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An American National Standard

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

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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 E 964, E 1057, E 1074, E 1121, E 1765, and E 1946). These methods differ in their measure and, to some extent, in their applicability to particular types of problems. Guide E 1185 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.

2. Referenced Documents

2.1 *ASTM Standards:*

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

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E 833 Terminology of Building Economics[2]
E 964 Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems[2]
E 1057 Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems[2]
E 1074 Practice for Measuring Net Benefits for Investments in Buildings and Building Systems[2]
E 1121 Practice for Measuring Payback for Investments in Buildings and Building Systems[2]
E 1185 Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems[2]
E 1765 Practice for Applying the Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems[3]
E 1946 Practice for Measuring Cost Risk of Building and Building Systems[3]

2.2 *ASTM Adjuncts:*
Discount Factor Tables—
Computer Program and User's Guide to Building Maintenance, Repair, and Replacement Database for Life-Cycle Cost Analysis, Adjunct to Standard Practices E 917, E 964, E 1057, E 1074, and E 1121[4]

3. Terminology

3.1 *Definitions*—For definitions of terms used in the practice, refer to Terminology E 833.

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.

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.

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[2] *Annual Book of ASTM Standards*, Vol 04.11.
[3] Available from
[3] *Annual Book of* ASTM Headquarters. Order ADJE091703. *Standards*, Vol 04.12.
[4] Available from ASTM Headquarters. Order ADJE091701 for the 3.5 in. disk. Order ADJE091702 for the 5.25 in. disk. ADJE091703.

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 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:

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

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 E 1765). (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). The microcomputer program database and adjunct user's guide (see 2.2) are helpful in estimating maintenance, repair, and replacement costs needed to perform LCC analyses.~~ 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:

$$C_t = C_0(1 + e)^t \tag{2}$$

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:

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

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[5]

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:

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

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.

$$\text{PVLCC} = \text{IC} + \text{PVM} + \text{PVR} + \text{PVF} - \text{PVS} \tag{5}$$

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.

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[5] A computer program that produces ~~LCC~~ economic measures consistent with ~~this standard practice~~ ASTM practices is ~~Petersen, S. R., "The NIST~~ BLCC5, the "NIST Building Life-Cycle Cost ~~(BLCC) Computer Program" and documentation—*The NIST*~~ *Program," Office of Applied Economics, Building* ~~*Life-Cycle Cost (BLCC) Program: User's Guide*~~ *and* ~~*Reference Manual*, NISTIR 5185-3,~~ Fire Research Laboratory, National Institute of Standards and Technology. Available at http://www.eren.doe.gov/femp. Click on "Technical Assistance" first, ~~1995~~ then on "Life-Cycle Cost Analysis.".

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, ... , 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, $P = A_0 \cdot N$.

[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.

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.

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.

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.

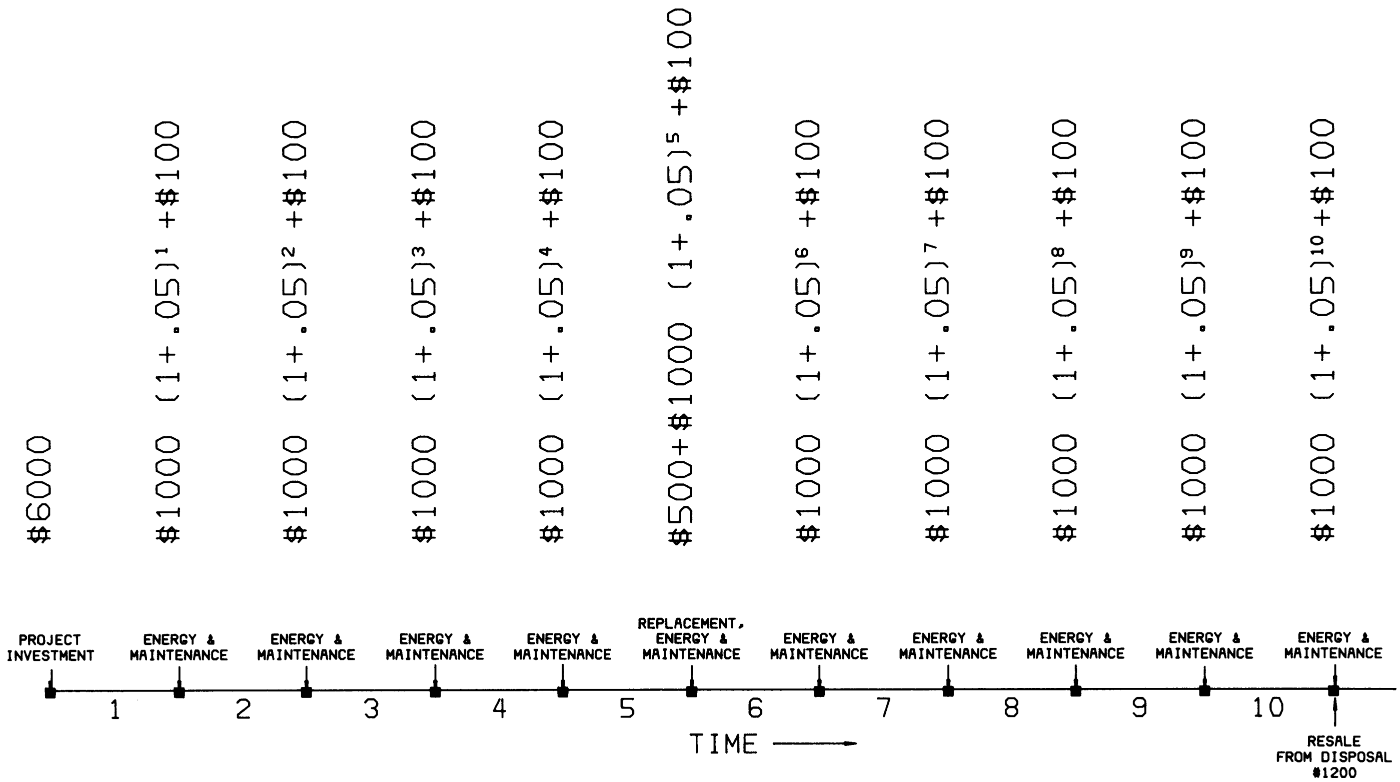
10.3.1.1 To illustrate, Fig. 3 shows the sensitivity of the present-value of fuel savings to three critical factors: study periods (0 to 25 years), discount rates (0, 5, 10, and 15 %), and energy price escalation rates (0, 5, 10, and 15 %).

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

TABLE 2 Illustration of Discounting Cash Flows
(Based on a Study Period of 10 Years and a 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 a Cash Flow Diagram

savings per year over 25 years is about $50 000 for a discount rate of 10 % and a fuel price escalation of 15 %, 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.

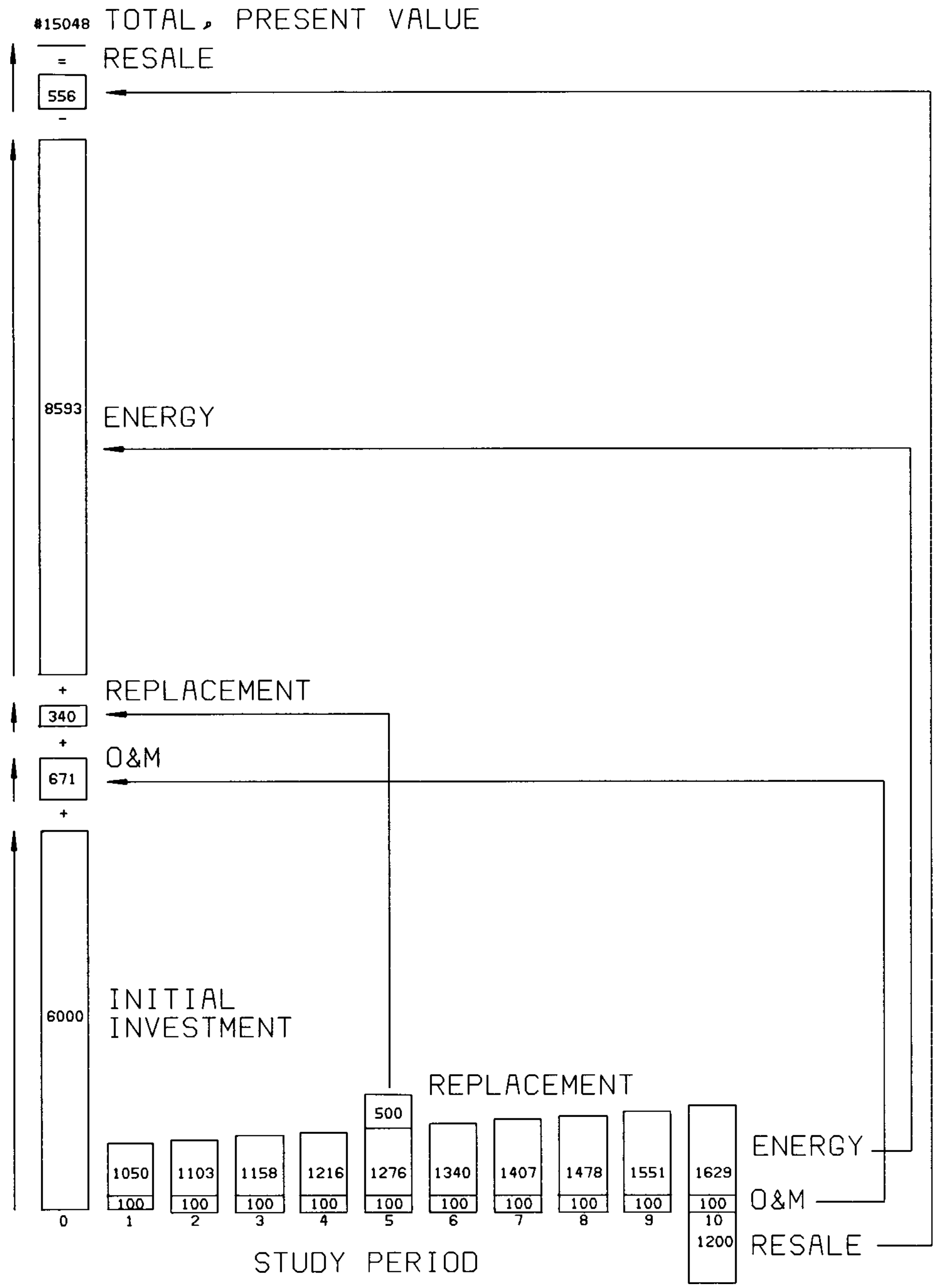
10.3.2 Probability analysis, sometimes called expected-value analysis, can be used to evaluate the costs and benefits of an event whose expected chance of occurrence can be predicted. Historical data, if available, can be used to generate probability data for existing technologies. Computer simulation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

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.

10.4 *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 E 1765 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.



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

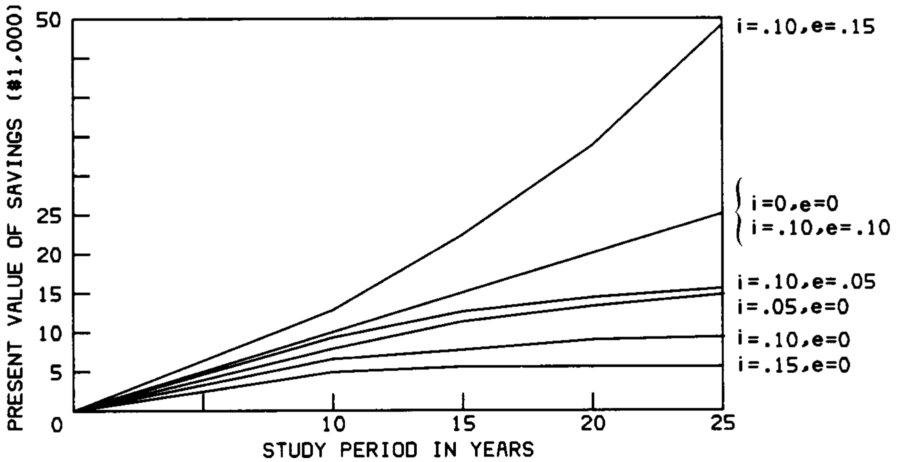
FIG. 2 Illustration of Discounting Cash Flows to Present Value

11. Report

11.1 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.

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



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

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

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)) 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

APPENDIX

(Nonmandatory Information)

X1. PROBLEM EXAMPLE

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	$3500
Loan interest rate	12.5 %
Loan life	7 years
Yearly loan payment	$7012
Asset life	20 years
Depreciation (straight-line)	$1750/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 $0.28 \cdot (1 - 0.05) + 0.05 = 0.316$.

TABLE X1.2 Alternative 1: Fuel Costs Without Addition of the 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	1000	$(1 + 0.08)^1$	7 560	0.316	2389	5171	0.8696	4 497
2	7.00	1000	$(1 + 0.08)^2$	8 165	0.316	2580	5585	0.7561	4 223
3	7.00	1000	$(1 + 0.08)^3$	8 818	0.316	2786	6032	0.6575	3 966
4	7.00	1000	$(1 + 0.08)^4$	9 523	0.316	3009	6514	0.5718	3 724
5	7.00	1000	$(1 + 0.08)^5$	10 285	0.316	3250	7035	0.4972	3 498
6	7.00	1000	$(1 + 0.08)^6$	11 108	0.316	3510	7598	0.4323	3 285
7	7.00	1000	$(1 + 0.08)^7$	11 997	0.316	3791	8206	0.3759	3 085
							Total PV, after-tax, fuel cost		$26 277

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

(1) PV of Fuel Costs	(2) PV of O ad M	(3) PVLCC, After Taxes and Inflation (1)+(2)
$26 277	$1751	$28 028

TABLE X1.5 Alternative 2: Fuel Costs with the 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 the 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	...	7012	3938	0.316	1244	5768	0.8696	5 015
2	...	7012	3553	0.316	1123	5889	0.7561	4 453
3	...	7012	3121	0.316	986	6026	0.6575	3 962
4	...	7012	2634	0.316	832	6180	0.5718	3 533
5	...	7012	2087	0.316	660	6352	0.4972	3 158
6	...	7012	1472	0.316	465	6547	0.4323	2 830
7	...	7012	779	0.316	246	6766	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 the 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 the 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	$3621	$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 the 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)	(2)	(3)	(4)	(5)
Investment Less Depreciation	O and M	Fuel	Resale[A]	Life-Cycle Cost (1)+(2)+(3)−(4)
$26 696	$2452	$2628	$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)	(2)	(3)	(4)	(5)
	Invest-ment, $ Less Depreciaton	O and M, $	Fuel, $	Resale,[A] $	Life-Cycle Cost, $ (1)+(2)+(3)−(4)
(1) No change	0	1751	26 277	0	28 028
(2) Install waste-heat recovery system	26 696	2452	2628	11 498	20 278

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