Fuel Cost After Escalation, $ (2)×(3)×(4)	(6) Corporate Income Tax Rate	(7) Tax Reduction Due to Fuel Cost Deductions (5)×(6)	(8) Annual Fuel Cost After Tax and Escal-ation, $ (5)–(7)	(9) Single Present Value (SPV) Factor	(10) PV of Annual Fuel Cost After Tax and Escalation, $ (8)×(9)
0	7.00	...	...	...	...	...	...	...	...
1	7.00	1 000	$(1 + 0.08)^1$	7 560	0.316	2 389	5 171	0.8696	4 497
2	7.00	1 000	$(1 + 0.08)^2$	8 165	0.316	2 580	5 585	0.7561	4 223
3	7.00	1000	$(1 + 0.08)^3$	8 818	0.316	2 786	6 032	0.6575	3 966
4	7.00	1 000	$(1 + 0.08)^4$	9 523	0.316	3 009	6 514	0.5718	3 724
5	7.00	1 000	$(1 + 0.08)^5$	10 285	0.316	3 250	7 035	0.4972	3 498
6	7.00	1 000	$(1 + 0.08)^6$	11 108	0.316	3 510	7 598	0.4323	3 285
7	7.00	1 000	$(1 + 0.08)^7$	11 997	0.316	3 791	8 206	0.3759	3 085
						Total PV, after-tax, fuel cost			$26 277

TABLE X1.3 Alternative 1: Operation and Maintenance Costs without Addition of Waste-Heat Recovery System

(1) Year	(2) O and M Cost in Base-Year Prices, $	(3) Inflation Multiplier	(4) Annual O and M Cost After Inflation, $ (2)×(3)	(5) Corporate Income Tax Rate	(6) Tax Reduction Due to O and M Cost Deductions, $ (4)×(5)	(7) Annual O and M Cost After Tax and Inflation, $ (4)–(6)	(8) Single Present Value (SPV) Factor	(9) PV of Annual O and M Cost After Tax and Inflation, $ (7)×(8)
0	500.00	...	...	...	...	...	...	...
1	500.00	$(1 + 0.06)^1$	530	0.316	167	363	0.8696	315
2	500.00	$(1 + 0.06)^2$	562	0.316	178	384	0.7561	291
3	500.00	$(1 + 0.06)^3$	596	0.316	188	407	0.6575	268
4	500.00	$(1 + 0.06)^4$	631	0.316	199	432	0.5718	247
5	500.00	$(1 + 0.06)^5$	669	0.316	211	458	0.4972	228
6	500.00	$(1 + 0.06)^6$	709	0.316	224	485	0.4323	210
7	500.00	$(1 + 0.06)^7$	752	0.316	238	514	0.3759	193
					Total PV, after-tax O and M cost			$1751

TABLE X1.4 Alternative 1: LCC of Continuing Use of the Existing Furnace without Addition of Waste-Heat Recovery System

(1) PV of Fuel Costs	(2) PV of O and M	(3) PVLCC, After Taxes and Inflation (1)+(2)
$26 277	$1 751	$28 028

TABLE X1.5 Alternative 2: Fuel Costs with Waste-Heat Recovery System

(1) Year	(2) Base Period Fuel Price, $/MBtu	(3) Annual Fuel Requirement, MBtu	(4) Fuel Price Escalation Multiplier	(5) Annual Fuel Cost After Escalation, $ (2)×(3)×(4)	(6) Corporate Income Tax Rate	(7) Tax Reduction from Fuel Cost Deductions, $ (5)×(6)	(8) Annual Cost After Tax and Escalation, $ (5)–(7)	(9) Single Present Value (SPV) Factor	(10) PV of Annual Fuel Cost After Tax and Escalation, $ (8)×(9)
0	7.00	...	...	...	...	...	...	...	...
1	7.00	100	$(1 + 0.08)^1$	756	0.316	239	517	0.8696	450
2	7.00	100	$(1 + 0.08)^2$	816	0.316	258	558	0.7561	422
3	7.00	100	$(1 + 0.08)^3$	882	0.316	279	603	0.6575	397
4	7.00	100	$(1 + 0.08)^4$	952	0.316	301	651	0.5718	372
5	7.00	100	$(1 + 0.08)^5$	1029	0.316	325	704	0.4972	350
6	7.00	100	$(1 + 0.08)^6$	1111	0.316	351	760	0.4323	328
7	7.00	100	$(1 + 0.08)^7$	1200	0.316	379	821	0.3759	308
						Total PV, after-tax, fuel cost			$2628
					Total PV, after-tax, fuel cost				$2628

TABLE X1.6 Alternative 2: Purchase and Installation Cost of Waste-Heat Recovery System

(1) Year	(2) Down Payment, $	(3) Annual Loan Payment, $	(4) Interest Payments,^{A} $	(5) Corporate Income Tax Rate	(6) Tax Reductions from Interest Deductions, $ (4)×(5)	(7) After-Tax Payment, $ (3)–(6)	(8) Single Present Value (SPV) Factor	(9) PV of After-Tax, After-Inflation Investment Financing, $ (7)×(8)
0	3500	...	...	...	...	...	...	...
1	...	7 012	3 938	0.316	1244	5 768	0.8696	5 015
2	...	7 012	3 553	0.316	1123	5 889	0.7561	4 453
3	...	7 012	3 121	0.316	986	6 026	0.6575	3 962
4	...	7 012	2 634	0.316	832	6 180	0.5718	3 533
5	...	7 012	2 087	0.316	660	6 352	0.4972	3 158
6	...	7 012	1 472	0.316	465	6 547	0.4323	2 830
7	...	7 012	779	0.316	246	6 766	0.3759	2 544
								25 496
							Down payment	+3 500
						Total PV, after-tax, investment cost		$28 996

^{A} Interest in year 1, based on a yearly loan payment ($35 000–3500) (0.125) = $3938; Interest in year 2 = [$(35 000 – 3500) – (7012 – 3938)] (0.125) = $3553, etc.

TABLE X1.7 Alternative 2: Depreciation Allowances for Waste-Heat Recovery System

(1) Annual Depreciation^A	(2) Corporate Income Tax Rate	(3) Annual Tax Reduction Due to Depreciation Allowance (1)+(2)	(4) Uniform Present Value Factor, 15 %, 7 years	(5) PV of Depreciation Allowance (3)×(4)
$1750	0.316	$553	4.160	$2300

^{A} Based on straight-line depreciation method, 20-year life, and book value of $3500.

TABLE X1.8 Alternative 2: Resale Value, Net of Capital Gains Tax, for Waste-Heat Recovery System

(1) Year	(2) Resale Value End of 7 Years^A	(3) Book Value End of 7 Years^B	(4) Capital Gains (2)–(3)	(5) Capital Gains Tax Rate	(6) Capital Gains Tax (4)×(5)	(7) Resale Value Net of Capital Gains (2)–(6)	(8) Single Present Value (SPV) Factor	(9) PV of Resale Value, Net of Capital Gains (7)×(8)
7	$34 208	$22 750	$11 458	0.316	$3 621	$30 587	0.3759	$11 498

^{A} Based on original system cost of $35 000, system deterioration prorated uniformly over 20 years, and appreciation at the rate of general price inflation.
^{B} Based on the original book value of $35 000 and 7 years straight-line depreciation of $1750 per year.

TABLE X1.9 Alternative 2: Nonfuel Operation and Maintenance Costs with Addition of Waste-Heat Recovery System

(1) Year	(2) O and M Cost in Base-Year Prices^A	(3) Inflation Multiplier	(4) Annual O and M Cost After Inflation, $ (2)×(3)	(5) Corporate Income Tax Rate	(6) Tax Reduction Due to O and M Cost Deductions, $ (4)×(5)	(7) Annual O and M Cost After Tax and Inflation, $ (4)–(6)	(8) Single Present Value (SPV) Factor	(9) PV of Annual O and M Cost After Tax and Inflation, $ (7)×(8)
0	700.00	...	...	...	...	...	...	...
1	700.00	$(1 + 0.06)^1$	742	0.316	234	508	0.8696	441
2	700.00	$(1 + 0.06)^2$	787	0.316	249	538	0.7561	407
3	700.00	$(1 + 0.06)^3$	834	0.316	263	570	0.6575	375
4	700.00	$(1 + 0.06)^4$	884	0.316	279	604	0.5718	346
5	700.00	$(1 + 0.06)^5$	937	0.316	296	641	0.4972	319
6	700.00	$(1 + 0.06)^6$	993	0.316	314	679	0.4323	294
7	700.00	$(1 + 0.06)^7$	1053	0.316	333	720	0.3759	271
						Total PV O and M cost		$2452

^{A} Includes O and M cost for both existing system ($500) and waste-heat recovery system ($200).

TABLE X1.10 Alternative 2: LCC with Addition of Waste-Heat Recovery System

Present-Value Costs (After Taxes and Inflation)				
(1) Investment Less Depreciation	(2) O and M	(3) Fuel	(4) Resale[A]	(5) Life-Cycle Cost (1)+(2)+(3)–(4)
$26 696	$2 452	$2 628	$11 498	$20 278

[A] Resale (or residual) value of investment at end of study period (7 years).

TABLE X1.11 LCC Comparison of Alternatives 1 and 2

Alternative	Present-Value Costs (After Taxes and Inflation)				
	(1) Investment, $ Less Depreciation	(2) O and M, $	(3) Fuel, $	(4) Resale,[A] $	(5) Life-Cycle Cost, $ (1)+(2)+(3)–(4)
(1) No change	0	1 751	26 277	0	28 028
(2) Install waste-heat recovery system	26 696	2 452	2 628	11 498	20 278

[A] Resale (or residual) value of investment at end of study period (7 years).

X2. LIFE-CYCLE COST APPLICATION 2: DATA CENTER CASE STUDY

X2.1 *Background*—This appendix describes a renovation project for a prototypical data center for a financial institution. The renovation is to upgrade the data center's heating, ventilation and air-conditioning (HVAC); telecommunications and data processing systems; and several security-related functions. Note that the cost estimates are for purposes of this illustration only—actual renovations of different building types will face different costs and different risk profiles.

X2.1.1 The data center undergoing renovation is a single-story structure located in a suburban community. The floor area of the data center is 40 000 ft^2 (3716 m^2). The replacement value of the data center is $20 million for the structure plus its contents. The data center corresponds to the type of structure that would be used by a major bank, credit card company, or insurance company as its primary data repository. It contains financial records that are in constant use by the firm and its customers. Thus, any interruption of service will result in both lost revenues to the firm and potential financial hardship for the firm's customers.

X2.1.2 The site upon which the data center is located is traversed by a thoroughfare that has been used by local residents since the data center was constructed. Alternative routes are available and convenient to local residents, subject to a short detour. Plans have been made by the community to put in a new street which better links the affected neighborhoods and does not traverse the data center's site. The new street will be available for use within two years of the renovation.

X2.2 *Alternatives*—The building owners wish to employ the most cost-effective risk mitigation plan (that is, the plan that results in the lowest life-cycle cost) that will meet their objectives. Two renovation strategies are available to the building owners. The first, referred to as the Base Case, employs upgrades that meet the minimum building performance and security requirements. The second, referred to as the Proposed Alternative, results in enhanced security as well as selected improvements in building performance. Both alternatives recognize that in the post-9/11 environment the data center faces heightened risks in two areas. These risks are associated with the vulnerability of information technology resources and the potential for damage to the facility and its contents from chemical, biological, radiological, and explosive (CBRE) hazards. Two scenarios—the potential for a cyber attack and the potential for a CBRE attack—are used to highlight these risks. The Proposed Alternative augments the Base Case by strengthening portions of the exterior envelope, limiting vehicle access to the data center site, significantly improving the building's HVAC, telecommunications and data processing systems, and providing better linkage of security personnel to the telecommunications network.

X2.3 *Analysis Strategy*—Two types of analyses are employed to evaluate the merits of the Proposed Alternative vis-à-vis the Base Case. First, a baseline analysis is performed in which all values are fixed. Second, a Monte Carlo simulation is performed in which 21 key input variables are allowed to vary in combination according to an experimental design (see Guide E1369). These analysis types complement and reinforce each other.

X2.4 *Assumptions and Cost Data*—The case study covers a 25-year period beginning in 2003. Life-cycle costs are calculated using a 4 % real discount rate for the baseline analysis. In the Monte Carlo Simulation, the discount rate varies from 0 to 8 %. Information on cost items is needed in order to calculate life-cycle costs. Cost items are classified under two broad headings: *(1)* input costs and *(2)* event-related costs.

X2.4.1 Input costs represent all costs tied to the building or facility under analysis that are not associated with an event. Input costs include the initial capital investment outlays for facilities and site work, future costs for electricity for lighting and space heating and cooling, future renovations, and any salvage value for plant and equipment remaining at the end of the study period. Input costs are classified as either investment costs or non-investment costs (that is, O&M or Other). Input costs for the Base Case are summarized in Table X2.1. Input costs for the Proposed Alternative are summarized in Table X2.2.

X2.4.2 Input costs serve to differentiate the Base Case and the Proposed Alternative. The additional costs of the "enhanced" renovation result not only in expected reductions in event-related costs, they also reduce the annual costs for electricity and telecommunications services and increase staff productivity due to improved indoor air quality. Finally, the change in the traffic pattern resulting from the enhanced renovation generates an increase in commuting costs for local residents until a new road is opened in two years.

X2.4.3 Event-related costs are based on annual outcomes, each of which has a specified probability of occurrence. Each outcome has a non-negative number of cost items associated with it (that is, an outcome may have no cost items associated with it if it results in zero costs). This example models the risks associated with cyber attacks and CBRE attacks exclusively. The event modeling methodology, however, can also be used to model multiple hazards, such as those associated with earthquakes, high winds, or an accident resulting in widespread damage due to fire or chemical spills.

X2.4.4 Annual probabilities for the outcomes associated with each attack scenario are postulated along with associated outcome costs. The annual probabilities and outcome costs differ by renovation strategy. However, both the Base Case and the Proposed Alternative have similar types of outcome costs. Should a cyber attack occur, it results in damage to financial records and identity theft for a small set of corporate customers. Should a CBRE attack occur, it results in several non-fatal injuries, physical damage to the data center, interruption of business services at the data center, and denial of service to corporate customers during recovery. Variations in outcome probabilities for both sets of attack scenarios (cyber and CBRE) are modeled explicitly in the experimental design employed in the Monte Carlo simulation. Event-related costs for the Base Case are summarized in Table X2.3. Event-related costs for the Proposed Alternative are summarized in Table X2.4.

X2.5 *Results of Baseline Analysis*—The results of the baseline analysis are summarized in Table X2.5 for the Base Case and Table X2.6 for the Proposed Alternative. All costs reported in Tables X2.5 and X2.6 are life-cycle costs. Tables X2.5 and X2.6 report both input and event-related costs in thousands of 2003 present value equivalent dollars ($K). In order to differentiate those costs which are input costs from those which are event-related, all event-related costs in Tables X2.5 and X2.6 are shown in bold-italics font face. Each input cost and each event-related cost is assigned to one of the three Budget Categories—Capital Investment, O&M, or Other. A Budget Category is a collection of individual cost items. Cost items, both input and event-related costs, are listed beneath the Budget Category to which they are assigned. Tables X2.5 and X2.6 report three sets of life-cycle cost information; the life-cycle cost of each cost item, of each Budget Category, and of the overall Total. Budget Category totals and the overall Total are shown in bold font face.

X2.5.1 Comparisons between the cost items reported in Tables X2.5 and X2.6 demonstrate why the Proposed Alternative is the cost-effective choice. Although the Proposed Alternative results in a significantly higher initial cost than the Base Case, these increased Capital Investment costs are more than offset through reductions in O&M and Other costs. Consequently, the life-cycle cost of the Proposed Alternative ($5255K) is significantly lower than the life-cycle cost of the Base Case ($5937K).

X2.5.2 Table X2.8 summarizes the key findings from the baseline analysis. It provides a brief description of each renovation strategy and covers the background, approach, and results of the economic evaluation. Table X2.8 is based on the summary format described in Guide E2204. The material presented in Table X2.8 provides a concise statement of why the Proposed Alternative is the "preferred" choice and documents the reasons for its selection.

X2.5.3 The life-cycle cost figures presented in Section 3.a of Table X2.8 enable us to calculate several additional economic measures that taken together provide useful information to decision makers. First, the difference between the life-cycle cost of the Base Case and the Proposed Alternative equals the present value of net savings (PVNS) resulting from choosing the Proposed Alternative. For the baseline analysis, the PVNS of the Proposed Alternative amounts to $682K. Second, the way in which the Budget Category cost items are defined

TABLE X2.1 Summary of Input Costs for Base Case

Cost Item	Cost Category	Occurrence	Escalation	Amount
Basic Renovation	Capital Investment	Initial	0.00 %	$1 000 000
Site Protection	Capital Investment	Initial	0.00 %	$100 000
HVAC Upgrade	Capital Investment	Future (year 17)	0.00 %	$25 000
Salvage	Capital Investment	Future (year 25)	0.00 %	-$10 000
Site Security	O&M	Annually Recurring	0.50 %	$125 000
Site Lighting	O&M	Annually Recurring	-0.10 %	$3 600
Electricity	O&M	Annually Recurring	-0.10 %	$72 000
Telecom Services	O&M	Annually Recurring	0.00 %	$40 000
HVAC Repairs	O&M	Periodic (years 1 through 24 in intervals of 4)	0.00 %	$5 000
Duct Cleaning	O&M	Future (year 17)	0.00 %	$5 000

TABLE X2.2 Summary of Input Costs for Proposed Alternative

Cost Item	Cost Category	Occurrence	Escalation	Amount
Enhanced Renovation	Capital Investment	Initial	0.00 %	$1 500 000
Site Protection	Capital Investment	Initial	0.00 %	$200 000
Special Security Features	Capital Investment	Initial	0.00 %	$50 000
HVAC Upgrade	Capital Investment	Future (year 17)	0.00 %	$30 000
Salvage	Capital Investment	Future (year 25)	0.00 %	-$12 500
Site Security	O&M	Annually Recurring	0.50 %	$100 000
Site Lighting	O&M	Annually Recurring	-0.10 %	$3 000
Electricity	O&M	Annually Recurring	-0.10 %	$60 000
Telecom Services	O&M	Annually Recurring	0.00 %	$36 000
HVAC Repairs	O&M	Periodic (years 1 through 24 in intervals of 6)	0.00 %	$6 000
Duct Cleaning	O&M	Future (year 17)	0.00 %	$7 500
Improved Productivity (IAQ)	O&M	Annually Recurring	0.00 %	-$4 000
Change in Traffic Pattern	Other Costs	Annually Recurring (years 1 and 2)	0.00 %	$50 000

TABLE X2.3 Summary of Event-Related Information for Base Case

Scenario	Years	Outcome	Probability	Cost Item	Cost Category	Amount in Dollars
Cyber Attack	1 Through 10	No Breaches	0.6	None	None	0
		Record Theft	0.4	Record Reconstruction	O&M	7 500
				Identity Theft	Other	75 000
	11 Through 25	No Breaches	0.5	None	None	0
		Record Theft	0.5	Record Reconstruction	O&M	10 000
				Identity Theft	Other	100 000
CBRE Attack	1 Through 25	No Breaches	0.994	None	None	0
		Minor Damage	0.005	Damage to Data Center	Capital Investment	80 000
				Business Interruption	O&M	250 000
				One Non-Fatal Injury	Other	75 000
				Denial of Service	Other	100 000
		Major Damage	0.001	Damage to Data Center	Capital Investment	3 000 000
				Business Interruption	O&M	5 000 000
				20 Non-Fatal Injuries	Other	1 500 000
				Denial of Service	Other	2 000 000

TABLE X2.4 Summary of Event-Related Information for Proposed Alternative

Scenario	Years	Outcome	Probability	Cost Item	Cost Category	Amount in Dollars
Cyber Attack	1 Through 10	No Breaches	0.75	None	None	0
		Record Theft	0.25	Record Reconstruction	O&M	3 000
				Identity Theft	Other	30 000
	11 Through 25	No Breaches	0.65	None	None	0
		Record Theft	0.35	Record Reconstruction	O&M	4 000
				Identity Theft	Other	40 000
CBRE Attack	1 Through 25	No Breaches	0.996	None	None	0
		Minor Damage	0.0035	Damage to Data Center	Capital Investment	50 000
				Business Interruption	O&M	250 000
				One Non-Fatal Injury	Other	75 000
				Denial of Service	Other	100 000
		Major Damage	0.0005	Damage to Data Center	Capital Investment	1 000 000
				Business Interruption	O&M	2 000 000
				8 Non-Fatal Injuries	Other	600 000
				Denial of Service	Other	1 000 000

enables us to calculate both the savings-to-investment ratio (SIR) and the adjusted internal rate of return (AIRR). The SIR equals the difference in non-investment costs—the savings stemming from the use of the Proposed Alternative rather than the Base Case—divided by the increased capital investment cost for the Proposed Alternative. Reference to Section 3.a of Table X2.8 shows that the increased capital cost of the Proposed Alternative of $604K results in savings of $1286K. These figures translate into an SIR of 2.13 (that is, every dollar invested in the Proposed Alternative is expected to generate $2.13 in cost savings). Using the computed value of the SIR, we can calculate the AIRR. In this case, the AIRR over the 25-year study period is 7.2 %, which exceeds the minimum acceptable rate of return of 4 %; that is, the rate of return on the next best investment of comparable risk. Finally, the use of multiple economic measures provides alternative views of the same decision process. Specifically, PVNS provides a measure of magnitude, whereas the SIR is a multiplier, and the AIRR is an annual rate of return.

X2.6 *Results of Monte Carlo Simulation*—Table X2.8 provides a compact summary of the results of the baseline analysis. Although the baseline analysis guides the formulation of the risk mitigation plan, it does not address the implications of uncertainty in the values of the key input variables. A Monte Carlo Simulation augments the baseline analysis by providing the decision maker with additional background and perspective. The Monte Carlo Simulation uses the same data and

TABLE X2.5 Life-Cycle Costs by Cost Category and Cost Item for Baseline Analysis: Base Case

Cost Category/Cost Item	Present Value Cost by Item ($K)	Present Value Cost by Category ($K)
Capital Investment		1168
Basic Renovation	1000.0	
Site Protection	100.0	
HVAC Upgrade	12.8	
Salvage	-3.8	
Damage to Data Center	59.4	
O&M		4082
Site Security	55.6	
Site Lighting	2064.0	
Electricity	1112.5	
Telecom Services	624.9	
HVAC Repairs	18.0	
Duct Cleaning	2.6	
Business Interruption	97.6	
Record Reconstruction	106.6	
Other		687
Non-fatal Injuries	29.3	
Denial of Service	39.1	
Identity Theft	618.9	
Total		5937

TABLE X2.6 Life-Cycle Costs by Cost Category and Cost Item for Baseline Analysis: Proposed Alternative

Cost Category/Cost Item	Present Value Cost by Item ($K)	Present Value Cost by Category ($K)
Capital Investment		1772
Enhanced Renovation	1500.0	
Site Protection	200.0	
Special Security Features	50.0	
HVAC Upgrade	15.4	
Salvage	-4.7	
Damage to Data Center	11.1	
O&M		3201
Site Security	1651.3	
Site Lighting	46.4	
Electricity	927.1	
Telecom Services	562.4	
HVAC Repairs	13.8	
Duct Cleaning	3.9	
Improved Productivity (IAQ)	-62.5	
Business Interruption	29.3	
Record Reconstruction	29.1	
Other		282
Change in traffic Pattern	94.3	
Non-fatal Injuries	8.8	
Denial of Service	13.3	
Identity Theft	166.0	
Total		5255

assumptions as the baseline analysis for its starting point. The objective of the Monte Carlo Simulation is to evaluate how uncertainty in the values of 21 input variables translates into changes in each of five key economic measures. The five economic measures evaluated in the Monte Carlo Simulation are: *(1)* the life-cycle costs of the Base Case (LCC_{BC}); *(2)* the life-cycle costs of the Proposed Alternative (LCC_{Alt}); *(3)* the present value of net savings (PVNS) resulting from the Proposed Alternative; *(4)* the savings-to-investment ratio (SIR) produced by the additional capital investment in the Proposed Alternative; and *(5)* the adjusted internal rate of return (AIRR) on the additional capital investments associated with the Proposed Alternative. The calculation of each economic measure is based on a "sample of 1000 observations" produced by the Monte Carlo simulation.

X2.6.1 The results of Monte Carlo simulation are presented in both tabular and graphical formats. The tabular format—Table X2.7—records information on each of the five economic measures; it reports a variety of computed statistics for each economic measure. Fig. X2.1 presents the graphical distribution of the observed values for the life-cycle costs of the Base Case and the Proposed Alternative side-by-side as an indication of the degree to which the Proposed Alternative is preferred to the Base Case.

X2.6.2 The statistical measure and its corresponding value are recorded under the heading Statistical Measure in Table X2.7. Seven statistical measures are reported to characterize the results of each Monte Carlo simulation. The calculation of these statistical measures is based on a "sample of 1000 observations" produced by the Monte Carlo simulation. These statistical measures are: *(1)* the minimum; *(2)* the 25th percentile, denoted by 25 %; *(3)* the 50th percentile (that is, the median), denoted by 50 %; *(4)* the 75th percentile, denoted by 75 %; *(5)* the maximum; *(6)* the mean; and *(7)* the standard deviation. The minimum and the maximum define the range of values for the results of the Monte Carlo simulation. The 50th percentile and the mean are measures of central tendency. The 25th and 75th percentiles define the interquartile range, a range that includes the middle 50 percent of the observations. The interquartile range is also a crude measure of central tendency. The standard deviation measures the variability of the results of the Monte Carlo simulation. The values reported for LCC_{BC}, LCC_{Alt}, and PVNS are all in thousands of 2003 dollars.

X2.6.3 Table X2.7 summarizes the results of the Monte Carlo simulation. A close examination of Table X2.7 reveals several interesting outcomes. First, the range of values—the difference between the minimum and maximum—is very wide. For example, the minimum value of life-cycle costs for the Base Case (LCC_{BC}) is approximately $4.3 million, whereas the maximum is approximately $9.0 million. Life-cycle costs for the Proposed Alternative (LCC_{Alt}) range from slightly more than $4.0 million to almost $7.5 million. Second, the computed value of the mean equals or exceeds the computed value of the median for each of the economic measures. This is because a small number of very large observations are pulling up the computed value of the mean. Finally, the computed values of the mean of each of the five economic measures are higher than the corresponding baseline values for the Base Case and the Proposed Alternative. This is due to a small number of very large observations.

X2.6.4 Life-cycle cost results of the Monte Carlo Simulation are shown graphically in Fig. X2.1. The life-cycle costs of the Base Case are compared to those of the Proposed Alternative, LCC_{Alt}. The results of the Monte Carlo simulation produced 1000 observations of LCC_{BC} and 1000 observations of LCC_{Alt}. These observations were used to produce the two traces shown in Fig. X2.1. The figure was constructed by first sorting the values of LCC_{BC} and LCC_{Alt} from smallest to largest. The resultant cumulative distribution function was then plotted. The vertical axis records the probability that the economic measure—LCC_{BC} or LCC_{Alt}—is less than or equal

TABLE X2.7 Summary Statistics Due to Changes in All Variables

Economic Measure	Statistical Measure						
	Minimum	25 %	50 %	75 %	Maximum	Mean	Standard Deviation
LCC_{BC}	$4344K	$5091K	$6008K	$7196K	$9023K	$6216K	$1301K
LCC_{Alt}	$4012K	$4649K	$5320K	$6157K	$7429K	$5451K	$926K
PVNS	$46K	$438K	$708K	$1050K	$1884K	$765K	$396K
SIR	1.06	1.72	2.20	2.86	6.14	2.36	0.83
AIRR	4.2 %	6.3 %	7.3 %	8.5 %	11.8 %	7.4 %	1.4 %

to a specified value. The values recorded on the horizontal axis cover the range of values encountered during the Monte Carlo simulation.

X2.6.5 In analyzing Fig. X2.1, it is useful to keep in mind that the values of LCC_{BC} and LCC_{Alt} from the baseline analysis were $5937K and $5255K, respectively. Comparisons between Fig. X2.1 and Table X2.7 are also helpful in interpreting the results of the Monte Carlo simulation. First, notice that the life-cycle cost trace of the Proposed Alternative in Fig. X2.1 always remains to the left of the life-cycle cost trace of the Base Case. Thus, for any given probability (for example, 0.40), the life-cycle cost of the Proposed Alternative ($5000K) is less than the life-cycle cost of the Base Case ($5600K). Similarly, for any given life-cycle cost (for example, $5000K), the probability of being less than or equal to that cost is higher for the Proposed Alternative (0.40) than for the Base Case (0.23). Second, the horizontal distance between the Proposed Alternative and the Base Case gets larger as the cumulative probability moves from 0.00 to 1.00. This translates into a wider range of life-cycle costs for the Base Case (that is, maximum minus minimum); it is reflected in the higher standard deviation for the Base Case recorded in the last column of Table X2.7. Fig. X2.1 clearly demonstrates that the Proposed Alternative is the most cost-effective renovation strategy.

X2.7 *Final Decision*—Both the baseline analysis and the Monte Carlo Simulation demonstrate that the Proposed Alternative results in lower life-cycle costs and is hence the more cost-effective risk mitigation plan. The additional economic measures shown in Tables X2.7 and X2.8 underscore the superior performance of the Proposed Alternative.

TABLE X2.8 Summary of Data Center Case Study

1.a Significance of the Project:

The data center undergoing renovation is a single-story structure located in a suburban community. The floor area of the data center is 40 000 ft^2 (3716 m^2). The replacement value of the data center is $20 million for the structure plus its contents. The data center contains financial records that are in constant use by the firm and its customers. Thus, any interruption of service will result in both lost revenues to the firm and potential financial hardship for the firm's customers.

The building owners employ two different renovation strategies. The first, referred to as the Base Case, employs upgrades that meet the minimum building performance and security requirements. The second, referred to as the Proposed Alternative, results in enhanced security as well as selected improvements in building performance. Both alternatives recognize that in the post-9/11 environment the data center faces heightened risks in two areas. These risks are associated with the vulnerability of information technology resources and the potential for damage to the facility and its contents from chemical, biological, radiological, and explosive (CBRE) hazards. Two scenarios—the potential for a cyber attack and the potential for a CBRE attack—are used to highlight these risks.

1.b Key Points:

(1) The objective of the renovation project is to provide cost-effective operations and security protection for the data center.

(2) The renovation is to upgrade the data center's HVAC, telecommunications and data processing systems and several security-related functions.

(3) Two upgrade alternatives are proposed: Base Case (Basic Renovation) and Proposed Alternative (Enhanced Renovation), which augments the Base Case by strengthening portions of the exterior envelope, limiting vehicle access to the data center site, significantly improving the building's HVAC, data processing and telecommunications systems, and providing better linkage of security personnel to the telecommunications network.

2. Analysis Strategy: How Key Measures are Estimated

The following economic measures are calculated as present-value (PV) amounts:

(1) Life-Cycle Costs (LCC) for the Base Case (Basic Renovation), LCC_{BC}, and for the Proposed Alternative (Enhanced Renovation), LCC_{Alt}, including all costs of acquiring and operating the data center over the length of the study period. The selection criterion is lowest LCC.

(2) Present Value Net Savings (PVNS) that will result from selecting the lowest-LCC alternative. PVNS > 0 indicates an economically worthwhile project.

Additional measures:

(1) Savings-to-Investment Ratio (SIR), the ratio of savings from the lowest-LCC to the extra investment required to implement it. A ratio of SIR >1 indicates an economically worthwhile project.

(2) Adjusted Internal Rate of Return (AIRR), the annual return on investment over the study period. An AIRR > minimum acceptable rate of return indicates an economically worthwhile project.

Data and Assumptions:

The Base Date is 2003.

The alternative with the lower first cost (Basic Renovation) is designated the Base Case.

The study period is 25 years and ends in 2027.

The discount rate is 4.0 % real.

The minimum acceptable rate of return is 4.0 % real.

Annual probabilities for the outcomes for each attack scenario are given along with outcome costs.

Annual probabilities and outcome costs differ by renovation strategy.

Both the Base Case and the Proposed Alternative have similar types of outcome costs. Should a cyber attack occur, it results in damage to financial records and identity theft for a small set of corporate customers. Should a CBRE attack occur, it results in several non-fatal injuries, physical damage to the data center, interruption of business services at the data center, and denial of service to corporate customers during recovery.

3.a Calculation of Savings, Costs, and Additional Measures

Savings and Costs in Thousands of Dollars ($K)

PV of Investment Costs	Base Case	Proposed Alt.
Capital Investment	$1168K	$1772K

PV of Increased Investment Costs for Proposed Alt. $604K

PV of Non-Investment Costs	Base Case	Proposed Alt.
O&M Costs	4082K	3201K
Other Costs	687K	282K
	$4769K	$3483K

PV of Non-Investment Savings for Proposed Alt. $1,286K

LCC	Base Case	Proposed Alt.
PV of Investment Costs	1168K	1772K
PV of Non-Investment Costs	4769K	3483K
	$5937K	$5255K

PVNS from Proposed Alternative $682K

Savings-to-Investment Ratio (SIR)

PV of Non-Investment Savings $1286K

Divided by PV of Incr. Investment 604K

SIR = 2.13

Adjusted Internal Rate of Return (AIRR)

(1+0.04) 2.131/25 – 1 = 0.072

AIRR = 7.2 %

which exceeds the minimum acceptable rate of return of 4.0 %

3.b Key Results:

LCC	
Base Case	$5937K
Proposed Alt.	$5255K
PVNS from Alt.	$682K
SIR	2.13
AIRR	7.2 %

3.c Traceability:

Life-cycle costs and supplementary measures were calculated according to Practices E917, E964, E1057, and E1074.

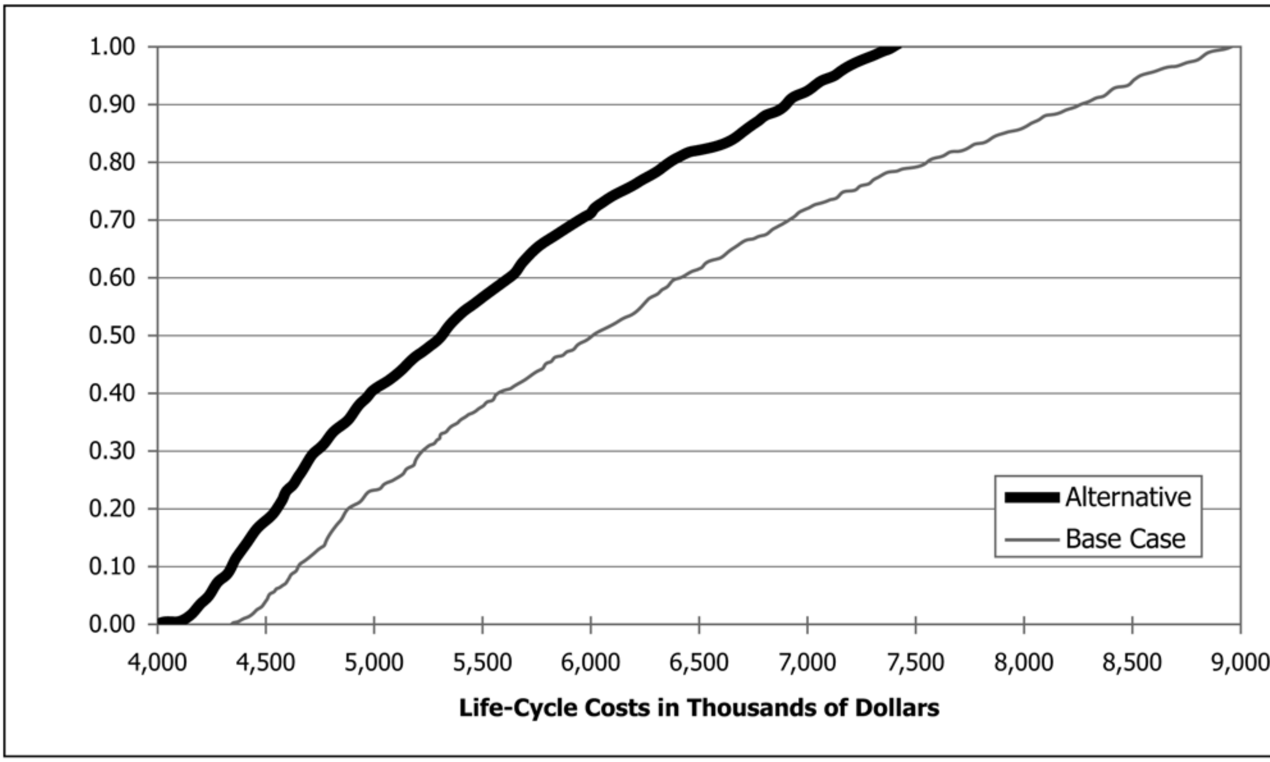


FIG. X2.1 Life-Cycle Costs for Each Alternative in Thousands of Dollars Due to Changes in All Variables

X3. USING THE LIFE-CYCLE COST METHOD TO EVALUATE ENERGY EFFICIENCY IMPROVEMENTS IN A HIGH SCHOOL BUILDING

X3.1 *Background*—A high school constructed in 2009 in the greater St. Louis, MO, metropolitan area is subjected to an economic analysis to determine if energy efficiency improvements would be cost effective. The community where the high school is located does not have an energy code requirement, so the 1999 Edition of the ASHRAE 90.1 Standard (**1**)[5] is used as the basis for all energy-related requirements associated with the base case building design. The alternative against which the base case is analyzed uses the 2007 Edition of the ASHRAE 90.1 Standard (**2**) as the basis for all energy-related requirements associated with its building design. The ASHRAE 90.1 1999 Edition is used as the base case because it is assumed to be "common practice" for building design requirements in states with no state-wide energy code (Kneifel, 2012) (**3**). The ASHRAE 90.1 2007 Edition is used as the alternative because it provided the most comprehensive energy-related design requirements when the school was constructed. In addition, information on a similar school design constructed in Louisville, KY, indicated that the ASHRAE 90.1 2007 Edition design option was cost effective vis-à-vis the ASHRAE 90.1 1999 Edition design option (**3**). Both localities are in the same climate zone and have similar heating degree day and cooling degree day requirements.

[5] The boldface numbers in parentheses refer to a list of references at the end of this standard.

X3.2 *Data and Assumptions*—Table X3.1 summarizes key assumptions, data elements and data values for the high school building being analyzed. The two-story building has a floor area of 130 000 ft^2 (12 077 m^2). The length of the study period is 25 years, which is less than the service life of the building but long enough to reflect a typical local government planning horizon. The economic analysis uses a 3 % real discount rate (net of general inflation or deflation) to convert future dollar values to present values. Because a real discount rate is being used, all dollar-denominated annual recurring costs and other future costs are expressed in 2009 constant dollars (dollars of uniform purchasing power exclusive of general inflation or deflation). The initial investment cost estimates for the base case, ASHRAE 90.1 1999 Edition, and the alternative, ASHRAE 90.1 2007 Edition, are based on data from RS Means CostWorks (**4**). The timing and values for all maintenance, repair, and replacement costs are based on data from Whitestone Research (**5**).

X3.2.1 *Investment Cost Data*—The investment cost data reported in Table X3.1 cover the initial investment cost, the residual value of the high school building at the end of the study period in year 25, the present value (PV) of the residual value, and the PV of replacement costs for energy-related system upgrades. The initial investment cost is already expressed in PV terms, so no discounting is required. The residual value at the end of the study period is a measure of the economic value of the remaining life of the building. The

TABLE X3.1 Economic Evaluation of Energy Efficiency Improvements in a High School Building: Data and Assumptions

Data Element	Value
Floor Area	130 000 ft^2 (12 077 m^2)
Study Period	25 Years
Discount Rate	3 % (real)
Investment Cost Data	
Initial Investment Cost	
ASHRAE 90.1 1999 Edition	$15 922 252
ASHRAE 90.1 2007 Edition	$15 967 212
Residual Value (Year 25)	
ASHRAE 90.1 1999 Edition	$5 412 217
ASHRAE 90.1 2007 Edition	$5 422 416
PV Residual Value	
ASHRAE 90.1 1999 Edition	$2 584 905
ASHRAE 90.1 2007 Edition	$2 589 776
PV Replacement Costs for Energy-Related System Upgrades	
ASHRAE 90.1 1999 Edition	$366 257
ASHRAE 90.1 2007 Edition	$388 167
Energy Cost Data	
Electricity	
Electricity Unit Cost	6.96¢/kWh
Annual Electricity Cost	
ASHRAE 90.1 1999 Edition	$98 358
ASHRAE 90.1 2007 Edition	$84 515
UPV* Factor for Electricity	17.60
PV Electricity Cost	
ASHRAE 90.1 1999 Edition	$1 731 096
ASHRAE 90.1 2007 Edition	$1 487 459
Natural Gas	
Natural Gas Unit Cost	$10.80/kft^3 ($305.82/m^3)
Annual Natural Gas Cost	
ASHRAE 90.1 1999 Edition	$53 351
ASHRAE 90.1 2007 Edition	$53 144
UPV* Factor for Natural Gas	19.92
PV Natural Gas Cost	
ASHRAE 90.1 1999 Edition	$1 062 757
ASHRAE 90.1 2007 Edition	$1 058 629
PV Energy Cost	
ASHRAE 90.1 1999 Edition	$2 793 853
ASHRAE 90.1 2007 Edition	$2 546 088
Future Maintenance and Repair Cost Data	
PV Baseline Maintenance and Repair Costs	
ASHRAE 90.1 1999 Edition	$4 311 735
ASHRAE 90.1 2007 Edition	$4 311 735
PV Maintenance and Repair Costs for Energy-Related System Upgrades	
ASHRAE 90.1 1999 Edition	$1 152 319
ASHRAE 90.1 2007 Edition	$1 099 783

residual value in year 25 is discounted to a PV through use of a single present value (SPV) factor (ASTM Discount Factor Tables Adjunct). The PV of replacement costs for energy-related system upgrades is calculated by multiplying the appropriate SPV factor based on the timing of each replacement item by the dollar value for each replacement item in that time period and summing over all time periods and all replacement items. All four sets of investment costs are separately tabulated for the base case, ASHRAE 90.1 1999 Edition, and the alternative, ASHRAE 90.1 2007 Edition.

X3.2.2 *Energy Cost Data*—The energy fuel types used in the building are natural gas for heating and electricity for cooling and lighting. Unit cost data for electricity and natural gas are based on values reported in (**3**). The product of the annual energy requirement for each fuel type and the unit cost for the fuel type equals the annual fuel cost in the first year. Although both electricity and natural gas are treated as annual expenditures, the rate at which their prices change fluctuates over time. These fluctuations are referred to as escalation rates. The escalation rates used in this analysis and the associated discount factors used to convert an annual stream of fuel costs to a PV are based on future fuel prices projected by the Energy Information Administration of the U.S. Department of Energy as reported in (**6**). The Modified Uniform Present Value (UPV*) factor for each fuel type is based on a 25-year study period; it is reported in Table X3.1 as 17.60 for electricity and 19.92 for natural gas. The UPV* factor is applied to the corresponding annual fuel cost to convert the annual fuel cost in the first year to a PV over the 25-year study period. The annual energy requirements for electricity and natural gas are based on simulations from the EnergyPlus software program (**7**) as reported in Kneifel (2011) (**8**) and Lippiatt et al. (2013) (**9**). The EnergyPlus software program takes into account the integrated design nature of a building's systems. Specifically, as the thermal integrity of the building envelope is improved, the load on the HVAC system is reduced. Thus, the capacity requirements for the HVAC system may be reduced. Consequently, some of the increased investment cost for improving the thermal integrity of the building envelope may be partially offset by reductions in HVAC system cost. All energy-related costs are separately tabulated for the base case, ASHRAE 90.1 1999 Edition, and the alternative, ASHRAE 90.1 2007 Edition.

X3.2.3 *Maintenance and Repair Cost Data*—The PV of maintenance and repair costs is broken into two categories. The first category, referred to as Baseline Maintenance and Repair Costs, corresponds to the basic building; these costs exclude all energy-related system upgrades and are independent of any energy-related system upgrades. The second category covers all Energy-Related System Upgrades maintenance and repair costs. The timing and values for each category of maintenance and repair costs, baseline and energy-related system upgrades, are based on data from Whitestone Research (**5**). All maintenance and repair costs are separately tabulated for the base case, ASHRAE 90.1 1999 Edition, and the alternative, ASHRAE 90.1 2007 Edition.

X3.3 *Life-Cycle Cost Calculation*—Tables X3.2-X3.4 provide the information needed to calculate life-cycle costs. All dollar values reported in Tables X3.2-X3.4 are expressed in PV.

TABLE X3.2 Economic Evaluation of Energy Efficiency Improvements in a High School Building: Calculation of Investment Costs

Energy-Related Design Option	Initial Investment Cost	Present Value Replacement Costs for Energy-Related System Upgrades	Present Value Residual Value	Present Value Investment Costs
(1)	(2)	(3)	(4)	(5) = (2) + (3) - (4)
ASHRAE 90.1 1999 Edition	$15 922 252	$366 257	$2 584 905	$13 703 604
ASHRAE 90.1 2007 Edition	$15 967 212	$388 167	$2 589 776	$13 765 603

TABLE X3.3 Economic Evaluation of Energy Efficiency Improvements in a High School Building: Calculation of Non-Investment Costs

Energy-Related Design Option	Present Value Energy Cost	Present Value Baseline Maintenance and Repair Costs	Present Value Maintenance and Repair Costs for Energy-Related System Upgrades	Present Value Non-Investment Costs
(1)	(2)	(3)	(4)	(5) = (2) + (3) + (4)
ASHRAE 90.1 1999 Edition	$2 793 853	$4 311 735	$1 152 319	$8 257 907
ASHRAE 90.1 2007 Edition	$2 546 088	$4 311 735	$1 099 783	$7 957 606

TABLE X3.4 Economic Evaluation of Energy Efficiency Improvements in a High School Building: Calculation of Life-Cycle Cost

Energy-Related Design Option	Present Value Investment Costs	Present Value Non-Investment Costs	Life-Cycle Cost
(1)	(2)	(3)	(4) = (2) + (3)
ASHRAE 90.1 1999 Edition	$13 703 604	$8 257 907	$21 961 511
ASHRAE 90.1 2007 Edition	$13 765 603	$7 957 606	$21 723 209

Tables X3.2 and X3.3 provide the basis for calculating the life-cycle cost of the base case, ASHRAE 90.1 1999 Edition, and the life-cycle cost of the alternative, ASHRAE 90.1 2007 Edition. Table X3.4 shows the calculation of both sets of life-cycle costs. Tables X3.2 and X3.3 separate the components of life-cycle cost into Investment Costs and Non-Investment Costs. Although such a separation is not necessary to calculate life-cycle costs, it does support the calculation of other measures of economic performance used by decision makers. Specifically, this separation supports the calculation of the present value net savings (Practice E1074), the savings-to-investment ratio (Practice E964) and the adjusted internal rate of return (Practice E1057). The columns in Tables X3.2 and X3.3 are numbered to better illustrate how the resultant values are calculated. Table X3.2 reports the values used to calculate PV Investment Cost for the base case and the alternative. Column 2 contains the initial investment cost, Column 3 contains the PV of all energy-related replacement costs, and Column 4 contains the PV of the residual value. Following the procedure laid out in Section 9, PV Investment Cost equals initial investment cost (Column 2) plus PV replacement costs (Column 3) minus PV residual value (Column 4). The resultant PV Investment Cost is $13 703 604 for the base case and $13 765 603 for the alternative. Table X3.3 reports the values used to calculate PV Non-Investment Cost for the base case and the alternative. Column 2 contains PV energy cost, Column 3 contains the PV of the baseline maintenance and repair costs, Column 4 contains the PV of maintenance costs for energy-related system upgrades, and Column 5 contains the PV of repair costs for energy-related system upgrades. Following the procedure laid out in Section 9, PV Non-Investment Cost equals PV energy cost (Column 2) plus PV of the baseline maintenance and repair costs (Column 3) plus PV of maintenance costs for energy-related system upgrades (Column 4) plus PV of repair costs for energy-related system upgrades (Column 5). The resultant PV Non- Investment Cost is $8 257 907 for the base case and $7 957 606 for the alternative. Table X3.4 reports the life-cycle cost calculation for the base case and the alternative. The resultant life-cycle cost is $21 961 511 for the base case and $21 723 209 for the alternative.

X3.4 *Decision*—The life-cycle cost of $21 723 209 recorded in Table X3.4 for the alternative demonstrates that the additional investment in energy efficiency associated with the ASHRAE 90.1 2007 design option is cost effective. Given that the energy-related system upgrades associated with the ASHRAE 90.1 2007 design option are focused on improving energy efficiency, it is instructive to also examine the PV of energy savings associated with the ASHRAE 90.1 2007 design option. Reference to Column 2 of Table X3.3 shows that the PV of energy costs for the base case is $2 793 853 whereas the PV of energy costs for the alternative is $2 546 088. Thus, the PV of energy savings associated with the alternative is $247 765, which translates into an 8.87 % energy cost savings. The magnitude of the PV of energy savings and the percent reduction in the PV of energy costs, in conjunction with its lower life-cycle cost, underscore the superior performance of the ASHRAE 90.1 2007 design option.

X4. DESCRIPTION OF ADJUNCT

X4.1 The Adjunct contains three sets of discount factor tables. The first set of tables presents values for the following six discount factors defined in Table 1: (*1*) Single Compound-Amount (SCA); (*2*) Single Present-Value (SPV); (*3*) Uniform Capital-Recovery (UCR); (*4*) Uniform Present-Value (UPV); (*5*) Uniform Sinking-Fund (USF); and (*6*) Uniform Compound Amount (UCA). The second set of tables presents values for the modified UPV discount factor (UPV*) where a series of payments is increasing from period to period at a given rate, rather than remaining constant over the entire study period as is the case for the UPV. The third set of tables presents values for the modified SPV discount factor (SPV*) for determining the present value of a single payment occurring at a future point in time when that payment is specified in base-time prices but is expected to increase in value over time at a specified periodic rate. The factors for all three sets of tables have been calculated to four significant digits. The tables cover discount rates from 1 to 25 % in 1 % increments, and for time periods from 1 to 40 years in 1 year increments.

X4.2 The Adjunct contains an introductory section where each discount factor is described. The description includes an equation that uniquely defines the factor; terms used in the equation for that factor are also defined. Where appropriate, a sample calculation using a discount factor is provided.

X4.3 Tables 1 through 25 present discount factors for each of the six discounting operations defined in Table 1. The formula for each discount factor appears at the top of each of the tables. Each table presents discount factors for a specified discount rate.

X4.4 The UPV* discount factors are provided in Tables U-1 through U-25. Each table presents discount factors for a specified discount rate and rates of price increase ranging from 1 to 20 % (even values only above 10 %).

X4.5 The SPV* discount factors are provided in Tables S-1 through S-25. Each table presents discount factors for a specified discount rate and rates of price increase ranging from 1 to 20 % (even values only above 10 %).

REFERENCES

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(3) Kneifel, J., *Prototype Commercial Buildings for Energy and Sustainability Assessment: Design Specification, Life-Cycle Costing and Carbon Assessment* (NIST Technical Note 1732), National Institute of Standards and Technology, Gaithersburg, MD, 2012.

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