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U.S. Department of Commerce
Technology Administration
National Institute of Standards and Technology

Office of Applied Economics
Building and Fire Research Laboratory
Gaithersburg, MD 20899

Applications of Life-Cycle Cost Analysis to Homeland Security Issues in Constructed Facilities: A Case Study

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Abstract

The Office of Applied Economics, a unit of the Building and Fire Research Laboratory at the National Institute of Standards and Technology, is developing economic tools—evaluation methods and software for implementing these methods—for evaluating the management of terrorist risks. This report is one in a series focused on these economic tools. It illustrates how to apply a series of standardized methods to evaluate and compare the cost-effectiveness of security-related investments in constructed facilities.

This report describes a renovation project for a prototypical data center. The renovation has been planned for some time to upgrade the data center's HVAC, telecommunications and data processing systems and to address a number of generic security concerns. The building owners employ two different renovation strategies. The first, referred to as the Base Case, employs upgrades which are consistent with pre-9/11 levels of security. The second, referred to as the Proposed Alternative, recognizes 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 capture these risks.

The results of this study demonstrate that the Proposed Alternative results in lower life-cycle costs and is hence the more cost-effective choice. Additional economic measures are reported that underscore the superior performance of the Proposed Alternative. Finally, this study demonstrates how a detailed cost-accounting framework promotes better decision making by identifying unambiguously who bears which costs, how costs are allocated among several widely-accepted budget categories, and how costs are allocated among key building components.

Keywords

Building economics; commercial buildings; construction; economic analysis; hazard mitigation; homeland security; life-cycle costing

Preface

This study was conducted by the Office of Applied Economics (OAE) in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). The study is designed to illustrate how to use economic analysis to evaluate security-related investments in constructed facilities. The intended audience is the National Institute of Standards and Technology as well as other government and private sector organizations that are concerned with evaluating how to efficiently allocate scarce financial resources among security-related investment alternatives.

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List of Acronyms

Acronym	Definition
AHP	Analytical Hierarchy Process
AIRR	Adjusted Internal Rate of Return
ASTM	American Society for Testing and Materials
BFRL	Building and Fire Research Laboratory
CBRE	Chemical, Biological, Radiological, and Explosive
CDF	Cumulative Distribution Function
HVAC	Heating, Ventilation, and Air-Conditioning
IAQ	Indoor Air Quality
LCC	Life-Cycle Cost
MARR	Minimum Acceptable Rate of Return
NIST	National Institute of Standards and Technology
OAE	Office of Applied Economics
O&M	Operations and Maintenance
OMB	Office of Management and Budget
PVC	Present Value of Non-Investment Costs
PVE(L)	Present Value of Expected Losses
PVI	Present Value of Investment Costs
PVII	Present Value of Increased Investment Costs
PVNS	Present Value of Net Savings
PVS	Present Value of Savings
SIR	Savings-to-Investment Ratio
TV	Terminal Value

1 Introduction

1.1 Background

The September 11th attacks on the World Trade Center buildings and the Pentagon galvanized the nation in strengthening its defenses against future terrorist attacks. Such attacks could result in physical damage to various constructed facilities, such as buildings, industrial facilities, and infrastructure (e.g., bridges and dams). It is also likely that any attacks on constructed facilities would result in personal injury and financial losses to employees, tenants, occupants, and other facility stakeholders (e.g., owners and managers, investors, and third parties).

Owners and managers of constructed facilities now face the challenge of responding in a financially responsible manner to the potential for future terrorist attacks. Three strategies for reducing exposure to terrorist-related losses are: (1) engineering alternatives; (2) management practices; and (3) financial mechanisms. Engineering alternatives include building designs and materials that can better withstand attack, and retrofits of existing structures to reduce the estimated loss of life and property from a terrorist attack. Management practices include selecting safer building sites and the use of physical security personnel. Financial mechanisms are of two types: insurance and financial incentives. The owners and managers of constructed facilities may transfer the risk of losses from terrorism by purchasing insurance for some types of losses. Financial incentives include tax write-offs, reduced insurance premiums, and government cost-sharing arrangements for investments that protect against terrorism. How investments in these "mitigation" strategies are integrated into a cohesive risk mitigation plan is a complex decision problem.

Economic tools—evaluation methods and software for implementing these methods—are needed to direct limited resources to investments in mitigation strategies that will provide the most cost-effective reduction in personal injuries, financial losses, and damages to constructed facilities. Such tools will enable key decision makers—the intended customers[1]—to produce a risk mitigation plan that responds to the potential for future terrorist attacks in a financially responsible manner. By using economic tools to promote more informed decisions, both intended customers and other stakeholders will accrue significant benefits through reduced exposure to terrorist-related losses.

The economic tool envisioned is a flexible decision methodology, embedded in user-friendly, decision-support software, that helps the owners and managers of buildings, industrial facilities, and infrastructure to maximize the likely reduction in terrorist-related losses while considering the tradeoffs among alternative levels of reliance on the three

[1] Customers are the intended users of the economic tools; they are either directly or indirectly empowered to decide which combination of mitigation strategies to employ. Stakeholders are organizations or individuals directly affected by mitigation activities or disaster-related losses. Therefore, customers are a subset of stakeholders.

mitigation strategies. The economic tool will provide decision makers with the basis for generating a risk mitigation plan.

The Office of Applied Economics (OAE) in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) is now developing such a tool. This report is the first in a series on how to apply economic tools to homeland security-related issues in constructed facilities.

1.2 Purpose

The report employs a case study approach to identify the most cost-effective levels of security-related investments in a typical constructed facility. This case study approach illustrates how to apply economic tools and interpret the results. It also provides the technical and theoretical foundations of these tools. A companion, follow-on document,[2] also planned for publication in 2003, provides an in-depth discussion of those foundations as well as additional data, material, and techniques needed to address a wide variety of homeland security-related issues in constructed facilities.

This report has four main purposes. First, it demonstrates how to apply life-cycle cost analysis to a complex homeland security investment decision. Life-cycle cost analysis is a widely used evaluation method for conducting economic evaluations in constructed facilities; it is supported by an ASTM (American Society for Testing and Materials) International voluntary industry consensus standard.[3] Economic analysis over a project's life cycle is the basis for formulating a number of other economic evaluation methods. Three of these methods—present value of net savings, savings-to-investment ratio, and adjusted internal rate of return—are also employed in this report and are supported by voluntary industry consensus standards.[4] These economic measures are all useful in evaluating whether or not to undertake a particular investment, since each measure provides a different perspective.[5]

Second, the case study demonstrates how a detailed cost-accounting framework promotes better decision making by identifying unambiguously who bears which costs, how costs are allocated among several widely-accepted budget categories, and how costs are allocated among key building components. A detailed cost-accounting framework is needed because costs affect stakeholders in different ways. Thus, knowing who bears

[2] Chapman, Robert E., and Chi J. Leng. Expected publication date 2003. *Cost-Effective Responses to Terrorist Risks*. NISTIR (in preparation). Gaithersburg, MD: National Institute of Standards and Technology.
[3] ASTM International. 2002. "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems." E 917. *Annual Book of ASTM Standards: 2002*. Vol. 04.11. West Conshohocken, PA: ASTM International.
[4] ASTM International. Fourth Edition, 1999. *ASTM Standards on Building Economics*. West Conshohocken, PA: ASTM International.
[5] The present value of net savings measures the overall magnitude of cost savings. The savings-to-investment ratio measures the cost savings per unit of capital investment. The adjusted internal rate of return measures the annual percentage yield from the capital investment.

which costs leads to a better understanding of stakeholder perspectives and helps create mutually beneficial solutions.

Third, the case study demonstrates how to combine information from two generic types of analysis—a baseline analysis and a sensitivity analysis—into a risk mitigation plan. The two generic types of analysis are designed to complement and reinforce each other. The baseline analysis provides a detailed snapshot of all costs associated with alternative levels of investment in mitigation strategies. These costs are summarized via the cost-accounting framework. The baseline analysis serves as the reference point for the sensitivity analysis. The baseline analysis also produces a preliminary ranking of the investment alternatives under consideration. The most cost-effective alternative identified in the baseline analysis is the starting point for creating a risk mitigation plan. The sensitivity analysis measures the impact on project outcomes (e.g., life-cycle cost) of changing the values of one or more key input values about which there is uncertainty. The sensitivity analysis enables the decision maker to evaluate the conditions under which other investment alternatives might result in a lower life-cycle cost. Coupling the two generic types of analysis with the cost-accounting framework promotes a better understanding of both expected costs and the variability of these costs across stakeholder groups.

Fourth, this case study provides the software development process with the basis for specifying linkages among screens, checking computational algorithms, and assessing analysis capabilities for the prototype of OAE's software product.

1.3 Scope and Approach

The "case study" approach employed here illustrates how to apply life-cycle cost analysis to a complex homeland security investment decision—the process of creating a risk mitigation plan. A case study approach is useful because creating a risk mitigation plan is complicated by the fact that investment costs often result in significant outlays, operations and maintenance costs are distributed over a period of many years, and costs affect stakeholders in different ways. The nature of these "cost considerations" introduces four complicating factors into the capital asset decision-making process. First, how do we identify which constructed facilities to protect and why? Second, which mitigation strategies do we employ and how will they operate, both singly and in combination?[6] Third, who bears which costs? Fourth, how do we produce a risk mitigation plan that demonstrates superior economic performance? Thus, a formal methodology is needed to insure that all relevant costs are captured and are analyzed via well-defined metrics to identify a risk mitigation plan that results in superior economic performance. Life-cycle cost analysis and the related economic methods covered in this report provide those metrics.

This report has five chapters in addition to the Introduction. The methodology and the standardized methods employed in the case study are described in Chapter 2.

[6] Responding to this complicating factor involves identifying whether there are any interdependencies that either positively or negatively affect the performance of any mitigation strategies.

Standardized methods are used to define the key measures of economic performance. The cost-accounting framework recommended for use in homeland security economic evaluations is then presented. A format for summarizing the results of an economic evaluation is also presented. This format is used to produce a two-page summary of the case study shown in Section 6.1.

The body of the report, Chapters 3 through 5, is a case study of a data center renovation project being undertaken to remedy a number of generic security concerns. The approach is to present all security-related information in sufficient detail for the reader to understand the basis for the economic evaluation and make it possible to reproduce the results of the economic evaluation.

Chapter 3 formulates the economic evaluation of the data center renovation. Following an overview of the case study, information on how the investment alternatives are specified is presented. Key assumptions and analysis issues are then presented.

Chapter 4 presents the baseline analysis. The chapter begins with a description of the cost items entering into the analysis. Information is presented on renovation costs, service life estimates, and estimates of operations, maintenance, and repair expenditures. Attack scenarios are also presented. These scenarios include probabilities of each attack outcome and its associated costs. Emphasis is then shifted to how the cost items are modeled and analyzed via the cost-accounting framework. Summary information is then presented to demonstrate how life-cycle cost analysis facilitates the identification of a cost-effective risk mitigation plan. Life-cycle cost information is supplemented with additional economic measures to demonstrate new insights provided by these measures. The chapter concludes with a discussion of how the baseline analysis links to the software product.

Chapter 5 includes a sensitivity analysis to provide the reader with additional background and perspective on the data center case study. The purpose of the sensitivity analysis is to evaluate the impact of changing the values of a number of key variables whose values are uncertain. Monte Carlo techniques are employed to evaluate how changing the values of these key variables in combination affects the calculated values of the key economic measures. The chapter concludes with a discussion of how the sensitivity analysis links to the software product. Chapter 6 concludes the report with a summary and suggestions for further research.

2 A Methodology for Measuring Economic Performance

This chapter focuses on laying out a methodology for measuring and summarizing the economic performance of alternative levels of investments in mitigation strategies. The economic evaluation methodology that emerges is both comprehensive and consistent. The methodology is based on two types of analysis, four measures of economic performance, a cost-accounting framework, and a format for summarizing the results of an economic evaluation. The two types of analysis are baseline analysis and sensitivity analysis. They are described in Section 2.1. The four measures of economic performance are life-cycle cost, present value of net savings, savings-to-investment ratio, and adjusted internal rate of return. They are described in Section 2.2. The cost-accounting framework is described in Section 2.3. The format for summarizing the results of the economic evaluation is described in Section 2.4.

An economic evaluation may be divided into four stages: (1) identification; (2) classification; (3) quantification; and (4) presentation. The identification stage involves identifying and listing all of the "effects" of the project/program being analyzed. In principle, this set of effects produces a checklist of all items that should be taken into consideration. The second stage entails classifying these effects into cost categories. The third stage produces year-by-year estimates of the values of each of the cost categories. The final stage is the presentation and analysis of the relevant information in a straightforward manner (i.e., in a form that clearly spells out the important assumptions underlying the economic evaluation and the implications of these assumptions for the study's conclusions).

2.1 Types of Analysis

2.1.1 Baseline Analysis

The starting point for conducting an economic evaluation is to do a baseline analysis. In the baseline analysis, all data (i.e., all input variables and any functional relationships among these variables) entering into the calculations are set at their likely values. For selected types of data, the input values are fixed (e.g., a physical constant or a value that is mandated by legislation). The input values associated with these data types are considered to be known with certainty. For other types of data, the likely values[7] reflect the fact that some information associated with these data is uncertain. Consequently, the values of any data subject to uncertainty are set based on some measure of central tendency.[8] Baseline data represent a fixed state of analysis based on likely values. For

[7] Throughout this report, the terms likely value and baseline value are used interchangeably.

[8] Two common measures of central tendency are the arithmetic mean (e.g., the sum of the individual values of the items divided by the number of items in the sample) and the median (e.g., the middle value in a rank ordering of the individual values of the items in the sample). In most cases in this report, the mean is used as the measure of central tendency. Any case where the median is used as the measure of central tendency is clearly indicated in the text. Consequently, if no explicit reference is made to the measure of central tendency, the measure used is the mean.

this reason, the results and the analysis of these results are referred to as the baseline analysis. Throughout this report, the term baseline analysis is used to denote a complete analysis in all respects but one; it does not address the effects of uncertainty.

2.1.2 Sensitivity Analysis

Sensitivity analysis measures the impact on project outcomes of changing the values of one or more key input variables about which there is uncertainty. Sensitivity analysis can be performed for any measure of economic performance (e.g., life-cycle cost, present value of net savings, savings-to-investment ratio, adjusted internal rate of return). Since sensitivity analysis is easy to use and understand, it is widely used in the economic evaluation of government and private-sector applications. Office of Management and Budget *Circular A-94* recommends sensitivity analysis to federal agencies as one technique for treating uncertainty in input variables.[9] Therefore, a sensitivity analysis complements the baseline analysis by evaluating the changes in output measures when selected key sets of data vary about their baseline values. Readers interested in a comprehensive survey on methods for dealing with uncertainty for use in government and private-sector applications are referred to the study by Marshall[10] and the subsequent video[11] and workbook.[12]

2.2 Overview of Evaluation Methods

Several methods of economic evaluation are available to measure the economic performance of a new technology, a building, a building system, or like investment, over a specified time period. These methods include, but are not limited to, life-cycle cost, present value of net savings, savings-to-investment ratio, and adjusted internal rate of return. These methods differ in their mathematical formulation and, to some extent, in their applicability to particular types of investment decisions.

To ensure consistency in computation, application, and interpretation, the four methods described in this section are based on ASTM International standard practices.[13] The four "standardized" evaluation methods used in this report are generic. Readers interested in an in-depth survey covering these as well as other methods are referred to Ruegg and Marshall.[14]

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[9] Executive Office of the President. 1992. *OMB Circular A-94*. Washington, DC: Office of Management and Budget.

[10] Marshall, Harold E. 1988. *Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Building Investments.* NIST Special Publication 757. Gaithersburg, MD: National Institute of Standards and Technology.

[11] Marshall, Harold E. 1992. *Uncertainty and Risk—Part II in the Audiovisual Series on Least-Cost Energy Decisions for Buildings.* Gaithersburg, MD: National Institute of Standards and Technology.

[12] Marshall, Harold E. 1993. *Least-Cost Energy Decisions for Buildings—Part II: Uncertainty and Risk Video Training Workbook*. NISTIR 5178. Gaithersburg, MD: National Institute of Standards and Technology.

[13] ASTM International. Fourth Edition, 1999. *ASTM Standards on Building Economics*. West Conshohocken, PA: ASTM International.

[14] Ruegg, Rosalie T. and Harold E. Marshall. 1990. *Building Economics: Theory and Practice.* New York: Chapman and Hall.

Once all costs have been identified and classified, it becomes necessary to develop year-by-year estimates for each of the cost categories for each alternative under analysis. We denote the alternatives as A_j (where the index for j ranges from $0,\ldots, N$, for a total of N+1 alternatives). Associated with each alternative are investment cost categories k (where the index k ranges from $1,\ldots, K_j$) and non-investment cost categories m (where the index m ranges from $1,\ldots, M_j$). The potential for future terrorist attacks—as well as other natural and man-made hazards—are measured by the expected value of annual losses. Associated with each alternative are expected loss categories p (where the index p ranges from $1,\ldots, P_j$). Some of the expected loss categories accrue to investment costs and some accrue to non-investment costs. Expected losses are modeled separately from investment costs and non-investment costs to better characterize the nature of low-probability high-consequence events. It is important to note that some costs entering the analysis may be negative. For example, the sale of equipment and components at the end of the study period results in a salvage value whose present value is subtracted from investment costs. Similarly, better indoor air quality may result in productivity improvements which favorably impact occupants; these "savings" are subtracted from non-investment costs. Any pure benefits which result (e.g., increased rental income due to improvements) are subtracted from project costs (i.e., benefits are treated as negative costs).

At the heart of the economic evaluation methodology is an economic concept referred to as the time value of money. This concept relates to the changing purchasing power of money as a result of inflation or deflation, along with consideration of the real earning potential of alternative investments over time.[15] The discount rate reflects the decision maker's time value of money. The discount rate is used to convert, via a process known as discounting, costs which occur at different times to a base time. Throughout this report, the term "present value" will be used to denote the value of a cost found by discounting cash flows (present and future) to the base time. The base time is the date (base year) to which costs are converted to time equivalent values.

In order to describe each of the four standardized methods, it is necessary to first introduce and define a series of terms. These terms are used to define each of the standardized methods. Throughout this section, the following terms are used as the basis for defining the standardized methods:

t = a unit of time;[16]

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[15] Inflation reduces the purchasing power of the dollar over time; deflation increases it. When amounts are stated in actual prices as of the year in which they occur, they are said to be in *current dollars*. Current dollars are dollars of any one year's purchasing power, inclusive of inflation/deflation. That is, they reflect changes in purchasing power of the dollar from year to year. In contrast, *constant dollars* are dollars of uniform purchasing power, exclusive of inflation/deflation. Constant dollars indicate what the same good or service would cost at different times if there were no change in the general price level to change the purchasing power of the dollar. For additional information on conducting economic analyses using either constant dollars or current dollars, see Fuller, Sieglinde K., and Stephen R. Petersen. 1996. *Life-Cycle Costing Manual for the Federal Energy Management Program*. NIST Handbook 135. Gaithersburg, MD: National Institute of Standards and Technology.

[16] Denote the beginning of the study period as the base year (i.e., t=0) and end of the study period as T. Thus, the length of the study period in years is T.

T	=	the length of the study period in years;
d	=	the discount rate expressed as a decimal.[17]

Throughout this section the prefix, *PV*, is used to designate dollar denominated quantities in present value terms. The present value is derived by discounting (i.e., using the discount rate) all costs—present and future—to the base year (i.e., t=0). The present value terms are: the present value of investment costs (*PVI*), the present value of non-investment costs (*PVC*), and the present value of expected losses (*PVE(L)*).

The cost terms that make up the four mathematical formulations are given in equations (2.1) through (2.6). While there may be many different ways of classifying costs (i.e., classification schemes), their explicit treatment in both the mathematical formulation and the standardized methods ensures that a comprehensive and consistent coupling results between the mathematical formulation and each standardized method.

The investment costs for alternative A_j in year t may now be expressed as:

$$I_{jt} = \sum_{k=1}^{K_j} I_{kjt} \tag{2.1}$$

The non-investment costs for alternative A_j in year t may now be expressed as:

$$C_{jt} = \sum_{m=1}^{M_j} C_{mjt} \tag{2.2}$$

The expected losses for alternative A_j in year t may now be expressed as:

$$E\left(L_{jt}\right) = \sum_{p=1}^{P_j} E\left(L_{pjt}\right) \tag{2.3}$$

The present value of investment costs for alternative A_j may now be expressed as:

$$PVI_j = \sum_{t=0}^{T}\left(\sum_{k=1}^{K_j} I_{kjt}\right)/(1+d)^t \tag{2.4}$$

The present value of non-investment costs for alternative A_j may now be expressed as:

$$PVC_j = \sum_{t=0}^{T}\left(\sum_{m=1}^{M_j} C_{mjt}\right)/(1+d)^t \tag{2.5}$$

[17] The discount rate used with constant-dollar amounts is different from the discount rate used with current-dollar amounts. A *real discount rate* (net of general inflation) is used with *constant-dollar amounts*. A market or *nominal discount rate* (inclusive of general inflation) is used with *current-dollar amounts*.

The present value of expected losses for alternative A_j may now be expressed as:

$$PVE\left(L_j\right) = \sum_{t=0}^{T}\left(\sum_{p=1}^{P_j} E\left(L_{pjt}\right)\right)/(1+d)^t \qquad (2.6)$$

2.2.1 Life-Cycle Cost Method[18]

The life-cycle cost (LCC) method measures, in present-value or annual-value terms, the sum of all relevant costs associated with owning and operating a constructed facility over a specified period of time. The basic premise of the LCC method is that to an investor or decision maker all costs arising from that investment decision are potentially important to that decision, including future as well as present costs. Applied to constructed facilities, the LCC method 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 design or system.

The LCC method is particularly suitable for determining whether the higher initial cost of a constructed facility or system specification is economically justified by lower future costs (e.g., losses due to natural or manmade hazards) when compared to an alternative with a lower initial cost but higher future costs. If a 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.

The LCC for alternative A_j may now be expressed as:

$$LCC_j = \sum_{t=0}^{T}\left(\sum_{k=1}^{K_j} I_{kjt} + \sum_{m=1}^{M_j} C_{mjt} + \sum_{p=1}^{P_j} E\left(L_{pjt}\right)\right)/(1+d)^t \qquad (2.7)$$

Denote the alternative with the lowest initial investment cost (i.e., first cost) as A_0; it is referred to as the base case. Then:

$$I_{00} < I_{j0} \qquad \text{for j = 1,…, N} \qquad (2.8)$$

The LCC method compares alternative (mutually exclusive) designs or system specifications that satisfy a given functional requirement on the basis of their life-cycle costs to determine which is the least-cost means (i.e., minimizes life-cycle cost) of satisfying that requirement over a specified study period. Should any pure benefits result from the project (e.g., increased rental income due to improvements); include them in the calculation of LCC.

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[18] ASTM International. 2002. "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems." E 917. *Annual Book of ASTM Standards: 2002*. Vol. 04.11. West Conshohocken, PA: ASTM International.

2.2.2 Present Value of Net Savings Method[19]

The present value of net savings (PVNS) method is reliable, straightforward, and widely applicable for finding the economically efficient choice among investment alternatives. It measures the net savings from investing in a given alternative instead of investing in the foregone opportunity (e.g., some other alternative or the base case). Any pure benefits that result from the project (e.g., increased rental income due to improvements) are included in the calculation of PVNS, since they are included in the LCC calculation.

The PVNS for a given alternative, A_j, vis-à-vis the base case, A_0, may be expressed as:

$$PVNS_{j:0} = LCC_0 - LCC_j \tag{2.9}$$

If $PVNS_{j:0}$ is positive, alternative A_j is economic; if it is zero, the investment is as good as the base case; if it is negative, the investment is uneconomical.

2.2.3 Savings-to-Investment Ratio Method[20]

The savings-to-investment ratio (SIR) is a numerical ratio whose size indicates the economic performance of a given alternative instead of investing in the foregone opportunity. The SIR is savings divided by investment costs. The LCC method provides all of the necessary information to calculate the SIR. The SIR for a given alternative, A_j, is calculated vis-à-vis the base case. The numerator and denominator of the SIR are derived through reference to equations (2.4) and (2.5).

The numerator equals the difference in the present value of non-investment costs between the base case and the given alternative, A_j. The resultant expression, denoted as present value of savings, is given by:

$$PVS_{j:0} = PVC_0 - PVC_j \tag{2.10}$$

The denominator equals the difference in the present values of investment costs for the given alternative, A_j, and the base case. The resultant expression, denoted as present value of increased investment costs, is given by:

$$PVII_{j:0} = PVI_j - PVI_0 \tag{2.11}$$

The SIR for a given alternative, A_j, vis-à-vis the base case may be expressed as:

[19] ASTM International. 2002. "Standard Practice for Measuring Net Benefits for Investments in Buildings and Building Systems." E 1074. *Annual Book of ASTM Standards: 2002*. Vol. 04.11. West Conshohocken, PA: ASTM International.
[20] ASTM International. 2002. "Standard Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Investments in Buildings and Building Systems." E 964. *Annual Book of ASTM Standards: 2002*. Vol. 04.11. West Conshohocken, PA: ASTM International.

$$SIR_{j:0} = \frac{PVS_{j:0}}{PVII_{j:0}} \tag{2.12}$$

A ratio less than 1.0 indicates that A_j an uneconomic investment relative to the base case; a ratio of 1.0 indicates an investment whose benefits or savings just equal its costs; and a ratio greater than 1.0 indicates an economic project. A ratio of, say, 2.75 means that the investor (e.g., the general public for a public-sector project/program) can expect to receive $2.75 in cost savings for every $1.00 invested (e.g., public funds expended), over and above the required rate of return imposed by the discount rate.

2.2.4 Adjusted Internal Rate of Return Method[21]

The adjusted internal rate of return (AIRR) is the average annual yield from a project over the study period, taking into account reinvestment of interim receipts. Because the AIRR calculation explicitly includes the reinvestment of all net cash flows, it is instructive to introduce a new term, terminal value (TV). The terminal value of an investment, A_j, is the future value (i.e., the value at the end of the study period) of reinvested net cash flows excluding all investment costs. The terminal value for an investment, A_j, is denoted as TV_j.

The reinvestment rate in the AIRR calculation is equal to the minimum acceptable rate of return (MARR), which is assumed to equal the discount rate, d, a constant. When the reinvestment rate is made explicit, all investment costs are easily expressible as a time equivalent initial outlay (i.e., a value at the beginning of the study period) and all non-investment cash flows as a time equivalent terminal amount. This allows a straightforward comparison of the amount of money that comes out of the investment (i.e., the terminal value) with the amount of money put into the investment (i.e., the time equivalent initial outlay).

The AIRR is defined as the interest rate, r_j, applied to the terminal value, TV_j, which equates (i.e., discounts) it to the time equivalent value of the initial outlay of investment costs. It is important to note that all investment costs are discounted to a time equivalent initial outlay (i.e., to the beginning of the study period) using the discount rate, d.

Several procedures exist for calculating the AIRR. These procedures are derived and described in detail in the report by Chapman and Fuller.[22] The most convenient procedure for calculating the AIRR is based on its relationship to the SIR. This procedure results in a closed-form solution for $r_{j:0}$. The AIRR for a given alternative, A_j, vis-à-vis the base case—expressed as a decimal—is that value of $r_{j:0}$ for which:

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[21] ASTM International. 2002. "Standard Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems." E 1057. *Annual Book of ASTM Standards: 2002*. Vol. 04.11. West Conshohocken, PA: ASTM International.

[22] Chapman, Robert E. and Sieglinde K. Fuller. 1996. *Benefits and Costs of Research: Two Case Studies in Building Technology*. NISTIR 5840. Gaithersburg, MD: National Institute of Standards and Technology.

$$r_{j:0} = (1+d)(SIR_{j:0})^{\frac{1}{T}} - 1 \quad (2.13)$$

If $r_{j:0}$ is greater than the discount rate (also referred to as the hurdle rate), alternative A_j is economic; if $r_{j:0}$ equals the discount rate, the investment is as good as the base case; if $r_{j:0}$ is less than the discount rate, the investment is uneconomical.

2.2.5 Summary of Methods[23]

The methods presented in the previous sections provide the basis for evaluating the economic performance of homeland security-related investments in constructed facilities. The equations underlying the methods presented earlier are all based on ASTM standard practices. All of the methods are appropriate for evaluating accept or reject type decisions. But among the methods are several distinctions that relate to the type of investment decision that the decision maker is facing.

There are four basic types of investment decisions for which an economic analysis is appropriate:

(1) whether to accept or reject a given project;

(2) the most efficient project size/level, system, or design;

(3) the optimal combination of interdependent projects (i.e., the right mix of sizes/levels, systems, and designs for a group of interdependent projects); and

(4) how to prioritize or rank independent projects when the allowable budget can not fund them all.

Each type of investment decision is important. First and foremost, decision makers need to know whether or not a particular project or program should be undertaken in the first place. Second, how should a particular project/program be configured? The third type of decision builds on the second and introduces an important concept, interdependence. Consequently, for a given set of candidate projects and implied interdependencies, the problem becomes how to choose that combination of projects that minimizes LCC (or equivalently maximizes PVNS). The fourth type of decision introduces a budget constraint. The key here is how to get the most impact for the given budget amount.

Table 2-1 provides a summary of when it is appropriate to use each of the evaluation methods described earlier. Note that the LCC and PVNS methods are appropriate in

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[23] For a comprehensive treatment of how to choose among economic evaluation methods, see the NIST/BFRL video (Marshall, Harold E. 1995. *Choosing Economic Evaluation Methods—Part III in the Audiovisual Series on Least-Cost Energy Decisions for Buildings*. Gaithersburg, MD: National Institute of Standards and Technology) and workbook (Marshall, Harold E. 1995. *Least-Cost Energy Decisions for Buildings—Part III: Choosing Economic Evaluation Methods Video Training Workbook*. NISTIR 5604. Gaithersburg, MD: National Institute of Standards and Technology).

three of the four cases. Only in the presence of a budget constraint is the use of either LCC or PVNS inappropriate and even in that case it plays an important role in computing the aggregate measure of performance.

Table 2-1. Summary of Appropriateness of Each Standardized Evaluation Method for Each Decision Type[24]

Decision Type	LCC	PVNS	SIR	AIRR
Accept/Reject	Yes	Yes	Yes	Yes
Design/Size	Yes	Yes	No	No
Combination (Interdependent)	Yes	Yes	No	No
Priority/Ranking (Independent)	No	No	Yes	Yes

In summary, no single evaluation method works for every decision type. First and foremost, managers want to know if a particular project is economic. Reference to Table 2-1 shows that all of the evaluation methods address this type of decision. Second, as issues of design, sizing, and packaging combinations of projects become the focus of attention—as often occurs in conjunction with budget reviews—the LCC and PVNS methods emerge as the principle means for evaluating a project's or program's merits.[25] Finally, the tightening budget picture involves setting priorities. Consequently, decision makers need both measures of magnitude, provided by LCC and PVNS, and of return, provided by either the SIR or the AIRR, to assess economic performance. Multiple measures, when used appropriately, ensure consistency in both setting priorities and selecting projects for funding.

2.3 The Need for a Detailed Cost-Accounting Framework

The cost categories represented in equations (2.1) through (2.6) provide the basis for calculating life-cycle costs. The flexibility of the life-cycle cost method, however, enables us to go beyond the generic cost categories represented in equations (2.1) through (2.6). The result is a more focused representation of costs; it is referred to as the detailed cost-accounting framework. The objective of producing this framework is to promote better decision making by identifying unambiguously who bears which costs, how costs are allocated among several widely-accepted budget categories, and how costs are allocated among key building components. A detailed cost-accounting framework is needed because costs affect stakeholders in different ways. Thus, knowing who bears

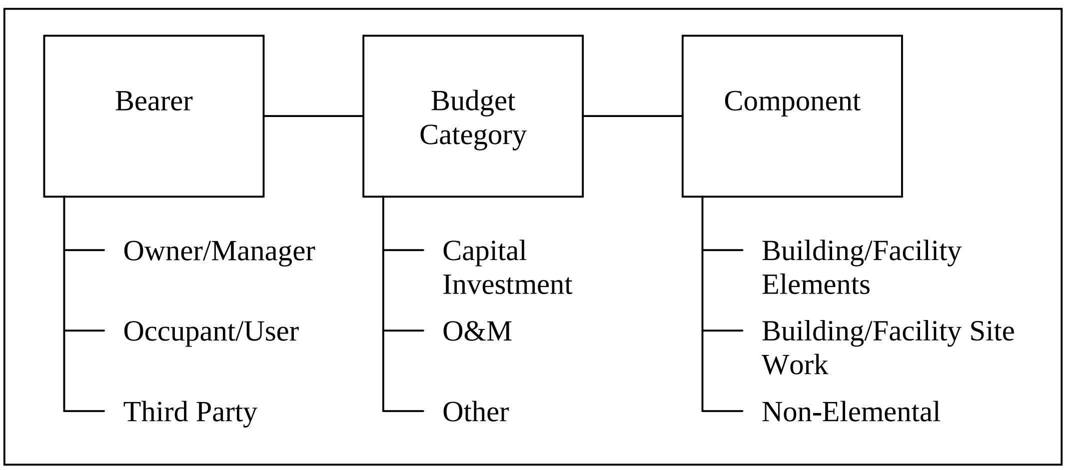
[24] ASTM International. 2002. "Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems." E 1185. *Annual Book of ASTM Standards: 2002*. Vol. 04.11. West Conshohocken, PA: ASTM International.

[25] If incremental values of the SIR or AIRR are computed, they can be used to make design/size and packaging decisions. See Ruegg and Marshall, *Building Economics*, pp. 54-58 and 85-87.

which costs leads to a better understanding of stakeholder perspectives and helps create mutually beneficial solutions. Finally, the cost-accounting framework promotes a detailed, consistent breakdown of life-cycle costs so that a clear picture emerges of the cost differences between competing alternatives.

Costs are classified along three dimensions within the detailed cost-accounting framework. To differentiate these costs from the generic cost categories, they are referred to as cost types and cost items. Each dimension contains a collection of cost types. The cost types are used as placeholders for summarizing and reporting aggregated cost information. Each cost type is a collection of cost items. Each cost item has a unique set of identifiers that places it within the cost-accounting framework. The three dimensions employed in the cost-accounting framework are: (1) bearer of costs; (2) budget category; and (3) building/facility component. Each dimension captures the full spectrum of costs (i.e., all costs summed across each dimension add up to the same total). A schematic representation of the cost-accounting framework is given in Figure 2-1.

Figure 2-1. Overview of the Cost-Accounting Framework



The description of the cost-accounting framework given here employs a project-oriented approach. Such an approach is instructive since most construction activity is summarized on a project basis. This approach also helps to link the methodology to the software product. A project could be the construction of a building, industrial facility, or infrastructure. A project could also be the renovation of an existing constructed facility.

The first of the three dimensions covers who bears which costs. This dimension covers all stakeholder groups.[26] A stakeholder group is defined as any collection of

[26] The companion document outlines a strategy for identifying, collecting, and measuring benefits and costs. See Chapman and Leng, *Cost-Effective Responses to Terrorist Risks*, pp. 15-28. The strategy includes a hierarchy of individual stakeholders and stakeholder groups and a hierarchy of benefits and costs. Although the benefits and costs appearing in their respective hierarchies are generic, the hierarchies are considered to be exhaustive. Two crosswalks are provided to demonstrate how benefits and costs accrue to stakeholder groups.

organizations or individuals directly affected by the project (e.g., by construction or risk mitigation activities or by disaster-related losses). The first dimension, Bearer, has three cost types based on who bears the costs. The three cost types are: (1) Owner/Manager; (2) Occupant/User; and (3) Third Party. Owner/Manager costs are all costs incurred by the project's owner or agent. These costs include but are not limited to design costs, capital investment costs, and selected types of repairs to the constructed facility. Occupant/User costs accrue to the direct users of the project. Occupant/User costs frequently include operations and maintenance costs and selected types of repairs not covered by the project's owner or agent. Occupant/User costs can also include delay costs and business interruption costs due to temporary closures for repair and reconstruction activities. Third-Party costs are all costs incurred by entities who are neither the project's owner or agent nor direct users of the project. One example of a Third-Party cost is the lost sales for a business establishment whose customer access has been impeded (e.g., due to a road closure during construction/reconstruction). Another example is damage to the environment from a construction process that pollutes the water, land, or atmosphere.

The second dimension, Budget Category, has three cost types based on which category of the budget the funds come from. These cost types are: (1) Capital Investment; (2) O&M (Operations and Maintenance); and (3) Other. These cost types correspond to widely used budget categories for private and public sector cost accounting. In the context of the previous section, Capital Investment costs accrue to the investment cost category (see equations 2.1 and 2.4) and O&M and Other costs accrue to the non-investment cost category (see equations 2.2 and 2.5). NIST Handbook 135 is especially helpful in determining how to allocate cost items among Capital Investment and O&M.[27] All acquisition costs, including costs related to planning, design, purchase, and construction, are investment-related costs and fall under the Capital Investment cost type. Residual values (resale, salvage, or disposal costs) and capital replacement costs are also investment-related costs. Capital replacement costs are usually incurred when replacing major systems or components and are paid from capital funds. Cost items falling under the O&M cost type include energy and water costs, maintenance and repair costs, minor replacements related to maintenance and repair activities, and insurance premiums paid by owners and/or occupants to reduce their risk exposure. O&M costs are usually paid from an annual operating budget, not from capital funds. Other costs are non-capital costs that can not be attributed to the O&M cost type. An example of an Other/Third-Party cost is damage to the environment stemming from the project.

The third dimension, Component, has three cost types. These cost types are: (1) Building/Facility Elements; (2) Building/Facility Site Work; and (3) Non-Elemental. The first two cost types are associated with the elemental classification UNIFORMAT II.[28]

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[27] Fuller, Sieglinde K., and Stephen R. Petersen. 1996. *Life-Cycle Costing Manual for the Federal Energy Management Program*. NIST Handbook 135. Gaithersburg, MD: National Institute of Standards and Technology.

[28] ASTM International. 2002. "Standard Classification for Building Elements and Related Site Work—UNIFORMAT II." E 1557. *Annual Book of ASTM Standards: 2002*. Vol. 04.11. West Conshohocken, PA: ASTM International.

Elements are an integral part of any construction project; they are often referred to as component systems or assemblies. Each element performs a given function regardless of the materials used, design specified, or method of construction employed. Non-Elemental costs are all costs that can not be attributed to specific functional elements of the project. An example of a Non-Elemental/Capital/Owner cost is the purchase of a right-of-way or an easement. An example of a Non-Elemental/Other/Third-Party cost is damage to the environment stemming from the project.

The previous discussion serves to highlight some of the differences in perspective between public sector and private sector decision makers. A private sector decision maker may not be concerned with costs that are external to their firm. This perspective has a significant impact on what is included and what is excluded in the Third Party and Other cost types. Generally, this is in contrast to the public sector decision maker who must assess all costs to whomsoever they accrue. In the case of homeland security activities, however, the private sector perspective is often more in line with the public sector's perspective. Natural hazards, industrial accidents, and terrorist acts that occur infrequently, but whose consequences are devastating, highlight the importance of including Third Party and Other cost types in the private sector's life-cycle cost calculus. Including these costs also helps to identify areas for public policy analysis (e.g., the role of economic incentives), bringing private sector and public sector perspectives into closer alignment.

2.4 Presentation and Analysis of the Results of an Economic Evaluation

The presentation and analysis of the results of an economic evaluation are central to understanding and accepting its findings. If the presentation is clear and concise, and if the analysis strategy is logical, complete, and carefully spelled out, then the results will stand up under close scrutiny. This section first outlines a generic format for economic evaluations that meets the two previously cited conditions. The generic format is patterned after an ASTM Standard Guide for summarizing economic impacts.[29] The generic format is built upon the following three factors: (1) why the project is important; (2) how the analysis strategy is employed; and (3) how the key cost measures are calculated, summarized, and traced to relevant standards, codes, and regulations. These factors, taken together, constitute a three-step procedure for summarizing the results of an economic evaluation.

A template for a specific format, tailored to homeland security applications, is given in Exhibit 2-1. The specific format is focused at the project or program level. The specific format is designed to provide a concise summary of key project- or program-related results within the organization. Documenting results for homeland security applications at the project or program level provides a means for "rolling up" results to senior management while supporting performance improvement activities for the organization's project managers. For example, the specific format is well suited to summarize lessons

[29] ASTM International. 2002. "Standard Guide for Summarizing the Economic Impacts of Building-Related Projects." E 2204. *Annual Book of ASTM Standards: 2002*. Vol. 04.12. West Conshohocken, PA: ASTM International.

learned from using a particular technology or practice on a project or group of projects and to highlight why efforts should be made to incorporate these lessons learned into on-going or planned projects. Thus, the specific format provides a vehicle for information sharing across the organization's major units/divisions and geographic regions.

The discussion that follows relates the three factors for the generic format referenced above to the specific format given in Exhibit 2-1. Exposition of the generic format serves two purposes. First, it provides a means for organizing the way to present material associated with an economic evaluation. Second, it provides a vehicle for clearly and concisely presenting the salient results of the analysis. Such a short summary is appropriate for use by senior managers as the basis for statements on the benefits of the project or program to the public, employees, or other stakeholders. A two-page summary of the results of the baseline analysis for the data center case study is provided at the beginning of Chapter 6 (see Exhibit 6-1).

Exhibit 2-1. Format for Summarizing an Economic Evaluation

<table>
<tr>
<td>1.a Significance of the Project:

Describe why the project or program is important.

Describe the changes brought about by the effort.</td>
<td>1.b Key Points:

Highlight two or three key points which convey why this project or program is important.</td>
</tr>
<tr>
<td colspan="2">2. Analysis Strategy:

Describe how the life-cycle cost of each alternative was calculated.

Describe how the present value of net savings of the preferred alternative was determined.

Describe how any additional measures were calculated.

Summarize key data and assumptions: (a) Base year; (b) Length of study period; (c) Discount rate or minimum acceptable rate of return; (d) Data; and (e) Any special homeland security considerations.</td>
</tr>
<tr>
<td rowspan="2">3.a Calculation of Life-Cycle Costs and Additional Measures:

Life-Cycle Costs:
Report the life-cycle costs of each alternative.

Net Savings:
Report the present value of net savings of the preferred alternative.

Additional Measures:
Report the values of any additional measures calculated.</td>
<td>3.b Key Measures:

Report the calculated value of the Present Value of Net Savings (PVNS) and at least one of the following:
❖ Savings-to-Investment Ratio (SIR)
❖ Adjusted Internal Rate of Return (AIRR)</td>
</tr>
<tr>
<td>3.c Traceability

Cite references to specific ASTM standard practices, ASTM adjuncts, or any other standards, codes, or regulations used.</td>
</tr>
</table>

2.4.1 Significance of the Project

This section of the summary format sets the stage for the results that follow. It consists of two subsections, designated as 1.a and 1.b.

Subsection 1.a calls for a concise summary of the project. The summary is sufficiently detailed to enable senior management and non-technical readers to understand the significance of the project. The goal at this point is to clearly describe:

(1) why the project is important; and

(2) why some or all of the changes brought about are noteworthy.

The objective of subsection 1.b is to highlight two or three points which convey why this project is important. These points are intended for use as talking points by senior management when they make presentations to non-technical audiences or for use in press releases.

2.4.2 Analysis Strategy

This section of the summary format focuses on documenting the steps taken to ensure that the analysis strategy is logical and complete. Particular emphasis is placed on summarizing the key assumptions, including any constraints that limited the scope of the study. Responses are provided for key assumptions concerning: (a) the base year for the study; (b) the length of the study period; (c) the discount rate or minimum acceptable rate of return used; and (d) any special homeland security considerations.

Special emphasis is placed on documenting the *sources and validity* of any data used to make estimates or projections of key cost measures. This section establishes an audit trail from the raw data, through data manipulations (e.g., represented by equations and formulae), to the results which describe how to determine:

(1) the **life-cycle cost** of each alternative evaluated;[30]

(2) the **present value of net savings** of the preferred alternative;[31] and

(3) the way in which any **additional measures** were calculated.

[30] As part of the discussion of life-cycle costs, include information on how life-cycle costs are distributed across the key stakeholder groups.

[31] If the preferred alternative is not the minimum life-cycle cost alternative, provide a rationale on why it is preferable to the minimum life-cycle cost alternative. For example, a rationale for not preferring the minimum life-cycle cost alternative could be due to its adverse impact (i.e., cost burden) on one of more of the key stakeholder groups.

2.4.3 Calculation of Life-Cycle Costs and Additional Measures

This section of the summary format focuses on reporting the calculated values of the key cost measures, as well as any additional measures that are deemed appropriate, and establishing traceabilty to standardized practices or, where appropriate, to statutory documents or procedures. It consists of three subsections, designated as 3.a, 3.b, and 3.c.

Subsection 3.a reports using text, mathematical expressions, tables, graphs, and comparative statistics the following information:

(1) the life-cycle cost of each alternative;

(2) the present value of net savings of the preferred alternative; and

(3) the values of any additional measures calculated.

Subsection 3.b reports the calculated value of the life-cycle cost for each alternative, the present value of net savings of the preferred alternative and at least one of the following:

(a) the savings-to-investment ratio, or

(b) the adjusted internal rate of return.

Subsection 3.c cites references to specific ASTM standard practices, ASTM adjuncts, or any other standards, codes, or regulations used.

3 Formulating the Economic Evaluation of the Data Center Renovation

This chapter formulates the economic evaluation of the data center renovation. Following an overview of the case study, information on how the investment alternatives are specified is presented. The chapter concludes with a discussion of key assumptions and analysis issues.

3.1 Data Center Renovation: Overview of the Case Study

This case study describes a renovation project for a prototypical data center for a financial institution. It is based on an actual building renovation project. However, for purposes of confidentiality, a number of key building features have been changed. Thus, the cost estimates are for purposes of illustration—actual renovations of different building types will face different costs and different risk profiles.

The case study, as in the actual building renovation project, focuses exclusively on two of the three mitigation strategies—engineering alternatives and management practices. The renovation has been planned for some time to upgrade the data center's HVAC, telecommunications and data processing systems and to address a number of generic security concerns.

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 (3,716 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. The occupants of the data center are part of the same parent company, but not part of the same corporate division responsible for facilities construction and renovation. Thus, costs associated with the "facility owners" are recorded separately from those associated with the data center's occupants.

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.

3.2 Defining the Base Case and the Alternative

The building owners employ one of two different renovation strategies. The first, referred to as the Base Case, employs upgrades which are consistent with pre-9/11 levels of security. Thus, the Base Case represents maintenance of the *status quo*. The second, referred to as the Proposed Alternative, recognizes 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 capture 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.[32]

3.3 Key Assumptions and Analysis Issues

A clear statement of the assumed values of key sets of parameters underlying the analysis is vital to understanding how the analysis was conducted. Documenting the assumptions and the rationale behind the setting of the assumed values of these key sets of parameters is necessary to ensure that: (1) all costs are discounted to an equivalent time basis for purpose of comparison; and (2) readers can follow the flow of the analysis, gain insights useful for their own applications, and reproduce our results.

Finally, there is the "analysis issue" concerned with the treatment of uncertainty. This analysis issue provides the necessary "direct" linkage between the baseline analysis and the sensitivity analysis. It is crucial in measuring how variations about the baseline input values affect the economic outcome measures. Dealing with uncertainty is the core concept in structuring the sensitivity analysis.

3.3.1 Key Assumptions

The assumptions covered in this section focus on the setting of the assumed values of the following key sets of parameters: (1) the base year; (2) the starting and ending points in the study period; and (3) the discount rate. The base year establishes the anchor point for all cost calculations. The starting and ending points in the study period define both the scope of the study period—those years over which costs are tabulated—and the length of the study period—a key parameter in the AIRR calculation. Because cash flows are distributed throughout the study period, the choice of the discount rate is of central importance to the analysis.

[32] A risk mitigation plan is usually composed of a combination of mitigation strategies. A well-chosen combination of mitigation strategies enables them to complement and reinforce each other, producing a more robust risk mitigation plan. The use of both engineering alternatives (e.g., strengthening portions of the exterior envelope) and management practices (e.g., limiting vehicle access to the site) in the data center renovation is an example of such a combination. Engineering alternatives and management practices differ in two key ways. First, engineering alternatives, once put in place, can be expected to remain in place for an extended period of time. Engineering alternatives are thus long-term investments. Second, management practices can be varied over the project life cycle. Management practices are thus capable of responding to changing conditions, giving them more of a short-term investment perspective.

The base year for computing life-cycle costs is 2003. There are two reasons why 2003 was selected as the base year.

(1) 2003 reflects heightened awareness to security-related problems. Since the September 11th attacks, a number of efforts have been launched to strengthen the nation's defenses against future terrorist attacks.[33]

(2) 2003 is a year for which construction industry cost data are available. The use of historic/industry cost data is desirable because this study employs constant dollar estimates for all costs.

The study period begins in 2003 and ends in 2027. Thus, the length of the study period is 25 years. A study period of 25 years is often used in both private sector and public sector life-cycle cost analyses. Any costs that occur after 2027 are not included. Two factors were instrumental in determining the beginning and end of the study period.

(1) The study period begins in 2003, since it reflects both heightened awareness to security-related issues and is grounded in the present.

(2) The end of the study period is 2027. By 2027, we can expect significant and fundamental changes in our nation's response to threats from terrorism.

The baseline analysis uses a real discount rate of 4 % to convert dollar amounts to present values. A 4 % real discount rate is used because it is appropriate for both private sector and public sector security-related investments.

The discount rate also figures prominently in the sensitivity analysis. Generally, both private sector and public sector investment decisions benefit from a critical analysis of the impact of changing the discount rate on project outcomes. For public sector projects, OMB recommends that separate analyses be used to evaluate the sensitivity of key economic measures to variations in the discount rate.[34] The sensitivity analysis presented in Chapter 5 evaluates the implications of raising the discount rate to 8 % or lowering the discount rate to 0 %. The 0 % to 8 % range of values for the real discount rate was chosen to bracket the historical values of real Treasury interest rates. These rates are periodically updated by OMB and published in Appendix C of *OMB Circular A-94*; they apply to government lease-purchase and cost-effectiveness analyses. All values of the discount rate used in this report are real rates, since constant dollar estimates of costs are used.

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[33] Interested readers are referred to the report on critical infrastructures (Executive Office of the President. 2003. *The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets*. Washington, DC: The White House.) and the Committee on Science and Technology for Countering Terrorism report (National Research Council. 2002. *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism*. Washington, DC: The National Academies Press.) for recommendations on how to strengthen the nation's defenses against future terrorist attacks.

[34] Executive Office of the President. 1992. *OMB Circular A-94*. Washington, DC: Office of Management and Budget.

3.3.2 Analysis Issues

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 sensitivity analysis is performed in which a number of variables are allowed to vary in combination according to an experimental design.

The two generic types of analysis are designed to complement and reinforce each other. The baseline analysis serves as a reference point for the sensitivity analysis. The sensitivity analysis uses the same data and assumptions as the baseline analysis for its starting point.

A goal of this case study is to illustrate how to combine the results of the two generic types of analysis to provide decision makers with the basis for generating a risk mitigation plan that responds to the potential for future cyber and CBRE attacks in a financially responsible manner. Creating a risk mitigation plan involves choices among investment alternatives. An investment alternative is comprised of a combination of any number of engineering alternatives, management practices, and financial mechanisms. Each investment alternative has a well-defined set of costs associated with it which must be estimated, discounted to a present value, and evaluated. The baseline analysis establishes the frame of reference for the economic evaluation by rank ordering the investment alternatives from lowest life-cycle cost to highest life-cycle cost. The investment alternative with the lowest life-cycle cost is the most cost-effective alternative. The sensitivity analysis provides the means for evaluating financial risks associated with a wide variety of project-related costs. The sensitivity analysis enables the decision maker to evaluate the conditions under which other investment alternatives might result in lower life-cycle costs vis-à-vis the "most cost-effective alternative" identified in the baseline analysis. Together the baseline analysis and the sensitivity analysis provide the necessary insights to produce the risk mitigation plan.

4 Baseline Analysis

The baseline analysis presented in this chapter is the reference point from which the Base Case is compared with the Proposed Alternative. The chapter begins with a description of the cost items entering into the analysis. Information is presented on renovation costs, service life estimates, and estimates of operations, maintenance, and repair expenditures. Attack scenarios are also presented. These scenarios include probabilities of each attack outcome and its associated costs. Emphasis is then shifted to how the cost items are modeled and analyzed via the cost-accounting framework. Summary information is then presented to demonstrate how life-cycle cost analysis facilitates the identification of a cost-effective risk mitigation plan. Life-cycle cost information is supplemented with additional economic measures to demonstrate new insights provided by these measures. The chapter concludes with a discussion of how the baseline analysis links to the software product.

4.1 Cost Items Entering the Analysis

Cost items are classified under two broad headings: (1) input costs and (2) event-related costs. 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. 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 (i.e., an outcome may have no cost items associated with it if it results in zero costs). Event modeling is used to evaluate natural and man-made risks. In this case study, we model 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.

4.1.1 Input Costs

Tables 4-1 and 4-2 summarize input cost information on the Base Case and the Proposed Alternative, respectively. The information presented in Tables 4-1 and 4-2 specifies the baseline values of input costs for the Base Case and the Proposed Alternative. Each table includes the individual cost items, its cost category, its occurrence rate, its escalation rate, and its estimated cost in constant 2003 dollars. Information on the cost category is included to help link the entries in Tables 4-1 and 4-2 to the entries in Tables 4-5 through 4-7 for the Base Case and Tables 4-8 through 4-10 for the Proposed Alternative. This is the first step in linking individual cost items into the cost-accounting framework. Note that several cost entries are negative (e.g., salvage value). Negative entries reflect either revenues received or costs avoided. The dollar entries in Tables 4-5 through 4-11 include these input costs, expressed in present value terms.

Table 4-1. Summary of Input Costs for the 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 4-2. Summary of Input Costs for the 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

The timing of costs is an important factor in any life-cycle cost analysis. The entries under the Occurrence column heading in Tables 4-1 and 4-2 provide information on the timing of cash flows. Four occurrence types are used to specify when costs are incurred: (1) initial; (2) future (one time); (3) annually recurring (multiple years); and (4) periodic (every n years). Qualifications on timing are recorded in the tables. For example, the HVAC upgrade for the Base Case occurs once, in year 17, and the change in the traffic pattern associated with the Proposed Alternative is an annually recurring cost, incurred only in years 1 and 2.

Tables 4-1 and 4-2 also contain information on differential escalation rates. Differential escalation rates are needed because not all cost items change at the same rate, even when expressed in real terms. For example, the real cost of electricity is expected to decline slightly over the next 25 years. This trend is recorded as a value of –0.10 % per year for both the Base Case and the Proposed Alternative. Conversely, the real costs of site security are expected to increase modestly over the next 25 years. This trend is recorded as a value of 0.50 % per year for both the Base Case and the Proposed Alternative.

4.1.2 Event-Related Costs

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.

Tables 4-3 and 4-4 summarize event-related information on the Base Case and the Proposed Alternative, respectively. The information presented in Tables 4-3 and 4-4 specifies the baseline values of event-related costs for the Base Case and the Proposed Alternative. Each table includes the scenario—cyber attack or CBRE attack—the years over which the scenario is run, the scenario-specific outcomes, their annual probabilities, their outcome-associated cost items, their cost categories, and their estimated costs in constant 2003 dollar amounts. For example, the cyber attack scenario covers two time periods—years 1 through 10 and years 11 through 25. Two time periods are used because cyber crime is on the rise and although new countermeasures are being produced regularly, hackers are becoming more adept at finding and exploiting weaknesses in countermeasures software. Note that a given outcome may have multiple cost items. For example, if the outcome in the cyber attack scenario is “record theft,” then outcome-associated cost items for “record reconstruction” and “identity theft” both occur. For each outcome-associated cost item, the annual outcome probability is multiplied by the dollar amount in the last column to produce an expected dollar value of event-related costs. The resultant “stream” of expected dollar values is discounted to a present value. The dollar entries in Tables 4-5 through 4-11 include these event-related costs, expressed in present value terms.

Table 4-3. Summary of Event-Related Information for the 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 4-4. Summary of Event-Related Information for the 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

4.2 How Cost Items are Modeled and Analyzed via the Cost-Accounting Framework

Tables 4-5 through 4-10 summarize input and event-related costs for the key budget categories for the Base Case and the Proposed Alternative. In order to differentiate those costs which are input costs from those which are event-related in Tables 4-5 through 4-10, all event-related costs are expressed as expected values; they are shown in a ***bold-italics*** font face.

Table 4-5 records the capital investment costs for the Base Case. All costs recorded in Table 4-5 are borne by the Owner/Manager (i.e., the division responsible for construction and renovation). Four input cost items are identified in Table 4-5. All but one of the four input cost items are listed under the Component column heading of Building/Facility Elements. The exception is the $100K for site protection; it appears under the Building/Facility Site Work column heading. Since the costs of site protection occur at the beginning of the 25-year study period, they are already expressed in present value terms. Referring to the column heading Building/Facility Elements, we see that "basic" renovation costs are $1,000K. Since these costs occur at the start of the 25-year study period, they are already in present value terms. The next two cost items represent cash flows which occur in the future. The HVAC upgrade occurs in year 17; the cost of the HVAC upgrade is $25K. The present discounted value of the HVAC upgrade cost is $12.8K. Since the HVAC system is expected to have several remaining years of service life, it is appropriate to record a salvage value at the end of the 25-year study period. Since the salvage value produces a net cash inflow, it appears as a negative cost (i.e., its value at the end of year 25 is -$10K). The present discounted value of the salvage value is -$3.7K. Table 4-5 also includes event-related cost information. All event-related costs which appear in Table 4-5 stem from the CBRE attack scenario. One event-related cost item is recorded in Table 4-5, ***damage to the data center***. ***Damage to the data center*** is expected to amount to $59.4K over the 25-year study period; it results from two outcomes—a CBRE attack resulting in major damage and a CBRE attack resulting in minor damage. Table 4-5 also records life-cycle costs across all bearers and all components. This total is $1,168K; it is recorded under the column heading Total.

Table 4-6 records the operations and maintenance (O&M) costs for the Base Case. Note that costs are borne by both the Owner/Manager and the Occupant/User, both of whom are part of the same parent company. Turning first to the Owner/Manager input cost items, we see that the bulk of these costs are associated with site security. Site security costs occur on an annual basis. Site security costs of $125K are assumed to escalate at 0.5 % per year. The present value of site security costs is therefore $2,064K. Site lighting costs are also borne by the Owner/Manager. Site lighting costs occur on an annual basis. Site lighting costs of $3.6K are assumed to escalate at –0.1 % per year. The present value of site lighting costs is $55.6K. The Occupant/User input cost items include electricity and telecommunication services, both of which occur on an annual basis. Electricity costs of $72K escalate at –0.1 % per year. Telecommunication services costs are $40K each year. These two cost items, expressed in present value terms, are

$1,113K and $625K, respectively. HVAC repairs in the amount of $5K occur every four years and a major duct cleaning procedure in the amount of $5K is done when the HVAC upgrade occurs in year 17. The present values of these cost items are $18.0K and $2.6K, respectively. Table 4-6 also records event-related cost information from both the CBRE and cyber attack scenarios. The costs of ***business interruption*** are expected to amount to $97.6K over the 25-year study period. The costs of ***record reconstruction*** due to record theft associated with a cyber attack are expected to amount to $107K over the 25-year study period.

Note that O&M costs over the 25-year study period exceed capital investment costs. Compare the entry in the Total column heading for all bearers in Table 4-6 to the corresponding entry in Table 4-5. Such differences point out opportunities for cost savings, such as might result from additional capital investments in energy conservation measures or improved telecommunication services.

Table 4-5. Base Case: Capital Investment Costs

Cost Item	**Component**			**Total**
	Building/Facility		**Non-Elemental**	
	Elements	**Site Work**		
All Bearers	1,068,484	100,000	0	1,168,484
Owner/Manager	1,068,484	100,000	0	1,168,484
Basic Renovation	1,000,000	0	0	
Site Protection	0	100,000	0	
HVAC Upgrade	12,834	0	0	
Salvage	-3,751	0	0	
Damage to Data Center	***59,401***	***0***	***0***	
Occupant/User	0	0	0	0
Third Party	0	0	0	0

Table 4-7 records the Other costs for the Base Case; it includes only event-related cost information from the CBRE and cyber attack scenarios. Event-related cost items associated with the CBRE attack scenario are ***non-fatal injuries*** and ***denial of service*** to corporate customers during the recovery period. Note that the costs of ***non-fatal injuries*** are apportioned equally to each bearer (i.e., $9.8K). The costs resulting from ***denial of service*** are expected to amount to $39K. The cyber attack scenario results in a single event-related cost item, ***identity theft***. The costs to corporate customers due to ***identity theft*** are expected to amount to $619K.

Table 4-6. Base Case: O&M Costs

Cost Item	Component			Total
	Building/Facility		Non-Elemental	
	Elements	Site Work		
All Bearers	1,757,917	55,626	2,268,349	4,081,892
Owner/Manager	0	55,626	2,064,088	2,119,714
Site Security	0	0	2,064,088	
Site Lighting	0	55,626	0	
Occupant/User	1,757,917	0	204,260	1,962,178
Electricity	1,112,515	0	0	
Telecom Services	624,883	0	0	
HVAC Repairs	17,953	0	0	
Duct Cleaning	2,567	0	0	
Business Interruption	***0***	***0***	***97,638***	
Record Reconstruction	***0***	***0***	***106,622***	
Third Party	0	0	0	0

Table 4-7. Base Case: Other Costs

Cost Item	Component			Total
	Building/Facility		Non-Elemental	
	Elements	Site Work		
All Bearers	0	0	687,233	687,233
Owner/Manager	0	0	9,764	9,764
Non-fatal Injuries	***0***	***0***	***9,764***	
Occupant/User	0	0	9,764	9,764
Non-fatal Injuries	***0***	***0***	***9,764***	
Third Party	0	0	667,705	667,705
Non-fatal Injuries	***0***	***0***	***9,764***	
Denial of Service	***0***	***0***	***39,055***	
Identity Theft	***0***	***0***	***618,886***	

Table 4-8 records the capital investment costs for the Proposed Alternative. All costs recorded in Table 4-8 are borne by the Owner/Manager (i.e., the division responsible for construction and renovation). Five input cost items are identified in Table 4-8. Three of the five input cost items are listed under the Component column heading of Building/Facility Elements. The first of the two exceptions is the $200K for site protection; it appears under the Building/Facility Site Work column heading. The second is the $50K for special security features; it appears under Non-Elemental column heading. Since the costs of site protection and special security features occur at the beginning of the 25-year study period, they are already expressed in present value terms. Referring to the column heading Building/Facility Elements, we see that "enhanced" renovation costs are $1,500K. Since these costs occur at the start of the 25-year study period, they are already in present value terms. The costs of the "enhanced" renovation and associated site work are significantly higher than the Base Case. For example, the improved HVAC system includes sensors and filters to address certain chemical and biological hazards. The higher initial costs of the "enhanced" renovation, however, result in reductions in several key operations and maintenance costs. In addition, the improved HVAC system results in improved indoor air quality which is expected to have a favorable impact on occupant productivity. The next two input cost items in Table 4-8 represent cash flows which occur in the future. The HVAC upgrade occurs in year 17; the cost of the HVAC upgrade is $30K. The present discounted value of the HVAC upgrade cost is $15.4K. Since the HVAC system is expected to have several remaining years of service life, it is appropriate to record a salvage value at the end of the 25-year study period. Since the salvage value produces a net cash inflow, it appears as a negative cost—its value at the end of year 25 is -$12.5K. The present discounted value of the salvage value is -$4.7K. Table 4-8 also records event-related cost information. All event-related costs which appear in Table 4-8 stem from the CBRE attack scenario. One event-related cost item is recorded in Table 4-8, ***damage to the data center***. ***Damage to the data center*** is expected to amount to $11.1K over the 25-year study period; it results from two outcomes—a CBRE attack resulting in major damage and a CBRE attack resulting in minor damage. Table 4-8 also records total life-cycle costs across all bearers and all components. This total is $1,772K; it is recorded under the column heading Total.

Table 4-9 records the O&M costs for the Proposed Alternative. Note that costs are borne by both the Owner/Manager and the Occupant/User, both of whom are part of the same parent company. Turning first to the Owner/Manager input cost items, we see that the bulk of these costs are associated with site security. Site security costs occur on an annual basis. Site security costs of $100K are assumed to escalate at 0.5 % per year. The present value of site security costs is therefore $1,651K. Site security costs are lower for the Proposed Alternative than for the Base Case due to additional investments in security technologies which reduce overtime demands for physical security staff. Site lighting costs are also borne by the Owner/Manager. Site lighting costs occur on an annual basis. Site lighting costs of $3.0K are assumed to escalate at –0.1 % per year. The present value of site lighting costs is $46.4K. The Occupant/User input cost items include electricity and telecommunication services, both of which occur on an annual basis. Annual electricity costs are $60K; they escalate at –0.1 % per year. Annual telecommunication services costs are $36K each year. These two cost items, expressed in present value terms, are $927K and $562K, respectively. The improved HVAC and telecommunications systems result in cost savings for space heating and cooling and telecom services for the Proposed Alternative. Specifically, annual electricity costs are reduced from $72K in the Base Case to $60K for the Proposed Alternative. Annual telecom services costs are reduced from $40K to $36K. HVAC repairs in the amount of $6K occur every six years and a major duct cleaning procedure in the amount of $7.5K is done when the HVAC upgrade occurs in year 17. The present values of these cost items are $13.8K and $3.9K, respectively. The improved HVAC system produces a spillover benefit in the form of improved indoor air quality. Better indoor air quality results in improved productivity for data center tenants. Previous studies have cited productivity improvements ranging from 3 % to 15 %.[35, 36] The data center case study uses a very conservative estimate of 0.5 %. The resultant annual value of improved productivity is $4.0K. Since improved productivity is a net benefit to the Occupant/User, it is subtracted from total life-cycle costs. The present value of improved productivity is estimated to be -$62.5K. Table 4-9 also records event-related cost information from both the CBRE and cyber attack scenarios. The costs of ***business interruption*** are expected to amount to $29.3K over the 25-year study period. The costs of r***ecord reconstruction*** due to record theft associated with a cyber attack are expected to amount to $29.1K over the 25-year study period.

Table 4-8. Proposed Alternative: Capital Investment Costs

Cost Item	Component			Total
	Building/Facility		Non-Elemental	
	Elements	Site Work		
All Bearers	1,521,858	200,000	50,000	1,771,858
Owner/Manager	1,521,858	200,000	50,000	1,771,858
Enhanced Renovation	1,500,000	0	0	
Site Protection	0	200,000	0	
Special Security Features	0	0	50,000	
HVAC Upgrade	15,401	0	0	
Salvage	-4,689	0	0	
Damage to Data Center	***11,146***	***0***	***0***	
Occupant/User	0	0	0	0
Third Party	0	0	0	0

[35] Fisk, William J., and Arthur H. Rosenfeld. 1997. "Estimates of Improved Productivity and Health from Better Indoor Environments," *Indoor Air* (Vol. 7): pp. 158-172.
[36] Lomonaco, Carol, and Dennis Miller. 1997. "Comfort and Control in the Workplace," *ASHRAE Journal* (September): pp. 50-56.

Note that O&M costs over the 25-year study period exceed capital investment costs. Compare the entry in the Total column heading for all bearers in Table 4-9 to the corresponding entry in Table 4-8. However, these differences are less than in the Base Case and O&M costs for the Proposed Alternative are less than the O&M costs of the Base Case, which serves to highlight that some cost savings result from the additional capital investments associated with the Proposed Alternative.

Table 4-9. Proposed Alternative: O&M Costs

Cost Item	Component			Total
	Building/Facility		Non-Elemental	
	Elements	Site Work		
All Bearers	1,507,133	46,355	1,647,198	3,200,685
Owner/Manager	0	46,355	1,651,271	1,697,625
Site Security	0	0	1,651,271	
Site Lighting	0	46,355	0	
Occupant/User	1,507,133	0	-4,073	1,503,060
Electricity	927,096	0	0	
Telecom Services	562,395	0	0	
HVAC Repairs	13,792	0	0	
Duct Cleaning	3,850	0	0	
Improved Productivity (IAQ)	0	0	-62,488	
Business Interruption	***0***	***0***	***29,291***	
Record Reconstruction	***0***	***0***	***29,124***	
Third Party	0	0	0	0

Table 4-10 records the Other cost entries for the Proposed Alternative. Table 4-10 includes a single input cost entry. This entry, change in traffic pattern, corresponds to $94.3K in “driver delay” costs incurred by local residents who no longer can traverse the data center site and hence must take a detour around the data center site. These non-elemental input costs are borne by third parties (i.e., local residents). When the new street is opened two years after the renovation, a more direct route is created and these “driver delay” costs disappear. Table 4-10 also records event-related cost information from both the CBRE and cyber attack scenarios. Event-related cost items associated with the CBRE attack scenario are ***non-fatal injuries*** and ***denial of service*** to corporate customers during the recovery period. The costs of ***non-fatal injuries*** are apportioned equally to each bearer (i.e., $2.9K). Costs resulting from ***denial of service*** are expected to amount to $13.3K. The cyber attack scenario results in a single event-related cost item, ***identity theft***. The costs to corporate customers due to ***identity theft*** are expected to amount to $166K.

Table 4-10. Proposed Alternative: Other Costs

Cost Item	Component			Total
	Building/Facility		Non-Elemental	
	Elements	Site Work		
All Bearers	0	0	282,359	282,359
Owner/Manager	0	0	2,929	2,929
Non-fatal Injuries	***0***	***0***	***2,929***	
Occupant/User	0	0	2,929	2,929
Non-fatal Injuries	***0***	***0***	***2,929***	
Third Party	0	0	276,501	276,501
Change in Traffic Pattern	0	0	94,305	
Non-fatal Injuries	***0***	***0***	***2,929***	
Denial of Service	***0***	***0***	***13,279***	
Identity Theft	***0***	***0***	***165,988***	

Because both the Base Case and the Proposed Alternative have similar sets of cost items, it is useful to compare some of the event-related costs. Consider the cyber attack scenarios for the Base Case (Table 4-3) and the Proposed Alternative (Table 4-4). Comparing the outcome probabilities and associated costs (see Tables 4-3 and 4-4), we see that the additional capital investments in telecommunications and data processing services for the Proposed Alternative, result in significantly lower expected costs both to the corporation (i.e., Occupant/User) and their corporate customers (i.e., Third Party). For example, compare the estimated values for the cost items ***record reconstruction*** and ***identity theft*** in Tables 4-6 and 4-7 for the Base Case to the corresponding entries in Tables 4-9 and 4-10 for the Proposed Alternative.

4.3 Baseline Results

Table 4-11 summarizes the results of the baseline analysis for the Base Case and the Proposed Alternative. All costs reported in Table 4-11 are life-cycle costs. Since Table 4-11 includes all input and event-related costs, it represents a complete picture of the baseline analysis. The entries in the Base Case column of Table 4-11 come from Tables 4-5, 4-6, and 4-7. The entries in the Proposed Alternative column of Table 4-11 come from Tables 4-8, 4-9, and 4-10.

Turning first to the Base Case column heading and the Budget Category classification, we see that the entries correspond to the All Bearers/Total cell in Table 4-5 for Capital Investment, in Table 4-6 for O&M, and in Table 4-7 for Other. Bearer costs for the Owner/Manager equal the sum of the Owner/Manager/Total cells in Tables 4-5, 4-6, and 4-7 (i.e., 3,297,962 = 1,168,484 + 2,119,714 + 9,764). Bearer costs for the

Occupant/User equal the sum of the Occupant/User/Total cells in Tables 4-6 and 4-7, since the corresponding entry in Table 4-5 is zero. Component costs for each component equal the sum of the respective Bearer/Component cells in Tables 4-5, 4-6, and 4-7. For example, the life-cycle costs of Building/Facility Elements equals the sum of the Bearer/Elements cells in Tables 4-5 and 4-6 (i.e., 2,826,402 = 1,068,484 + 1,757,917). Note that the Life-Cycle Cost for the Base Case of $5,937,608 equals the sum of the cost items listed under each Cost Classification[37] (i.e., 5,937,608 = 3,297,962 + 1,971,941 + 667,705 = 1,168,484 + 4,081,892 + 687,233 = 2,826,402 + 155,626 + 2,955,581). ***Thus, whether we look at costs from the Bearer perspective, from the Budget Category perspective, or by Component, all costs are included and classified accordingly.***

Table 4-11. Summary of Life-Cycle Costs

Cost Classification	**Decision Criterion/ Cost Type**	**Base Case**	**Proposed Alternative**
	Life-Cycle Cost	5,937,608	5,254,903
Bearer:	Owner/Manager	3,297,962	3,472,413
	Occupant/User	1,971,941	1,505,989
	Third Party	667,705	276,501
Category:	Capital Investment	1,168,484	1,771,858
	O&M	4,081,892	3,200,685
	Other	687,233	282,359
Component:	Building/Facility Elements	2,826,402	3,028,991
	Building/Facility Site Work	155,626	246,355
	Non-Elemental	2,955,581	1,979,557

Life-cycle costs for the Proposed Alternative are calculated in exactly the same manner as for the Base Case, but using Tables 4-8, 4-9, and 4-10. The Life-Cycle Cost for the Proposed Alternative is $5,254,903. Note that this cost is less than the Life-Cycle Cost of the Base Case. This is because the Proposed Alternative includes a number of features that produce future cost savings. These cost savings partially offset the increased Capital Investment costs for the Proposed Alternative. As a general rule, whenever the potential for a spillover benefit exists (e.g., improved indoor air quality), consider incorporating it into the risk mitigation plan ***and*** evaluating its impact on life-cycle cost.

[37] Due to rounding, some Cost Classification totals may differ slightly from the Life-Cycle Cost total.

Reference to Table 4-11 demonstrates that the Proposed Alternative is the most cost-effective choice, since it results in the lowest life-cycle cost (i.e., $5,254,903 versus $5,937,608).

The life-cycle cost figures presented in Table 4-11 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 $682,706. Second, the way in which the Budget Category cost items are defined 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 Table 4-11 shows that the increased capital cost of the Proposed Alternative of $603,374 results in savings of $1,286,080. These figures translate into an SIR of 2.13 (i.e., 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 hurdle rate of 4 %. 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.

4.4 How the Baseline Analysis Links to the Software Product

The software product has two analysis options: (1) baseline analysis and (2) sensitivity analysis. The baseline analysis, as presented in Sections 4.1 through 4.3, links directly to four key features of the software product. These features are illustrated in Tables 4-1 through 4-11; they are concerned with: (1) the cost-accounting framework; (2) selected data inputs; (3) selected output reports; and (4) the "Cost Summary" screen of the software product.

The software product employs the same cost-accounting framework as described in Section 2.3 and illustrated in Sections 4.1 through 4.3. As the user of the software product inputs data on each cost item, each cost item is classified according to its Bearer, Budget Category, and Building Component. The input screens, Cost Summary screen, and output reports for the baseline analysis option of the software product are all identical in their use of the cost-accounting framework to the information recorded in Tables 4-1 through 4-11.

Tables 4-1 through 4-4 record the types of cost-related information requested of the software product's user in the input screens. Cost-related input screens for the software product are of two basis types: (1) input costs and (2) event-related costs. The user accesses these screens by selecting the Costs or Events options on the Main Menu, which appears as a side bar on the Cost Summary screen. The input screens presented to the user ask for the same type of information for input costs as recorded in Tables 4-1 and 4-2 and for event-related costs as recorded in Tables 4-3 and 4-4. The software product includes additional input screens designed to collect information on the project under analysis and its associated investment alternatives (e.g., the Base Case and the Proposed Alternative). This more basic information is covered in Chapter 3 (e.g., description of the data center, specification of the Base Case and the Proposed Alternative, the base year, the years over which costs are analyzed, and the discount rate).

Tables 4-5 through 4-10 are indicative of selected sets of output reports from the software product. The software product is designed to help the user "drill down" on how individual cost items are distributed across Bearer, Budget Category, and Building Component. The software product drills down according to the Budget Category, just as is done in Tables 4-5 through 4-10. This approach gives users a snapshot of all of the costs entering the analysis, expressed in present value terms, which "roll up" into the life-cycle costs recorded in the Cost Summary screen.

With the exception of the Main Menu options, editing/screening options for the alternatives under analysis, and some descriptive information, Table 4-11 is identical to the Cost Summary screen. Both Table 4-11 and the Cost Summary screen of the software product employ the cost-accounting framework, express costs in present value terms, and support the calculation of additional economic measures.

It is also worth noting that the information presented in Tables 4-1 through 4-11 may be used as a test problem for prospective users of the software product. Thus, the users of the software product have a convenient frame of reference through which they can gain familiarity with the software product.

5 Sensitivity Analysis

This chapter includes a sensitivity analysis to provide the reader with additional background and perspective on the data center case study. The purpose of the sensitivity analysis is to evaluate the impact of changing the values of a number of key variables whose values are uncertain on the calculated values of the key economic measures (e.g., PVNS). The results of the sensitivity analysis are summarized in a series of tables and figures. The chapter concludes with a discussion of how the sensitivity analysis links to the software product.

5.1 Methodology

Sensitivity analysis may be divided into two polar cases: (1) deterministic; and (2) probabilistic. Deterministic sensitivity analyses are the most straightforward. Their advantage is that they are easy to apply and the results are easy to explain and understand. Their disadvantage is that they do not produce results that can be tied to probabilistic levels of significance (i.e., the probability that PVNS is greater than zero).

For example, a deterministic sensitivity analysis might use as inputs a pessimistic value, a value based on a measure of central tendency (e.g., mean or median), and an optimistic value for the variable of interest. Then an analysis could be performed to see how each outcome (e.g., PVNS) changes as each of the three chosen values for the selected input is considered in turn, while all other input variables are maintained at their baseline values. A deterministic sensitivity analysis can also be performed on different combinations of input variables. That is, several variables are altered at once and then an outcome measure is computed.

In a probabilistic sensitivity analysis, a small set of key input variables is varied either singly or in combination according to an experimental design. In most cases, probabilistic sensitivity analyses are based on Monte Carlo techniques, or some other form of simulation. The major advantage of probabilistic sensitivity analysis is that it permits the effects of uncertainty to be rigorously analyzed. For example, not only the expected value of each economic measure can be computed but also the variability of that value. In addition, probabilistic levels of significance can be attached to the computed values of each economic measure. The disadvantage of a probabilistic sensitivity analysis is that it requires many calculations carried out according to an experimental design, and is therefore practical only when used with a computer.

Both deterministic and probabilistic sensitivity analyses are employed in the data center case study. A deterministic sensitivity analysis is first performed to identify the input variables with the greatest impact on PVNS. PVNS is used as the ranking criterion because it measures the difference between the life-cycle costs of the Base Case and the Proposed Alternative. Probabilistic sensitivity analyses, based on Monte Carlo simulation, are then performed on selected variables singly (i.e., those with the greatest impact on PVNS) and then for a selected set of variables in combination.

5.2 Key Variables

Information on the 21 variables that are the focus of the sensitivity analysis is presented in this section. The sensitivity analysis uses the same data and assumptions as the baseline analysis for its starting point. The 21 variables are listed in Table 5-1. Three of the 21 variables apply to both the Base Case and the Proposed Alternative. Eight of the variables apply to the Base Case. The 10 remaining variables apply to the Proposed Alternative.

The objective of the sensitivity analysis is to evaluate how uncertainty in the values of the 21 variables translates into changes in each of five key economic measures. The five economic measures evaluated in the sensitivity analysis 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. Variations in the values of the 21 variables translate into the value of each outcome (e.g., the SIR) in such a manner that the impacts of uncertainty can be measured quantitatively.

The approach selected for this study makes use of both deterministic sensitivity analyses and probabilistic sensitivity analyses. The probabilistic sensitivity analyses presented in this report are based on the method of model sampling. Model sampling is a procedure for sampling from a stochastic process to determine, through multiple trials, the characteristics of a probability distribution.

Any software product that has the capability to randomly sample from the known or hypothesized parent probability distribution for each variable of interest may be used to implement the method of model sampling. For the data center case study, the method of model sampling was implemented through application of the *@RISK* software product.[38] This software product is a risk analysis tool for spreadsheets. For the case at hand, selected columns of the spreadsheet were associated with the 21 variables. The *@RISK* software product allows the user to specify a unique probability distribution for each variable. Specification of the experimental design involves defining which variables are to be simulated and the number of simulations. Throughout this sensitivity analysis, 1,000 simulations were run for the combination of the 21 variables under analysis. The number of simulations was chosen to ensure that values in the tails of the distribution for each variable would be selected for inclusion in the analysis.

In reality, the exact nature of the parent probability distribution for each variable is unknown. Estimates of the parameters (e.g., mean and variance) of the parent probability distribution can be made and uncertainty can be reduced by investigation and research. However, uncertainty can never be eliminated completely. Therefore, in order to implement the procedure without undue attention to the characterization of the parent

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[38] Palisade Corporation. 1997. *Guide to Using @RISK: Risk Analysis and Simulation Add-In for Microsoft Excel or Lotus 1-2-3*. Newfield, NY: Palisade Corporation.

probability distribution, it was decided to focus on only two probability distributions: (1) the triangular and (2) the uniform. One reason for using these probability distributions is that they are both defined over a finite interval. They are also used frequently in cost-risk analyses.[39] Furthermore, the specification of each probability distribution is accomplished with as few as two data points. The triangular distribution is widely used in simulation modeling; its specification requires three data points, the minimum value, the most likely value, and the maximum value. The triangular distribution is used whenever the range of input values is continuous and a clustering about some central value is expected. The uniform distribution is also widely used in simulation modeling; its specification requires only two data points, the minimum value and the maximum value. In addition, all values between the minimum and maximum are equally likely. The uniform distribution is used whenever the range of input values is continuous but no *a priori* reason can be given for expecting clustering about some central value.

Table 5-1 summarizes information on each of the 21 variables. The table includes information on the applicability of the variable of interest (i.e., whether it applies to the Base Case, the Proposed Alternative, or both), information on the type of probability distribution used to model variations about the baseline value for each variable, the baseline value for each variable, and the minimum and maximum values for each variable. References to the entries under the heading Probability Distribution shows that seven of the 21 variables use the uniform distribution and 14 use the triangular distribution to model variations about the baseline value for that variable. The next three headings record, for each variable, its setting (i.e., baseline, minimum, and maximum) and value. For each variable, the baseline value is recorded first. For example, the baseline value for the discount rate is 4 % (real); it is recorded in decimal form as 0.04. Two other values for the discount rate, 0 % and 8 %, are selected to bracket the baseline value. These values are recorded in decimal form as 0 and 0.08, respectively.

The seven variables that use the uniform distribution are all associated with either percentage rates or probabilities. The first three variables—the discount rate, escalation rate for site security, and escalation rate for electricity—are percentage rates; they apply to both the Base Case and the Proposed Alternative. The two sets of probabilities (i.e., major damage and minor damage) apply to the Base Case and the Proposed Alternative, respectively. The baseline value for the probability of major damage is drawn directly from Table 4-3 for the Base Case and from Table 4-4 for the Proposed Alternative. In the sensitivity analysis, the probabilities for minor damage is assumed to be functionally related to the probability of major damage. For example, in the Base Case, the probability of major damage is 0.001 and the probability of minor damage is 0.005. Thus, the probability of minor damage differs from the probability of major damage by a factor of five (i.e., it is multiplied by 5.0). Because the probabilities of all outcomes associated with an attack scenario must add up to 1.0, applying a factor to the probability of major damage establishes a relationship that forms the basis for a constraint.

[39] ASTM International. 2002. "Standard Practice for Measuring Cost Risk of Buildings and Building Systems." E 1946. *Annual Book of ASTM Standards: 2002*. Vol. 04.12. West Conshohocken, PA: ASTM International.

Table 5-1. Baseline and Extreme Values of the Twenty-one Variables Used in the Sensitivity Analysis

Variable Name	Applies to	Probability Distribution	Setting and Value		
			Baseline	Minimum	Maximum
(1) Discount Rate	Both	Uniform	0.04	0	0.08
(2) Escalation Rate for Site Security	Both	Uniform	0.005	0.003	0.007
(3) Escalation Rate for Electricity	Both	Uniform	-0.001	-0.0015	-0.0005
(4) Probability of Major Damage	Base Case	Uniform	0.001	0.0005	0.0015
(5) Probability of Minor Damage Factor	Base Case	Uniform	5	3	7
(6) Electricity	Base Case	Triangular	1.80	1.675	1.925
(7) Basic Renovation	Base Case	Triangular	1,000,000	900,000	1,100,000
(8) Damage to Data Center	Base Case	Triangular	3,000,000	2,500,000	3,500,000
(9) Business Interruption	Base Case	Triangular	5,000,000	4,000,000	6,000,000
(10) Non-fatal Injuries for Major Attack	Base Case	Triangular	20	15	25
(11) Denial of Service	Base Case	Triangular	2,000,000	1,500,000	2,500,000
(12) Probability of Major Damage	Alternative	Uniform	0.0005	0.0003	0.0007
(13) Probability of Minor Damage Factor	Alternative	Uniform	7	5	9
(14) Electricity	Alternative	Triangular	1.50	1.375	1.625
(15) Enhanced Renovation	Alternative	Triangular	1,500,000	1,300,000	1,700,000
(16) Improved Productivity (IAQ)	Alternative	Triangular	-4,000	-5,500	-2,500
(17) Change in Traffic Pattern	Alternative	Triangular	50,000	40,000	60,000
(18) Damage to Data Center	Alternative	Triangular	1,000,000	750,000	1,250,000
(19) Business Interruption	Alternative	Triangular	2,000,000	1,500,000	2,500,000
(20) Non-fatal Injuries for Major Attack	Alternative	Triangular	8	6	10
(21) Denial of Service	Alternative	Triangular	1,000,000	750,000	1,250,000

All of the variables that use the triangular distribution vary about a central value. For the Base Case, four of the six variables that use the triangular distribution are associated with the costs stemming from the CBRE attack scenario. The two exceptions are electricity and the costs of the basic renovation. For the Proposed Alternative, four of the eight variables that use the triangular distribution are associated with the costs stemming from the CBRE attack scenario. Two of the four remaining are similar to the Base Case; they are electricity costs and the costs of the enhanced renovation. The two remaining variables are associated with increases in productivity due to improved indoor air quality, which appear as a negative cost, and the added costs to local residents due to the change in traffic patterns during the first two years.

5.3 Sensitivity Results

The results of the sensitivity analysis are summarized in a series of tables and figures. Two sets of results are presented. The first set covers the case where each of the 21 input variables is varied singly. The first set of results is designed to show the effect of each input on PVNS. This is done by varying each input variable singly while holding all other input variables at their baseline values. The results of this deterministic sensitivity analysis are summarized in Table 5-2. Tables 5-3 through 5-6 summarize the results of a probabilistic sensitivity analysis for the four input variables having the greatest impact on PVNS. The second set covers the case where all 21 input variables are varied in combination. The second set of results is designed to produce a data set that facilitates an in-depth analysis of the results, and promotes an understanding of what these results mean. These results are summarized in Tables 5-7 through 5-10 and in Figures 5-1 through 5-4. To facilitate comparisons among each of the Monte Carlo simulations, Tables 5-3 through 5-7 use the same presentation format. Table 5-8 summarizes in tabular form the results plotted in Figures 5-1 through 5-4. Tables 5-9 and 5-10 use the same presentation format, which is a slight variation in the presentation format used in Tables 5-3 through 5-7, due to its focus on life-cycle cost comparisons.

5.3.1 Changing One Variable

Table 5-2 summarizes the results of a deterministic sensitivity analysis in which each of the 21 variables are varied singly while holding all other input variables at their baseline values. The table records the variable’s name, its applicability (i.e., whether it applies to the Base Case, the Proposed Alternative, or Both), its values of PVNS resulting from its minimum and maximum settings, its delta PVNS, and its rank. Note that minimum and maximum refer to the value of the input variable (see Table 5-1 for these settings) and not the value of PVNS. For example, the minimum setting of the discount rate (i.e., 0 %) results in a higher value of PVNS (i.e., $1,533K) than the maximum setting (i.e., 8 % and $246K). Each variable is assigned a rank based on the value of delta PVNS. The value of delta PVNS equals the absolute value of the difference between the values under the Minimum and Maximum column headings. Variables are ranked from most important (i.e., a rank of 1) to least important (i.e., a rank of 20). The least important variable is assigned a rank of 20 instead of 21 because two variables produced the same value of delta PVNS; based on their computed value of delta PVNS, they are assigned a rank of 5.

Table 5-2. Results of Deterministic Sensitivity Analysis: Summary of Present Value Net Savings Calculations

Variable Name	Applies to	Setting and PVNS		Delta PVNS	Rank
		Minimum	Maximum		
(1) Discount Rate	Both	1,533.143	246.479	1,286.664	1
(2) Escalation Rate for Site Security	Both	673.604	692.077	18.473	11
(3) Escalation Rate for Electricity	Both	681.643	683.776	2.133	20
(4) Probability of Major Damage	Base Case	570.013	795.398	225.385	3
(5) Probability of Minor Damage Factor	Base Case	666.631	698.780	32.149	9
(6) Electricity	Base Case	601.585	763.826	162.241	5
(7) Basic Renovation	Base Case	582.706	782.706	200.000	4
(8) Damage to Data Center	Base Case	673.970	691.441	17.471	12
(9) Business Interruption	Base Case	667.084	698.328	31.244	10
(10) Non-fatal Injuries for Major Attack	Base Case	676.847	688.564	11.717	15
(11) Denial of Service	Base Case	674.895	690.517	15.622	13
(12) Probability of Major Damage	Alternative	707.707	657.704	50.003	6
(13) Probability of Minor Damage Factor	Alternative	690.171	675.241	14.930	14
(14) Electricity	Alternative	763.826	601.585	162.241	5
(15) Enhanced Renovation	Alternative	882.706	482.706	400.000	2
(16) Improved Productivity (IAQ)	Alternative	706.139	659.272	46.867	7
(17) Change in Traffic Pattern	Alternative	701.567	663.845	37.722	8
(18) Damage to Data Center	Alternative	684.770	680.641	4.129	17
(19) Business Interruption	Alternative	686.611	678.800	7.811	16
(20) Non-fatal Injuries for Major Attack	Alternative	683.877	681.534	2.343	19
(21) Denial of Service	Alternative	684.658	680.753	3.905	18

Reference to the table reveals that the discount rate has the highest impact on PVNS, resulting in a delta PVNS of $1,287K. Note that the discount rate affects both the Base Case and the Proposed Alternative. The next most important variable is the cost of the enhanced renovation; it affects only the costs of the Proposed Alternative. The third and fourth most important variables affect only the costs of the Base Case; they are the probability of major damage and the costs of the basic renovation.

Tables 5-3 through 5-6 report a series of statistical measures for the four variables having the greatest impact on PVNS. To facilitate comparisons among the economic measures, a shorthand notation for each is used. The five economic measures reported in the tables 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 statistical measure and its corresponding value are recorded under the heading Statistical Measure. 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 1,000 observations" produced by each Monte Carlo simulation. These statistical measures are: (1) the minimum; (2) the 25^{th} percentile, denoted by 25%; (3) the 50^{th} percentile (i.e., the median), denoted by 50%; (4) the 75^{th} 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 from each of the Monte Carlo simulations. The 50^{th} percentile and the mean are measures of central tendency. The 25^{th} and 75^{th} 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 from each of the Monte Carlo simulations. The values reported for LCC_{BC}, LCC_{Alt}, and PVNS are all in thousands of 2003 dollars.

Table 5-3 shows how variations about the baseline value of the discount rate (4 % (real)) affect each economic measure. The discount rate affects calculations in a number of ways. For example, LCC_{BC}, LCC_{Alt}, and PVNS are all affected by the discount rate. Reference to Table 5-3 reveals that LCC_{BC} is more sensitive to changes in the discount rate than is LCC_{Alt}. This is due to the fact that while the Base Case has lower first costs than the Proposed Alternative, it has higher future costs. Thus, costs occurring in the out years are penalized by a lower discount rate and benefit from a higher discount rate. Note that the range of values for LCC_{BC} (i.e., maximum minus minimum) is about 25 % greater than the range of values for LCC_{Alt} (i.e., $4.4 million versus $3.2 million). The value of PVNS also varies considerably. However, in no instance does PVNS turn negative. Thus, for all "observations" associated with this Monte Carlo simulation, the Proposed Alternative is the most cost-effective investment choice. The computed values of the SIR and the AIRR provide additional support for the superior performance of the Proposed Alternative vis-à-vis the Base Case when the discount rate is allowed to vary about its baseline value.

Table 5-3. Summary Statistics Due to Changes in the Input Variable Discount Rate

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
LCC_{BC}	4,408.711	5,059.926	5,894.800	7,128.006	8,865.249	6,144.757	1,247.033
LCC_{Alt}	4,162.097	4,628.684	5,224.410	6,101.412	7,333.412	5,400.784	887.470
PVNS	246.613	431.242	670.390	1,026.594	1,531.837	743.973	359.567
SIR	1.399	1.704	2.110	2.736	3.671	2.251	0.631
AIRR	0.054	0.062	0.072	0.083	0.096	0.073	0.012

Table 5-4 summarizes the results of the Monte Carlo simulation of variations about the baseline value for the cost of the enhanced renovation. Because the costs of the enhanced renovation only apply to the Proposed Alternative, LCC_{BC} does not change from its baseline value. The range of values for LCC_{Alt} is nearly $400K. The range of values for PVNS is also nearly $400K, since it is the difference between LCC_{BC} and LCC_{Alt} and LCC_{BC} is a constant. This close coupling is seen through reference to the value of the standard deviation for LCC_{Alt} and PVNS, which are equal. Note that PVNS is always positive, indicating that the Proposed Alternative is the most cost-effective investment choice. The computed values for the SIR and the AIRR serve to reinforce the previous statement.

Table 5-4. Summary Statistics Due to Changes in the Input Variable Enhanced Renovation for the Proposed Alternative

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
LCC_{BC}	5,937.609	5,937.609	5,937.609	5,937.609	5,937.609	5,937.609	0.0
LCC_{Alt}	5,062.580	5,192.650	5,251.010	5,307.479	5,443.325	5,250.707	81.751
PVNS	494.284	630.130	686.599	744.959	875.029	686.902	81.751
SIR	1.624	1.961	2.145	2.377	3.129	2.188	0.309
AIRR	0.060	0.068	0.072	0.077	0.089	0.073	0.006

Table 5-5 shows how variations about the baseline value of the probability of major damage for the Base Case affect each economic measure. Because this probability only applies to the Base Case, LCC_{Alt} does not change from its baseline value. The range of values for LCC_{BC} is approximately $225K. The range of values for PVNS is also approximately $225K. Because PVNS equals the difference between LCC_{BC} and LCC_{Alt}, which is a constant, the standard deviations of the two economic measures—LCC_{BC} and PVNS—are equal in value. Note that PVNS is always positive, indicating that the Proposed Alternative is the most cost-effective investment choice. The computed values for the SIR and the AIRR serve to reinforce the previous statement.

Table 5-5. Summary Statistics Due to Changes in the Input Variable Probability of Major Damage for the Base Case

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
LCC_{BC}	5,824.959	5,879.687	5,938.149	5,990.735	6,049.548	5,937.191	64.131
LCC_{Alt}	5,254.903	5,254.903	5,254.903	5,254.903	5,254.903	5,254.903	0.0
PVNS	570.056	624.784	683.246	735.832	794.645	682.288	64.131
SIR	1.900	2.010	2.133	2.249	2.385	2.134	0.138
AIRR	0.067	0.069	0.072	0.074	0.077	0.072	0.003

Table 5-6 shows how variations about the baseline value of the cost of the basic renovation affect each economic measure. Because the cost of the basic renovation only applies to the Base Case, LCC_{Alt} does not change from its baseline value. The range of values for LCC_{BC} is approximately \$200K. The range of values for PVNS is also approximately \$200K. Because PVNS equals the difference between LCC_{BC} and LCC_{Alt}, which is a constant, the standard deviations of the two economic measures—LCC_{BC} and PVNS—are equal in value. Note that PVNS is always positive, indicating that the Proposed Alternative is the most cost-effective investment choice. The computed values for the SIR and the AIRR serve to reinforce the previous statement.

Table 5-6. Summary Statistics Due to Changes in the Input Variable Basic Renovation for the Base Case

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
LCC_{BC}	5,838.695	5,908.166	5,938.153	5,967.072	6,035.233	5,937.996	41.652
LCC_{Alt}	5,254.903	5,254.903	5,254.903	5,254.903	5,254.903	5,254.903	0.0
PVNS	583.792	653.263	683.249	712.169	780.330	683.093	41.652
SIR	1.831	2.032	2.133	2.241	2.543	2.143	0.150
AIRR	0.065	0.070	0.072	0.074	0.080	0.072	0.003

5.3.2 Changing All Variables in Combination

The results of Monte Carlo simulations may be presented in a number of ways. In this section, they are presented in both tabular and graphical formats. The tabular formats record information on each of the five economic measures. The two tables, Table 5-7 and Table 5-8, report a variety of computed statistics for each economic measure. The four figures record the distribution of the observed values for the Base Case and the Proposed Alternative either side-by-side (Figure 5-1) or as an indication of the degree to which the Proposed Alternative is preferred to the Base Case (Figures 5-2 through 5-4).

Table 5-7 summarizes the results of the Monte Carlo simulation in which all 21 of the variables were varied in combination. A close examination of Table 5-7 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 value. This is due to a small number of very large observations.

Table 5-7. Summary Statistics Due to Changes in All of the Variables

Economic Measure	Statistical Measure						
	Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
LCC_{BC}	4,344.264	5,090.509	6,007.620	7,196.295	9,022.518	6,216.082	1,300.610
LCC_{Alt}	4,012.033	4,648.762	5,319.521	6,157.292	7,428.776	5,450.631	925.923
PVNS	45.546	438.144	707.783	1,049.742	1,884.364	765.451	396.182
SIR	1.055	1.718	2.196	2.864	6.144	2.357	0.827
AIRR	0.042	0.063	0.073	0.085	0.118	0.074	0.014

The fact that the range of outcomes is so wide suggests that an in-depth examination of the results of this Monte Carlo simulation is warranted. We now turn to this in-depth examination.

Additional tabular results of the sensitivity analysis are recorded in Table 5-8. The table lists each of the calculated percentiles from the distribution of observed values. The range of percentiles included in the table goes from the 1^{st} to the 99^{th}. For purposes of this analysis, the 0^{th} percentile is set equal to the minimum value, and the 100^{th} percentile is set equal to the maximum value, both of which are recorded in Table 5-7. This enables a close coupling of the values recorded in Table 5-7 and the values used to plot each figure. Table 5-8 includes for each percentile the computed value for LCC_{BC}, LCC_{Alt}, PVNS, SIR, and AIRR. The percentiles are computed based on all 1,000 data points (i.e., observations) for each economic measure. The percentiles are estimated by first ordering each economic measure and then applying a statistical procedure.

Table 5-8. Percentiles for Statistical Measures Due to Changes in All of the Variables

Percentile	Economic Measure				
	LCC Base Case	LCC Proposed Alternative	PVNS	SIR	AIRR
1ST	4,408.939	4,131.020	113.571	1.170	0.047
2ND	4,447.807	4,166.421	165.689	1.239	0.049
3RD	4,471.871	4,192.933	196.449	1.275	0.050
4TH	4,499.119	4,215.310	212.869	1.307	0.051
5TH	4,514.646	4,232.637	231.645	1.332	0.052
6TH	4,556.499	4,251.961	240.219	1.358	0.053
7TH	4,590.336	4,278.672	258.973	1.377	0.053
8TH	4,616.113	4,300.847	272.651	1.403	0.054
9TH	4,635.000	4,325.696	284.012	1.416	0.055
10TH	4,654.661	4,343.490	295.988	1.436	0.055
11TH	4,681.120	4,364.229	302.565	1.459	0.056
12TH	4,721.964	4,383.464	310.806	1.479	0.056
13TH	4,758.266	4,403.611	314.475	1.496	0.057
14TH	4,770.549	4,421.375	323.981	1.518	0.058
15TH	4,791.359	4,439.894	333.398	1.531	0.058
16TH	4,811.403	4,458.578	348.714	1.546	0.058
17TH	4,825.715	4,487.720	358.007	1.556	0.059
18TH	4,847.179	4,505.870	373.479	1.573	0.059
19TH	4,864.959	4,530.502	382.957	1.601	0.060
20TH	4,893.068	4,549.341	392.742	1.629	0.060
21ST	4,927.469	4,563.671	404.246	1.647	0.061
22ND	4,961.376	4,585.233	412.618	1.665	0.061
23RD	4,994.424	4,605.595	418.045	1.677	0.062
24TH	5,045.221	4,629.449	428.964	1.689	0.062
25TH	5,090.509	4,648.762	438.144	1.718	0.063
26TH	5,139.193	4,667.035	446.522	1.738	0.063
27TH	5,165.694	4,687.329	454.925	1.753	0.064
28TH	5,183.902	4,703.428	465.935	1.775	0.064
29TH	5,200.027	4,715.920	473.315	1.784	0.064
30TH	5,229.603	4,743.970	487.034	1.806	0.065
31ST	5,260.299	4,774.719	496.304	1.824	0.065
32ND	5,292.044	4,794.741	509.277	1.845	0.066
33RD	5,316.582	4,806.027	518.374	1.859	0.066

Table 5-8. Percentiles for Statistical Measures Due to Changes in All of the Variables (continued)

Percentile	Economic Measure				
	LCC Base Case	LCC Proposed Alternative	PVNS	SIR	AIRR
34TH	5,355.592	4,837.197	531.068	1.879	0.067
35TH	5,386.135	4,856.793	540.145	1.901	0.067
36TH	5,423.031	4,892.186	547.338	1.918	0.067
37TH	5,474.066	4,910.952	559.021	1.942	0.068
38TH	5,512.934	4,935.236	569.980	1.955	0.068
39TH	5,555.517	4,959.474	583.781	1.969	0.069
40TH	5,595.710	4,981.664	592.758	1.978	0.069
41ST	5,635.408	5,028.569	601.838	1.994	0.069
42ND	5,686.331	5,065.051	615.758	2.011	0.069
43RD	5,721.935	5,099.141	625.336	2.044	0.070
44TH	5,772.212	5,123.306	638.736	2.070	0.071
45TH	5,791.412	5,152.538	651.871	2.079	0.071
46TH	5,832.964	5,182.370	658.751	2.104	0.071
47TH	5,883.409	5,217.566	667.990	2.130	0.072
48TH	5,934.622	5,255.633	678.921	2.151	0.072
49TH	5,968.606	5,297.741	694.183	2.172	0.073
50TH	6,007.620	5,319.521	707.782	2.196	0.073
51ST	6,063.680	5,332.664	716.300	2.229	0.074
52ND	6,106.014	5,359.889	728.052	2.260	0.074
53RD	6,148.621	5,381.234	747.341	2.269	0.075
54TH	6,207.593	5,419.186	755.026	2.299	0.075
55TH	6,225.512	5,462.661	768.750	2.319	0.076
56TH	6,264.406	5,500.216	780.426	2.338	0.076
57TH	6,298.690	5,527.885	788.764	2.352	0.076
58TH	6,326.879	5,563.722	799.785	2.378	0.077
59TH	6,377.325	5,589.093	812.249	2.397	0.077
60TH	6,426.842	5,627.975	822.709	2.410	0.077
61ST	6,460.302	5,643.796	826.608	2.442	0.078
62ND	6,519.807	5,671.304	844.042	2.466	0.078
63RD	6,558.826	5,691.569	866.645	2.495	0.079
64TH	6,618.551	5,729.749	879.277	2.517	0.079
65TH	6,651.548	5,758.683	892.120	2.544	0.080
66TH	6,703.771	5,793.341	911.049	2.574	0.080

Table 5-8. Percentiles for Statistical Measures Due to Changes in All of the Variables (continued)

Percentile	Economic Measure				
	LCC Base Case	LCC Proposed Alternative	PVNS	SIR	AIRR
67TH	6,770.153	5,834.585	925.657	2.605	0.081
68TH	6,827.283	5,869.818	937.659	2.626	0.081
69TH	6,870.662	5,900.864	954.495	2.657	0.081
70TH	6,913.685	5,948.606	976.590	2.684	0.082
71ST	6,952.237	5,989.425	989.883	2.728	0.083
72ND	6,990.303	6,015.056	1,000.831	2.777	0.083
73RD	7,068.004	6,057.059	1,020.912	2.823	0.084
74TH	7,138.904	6,111.740	1,034.297	2.841	0.084
75TH	7,196.295	6,157.292	1,049.742	2.864	0.085
76TH	7,263.727	6,194.589	1,077.578	2.893	0.085
77TH	7,309.931	6,249.632	1,097.065	2.935	0.086
78TH	7,356.209	6,285.977	1,113.470	2.959	0.086
79TH	7,455.522	6,321.390	1,137.340	2.993	0.087
80TH	7,547.515	6,372.358	1,157.499	3.020	0.087
81ST	7,617.376	6,424.954	1,175.125	3.055	0.088
82ND	7,683.960	6,495.491	1,189.019	3.106	0.088
83RD	7,771.339	6,601.461	1,208.726	3.140	0.089
84TH	7,843.874	6,651.722	1,229.132	3.179	0.089
85TH	7,909.649	6,686.210	1,251.006	3.228	0.090
86TH	7,997.986	6,722.381	1,273.997	3.276	0.091
87TH	8,042.787	6,773.367	1,292.204	3.313	0.091
88TH	8,124.799	6,806.513	1,310.231	3.374	0.092
89TH	8,197.230	6,859.746	1,339.281	3.417	0.092
90TH	8,260.406	6,890.234	1,361.483	3.469	0.093
91ST	8,316.132	6,915.155	1,383.361	3.551	0.094
92ND	8,391.509	6,987.816	1,404.434	3.635	0.095
93RD	8,425.666	7,026.362	1,422.436	3.703	0.096
94TH	8,500.261	7,058.668	1,442.569	3.793	0.097
95TH	8,541.554	7,103.044	1,471.245	3.934	0.099
96TH	8,625.981	7,136.917	1,500.697	4.015	0.099
97TH	8,725.047	7,203.183	1,530.541	4.190	0.101
98TH	8,801.704	7,266.987	1,585.247	4.400	0.103
99TH	8,856.323	7,341.796	1,665.578	4.884	0.108

The graphical results of the sensitivity analysis where all 21 variables were varied in combination are shown in Figures 5-1 through 5-4. The figures were constructed by first sorting the values of each economic measure from smallest to largest. The resultant cumulative distribution function (CDF) was then plotted. In each figure, the vertical axis records the probability that the economic measure (e.g., PVNS) is less than or equal to a specified value. The values recorded on the horizontal axis cover the range of values encountered during this Monte Carlo simulation.

Figure 5-1 shows how the life-cycle costs of the Base Case compare to those of the Proposed Alternative when all 21 variables are varied in combination. In analyzing Figure 5-1, it is useful to keep in mind that the values of LCC_{BC} and LCC_{Alt} from the baseline analysis were \$5,937K and \$5,255K, respectively. Comparisons between Figure 5-1 and Table 5-8 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 Figure 1 always remains to the left of the life-cycle cost trace of the Base Case. Thus, for any given probability (e.g., 0.40, as measured by the 40^{th} percentile recorded in Table 5-8), the life-cycle cost of the Proposed Alternative (\$4,982K) is less than the life-cycle cost of the Base Case (\$5,596K). Similarly, for any given life-cycle cost (e.g., \$5,000K), 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 (i.e., maximum minus minimum); it is reflected in the higher standard deviation for the Base Case recorded in the last column of Table 5-7. Figure 5-1 clearly demonstrates that the Proposed Alternative is the most cost-effective renovation strategy. However, it is instructive to examine how the use of other economic measures sheds light on other aspects of its cost-effectiveness.

Figure 5-2 shows how present value net savings due to the use of the Proposed Alternative varies when all 21 variables are varied in combination. In analyzing Figure 5-2, it is useful to keep in mind that the value of PVNS resulting from the baseline analysis was \$682K. As was seen in Table 5-7, the median value of the 1,000 observations of \$708K was \$25K more than the value of PVNS calculated in the baseline analysis. The mean value of \$765K exceeds the baseline value by \$80K. It is important to note that the values of PVNS shown in Figure 5-2 and recorded in Tables 5-7 and 5-8 are based on each of the 1,000 outcomes of the Monte Carlo simulation. Thus, for each simulation s, where $1 \leq s \leq 1,000$, values of $LCC_{BC}(s)$ and $LCC_{Alt}(s)$ are calculated. These individual calculations are based on random draws for the 21 variables in Table 5-1. Their difference equals PVNS(s). Since the values of LCC_{BC} and LCC_{Alt} are rank-ordered in both Figure 5-1 and Table 5-8, their differences approximate but do not equal the computed values for PVNS shown in Figure 5-2 or recorded in Table 5-8. Referring to Table 5-1, we see that only 3 of the 21 variables are common to both the Base Case and the Proposed Alternative. Both the Base Case and the Proposed Alternative have similar sets of variables analyzed in the Monte Carlo simulation (e.g., the probability of major damage), but these variables are treated independently in the Monte Carlo simulation. The Proposed Alternative also has two variables—improved productivity and the change in traffic patterns—that do not occur in the Base Case (see entries 16 and 17 in Table 5-1). Thus, care is needed when comparing the economic measures calculated via the Monte Carlo simulation. Turning now to Figure 5-2, we see that a value of PVNS equal to $400K occurs at 0.20 on the cumulative distribution function (CDF). Stated another way, there is a probability of 0.80 that PVNS will exceed $400K. Reference to Figure 5-2 and Table 5-8 reveals that for almost 30 % of the observations resulting from the Monte Carlo simulation PVNS exceeds $1,000K.

Figure 5-3 shows how the savings-to-investment ratio, SIR, on the Proposed Alternative's investments varies when all 21 variables are varied in combination. In analyzing Figure 5-3, it is useful to keep in mind that the value of the SIR resulting from the baseline analysis was 2.13. As was seen in Table 5-7, the median value of the SIR for the 1,000 observations was 2.196 and the mean value was 2.357. The difference between the mean value of the SIR in the sensitivity analysis and the baseline value can be explained through reference to Figure 5-3 and Table 5-8. Reference to Figure 5-3 demonstrates that it trails off very slowly as the cumulative probability approaches 1.0. This means that the CDF for the SIR is highly, positively skewed (examine the upper tail of the CDF trace). Thus, a few very high values are pulling up the mean. To gain a more complete picture, refer both to Figure 5-3 and the entries under the SIR column heading of Table 5-8. First, note that the lower limit shown on Figure 5-3 extends almost to 1.0. Second, the trace of the SIR first increases rapidly until about the 10th percentile. The trace then increases at a fairly linear rate until about the 50th percentile, after which it increases at a slower (i.e., decreasing) rate. Third, the values for the 90th and 99th percentile are 3.469 and 4.884, respectively. Finally, the maximum value for the SIR is 6.144 (see Table 5-7). Thus, nearly 25 % of the total range of the SIR values is due to less than 1 % of the observations.

The presence of extreme values poses a number of challenges to the decision-making process. However, the results of the Monte Carlo simulation produce a wealth of information that may be employed by the decision maker. In this case, the extreme values serve to reinforce the preferred outcome. Since this is not always the case, it is useful to explore how some of the additional information from the Monte Carlo simulation can be brought into play. Both the mean and median are measures of central tendency for the CDF. In this case, the computed SIR values for both the mean and the median indicate that the Proposed Alternative is the most cost-effective renovation strategy. A generic measure of central tendency is the inter-quartile range. The inter-quartile range contains the middle 50 % of the observations. For the SIR values resulting from the Monte Carlo simulation, the inter-quartile range goes from 1.718 (i.e., the 25th percentile) to 2.864 (i.e., the 75th percentile). These values imply that every dollar invested in the Proposed Alternative will generate between $1.72 and $2.86 in savings (expressed in present value terms). Thus, the bulk of the observations are located in a range that indicates strong preference for the Proposed Alternative. Another outcome measure of use to decision makers, is the probability that the SIR exceeds 1.0. In this case, the probability is 1.0.

Figure 5-1. Life-Cycle Costs for Each Alternative in Thousands of Dollars Due to Changes in All of the Variables

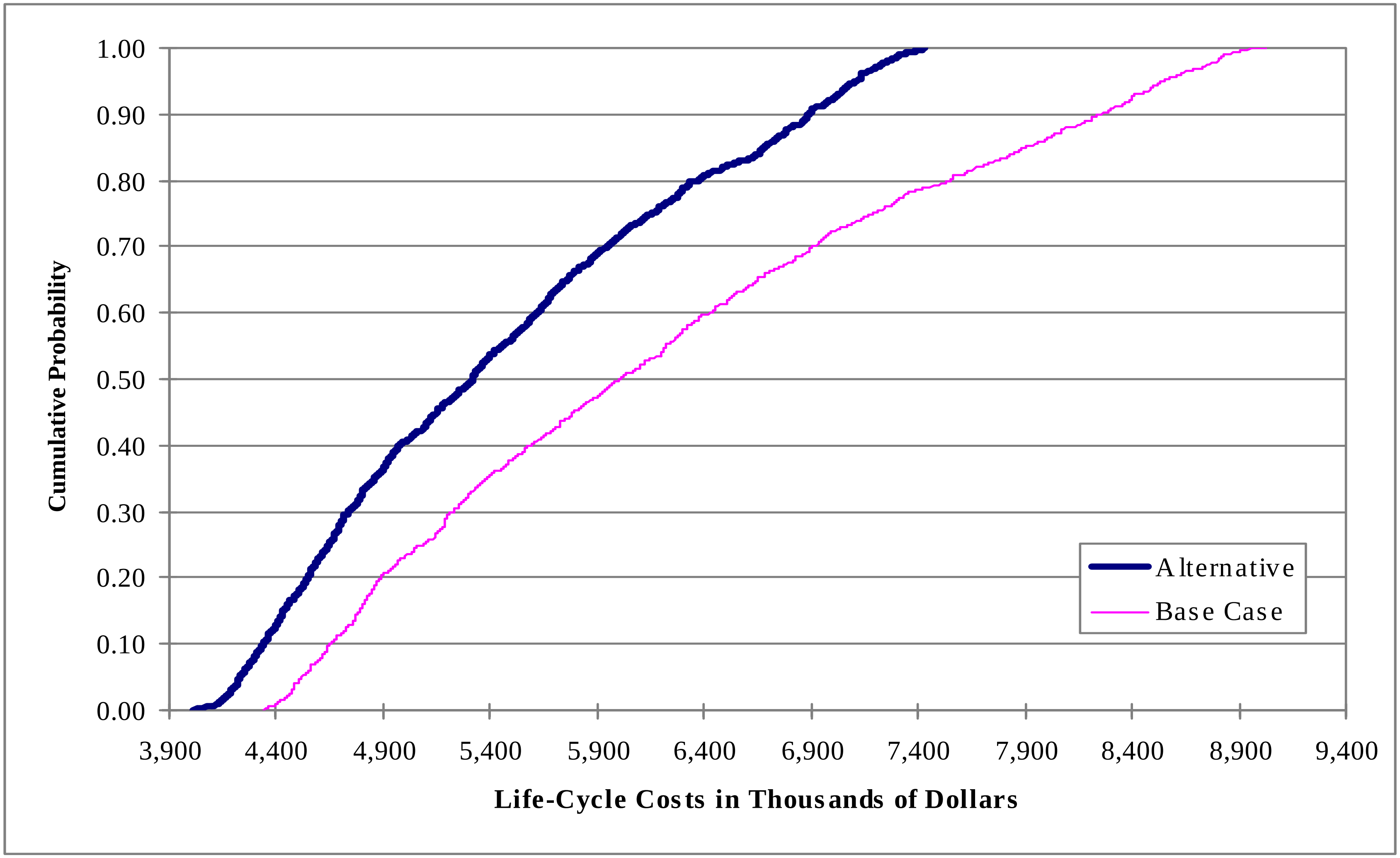

Figure 5-2. Present Value Net Savings in Thousands of Dollars Due to Changes in All of the Variables

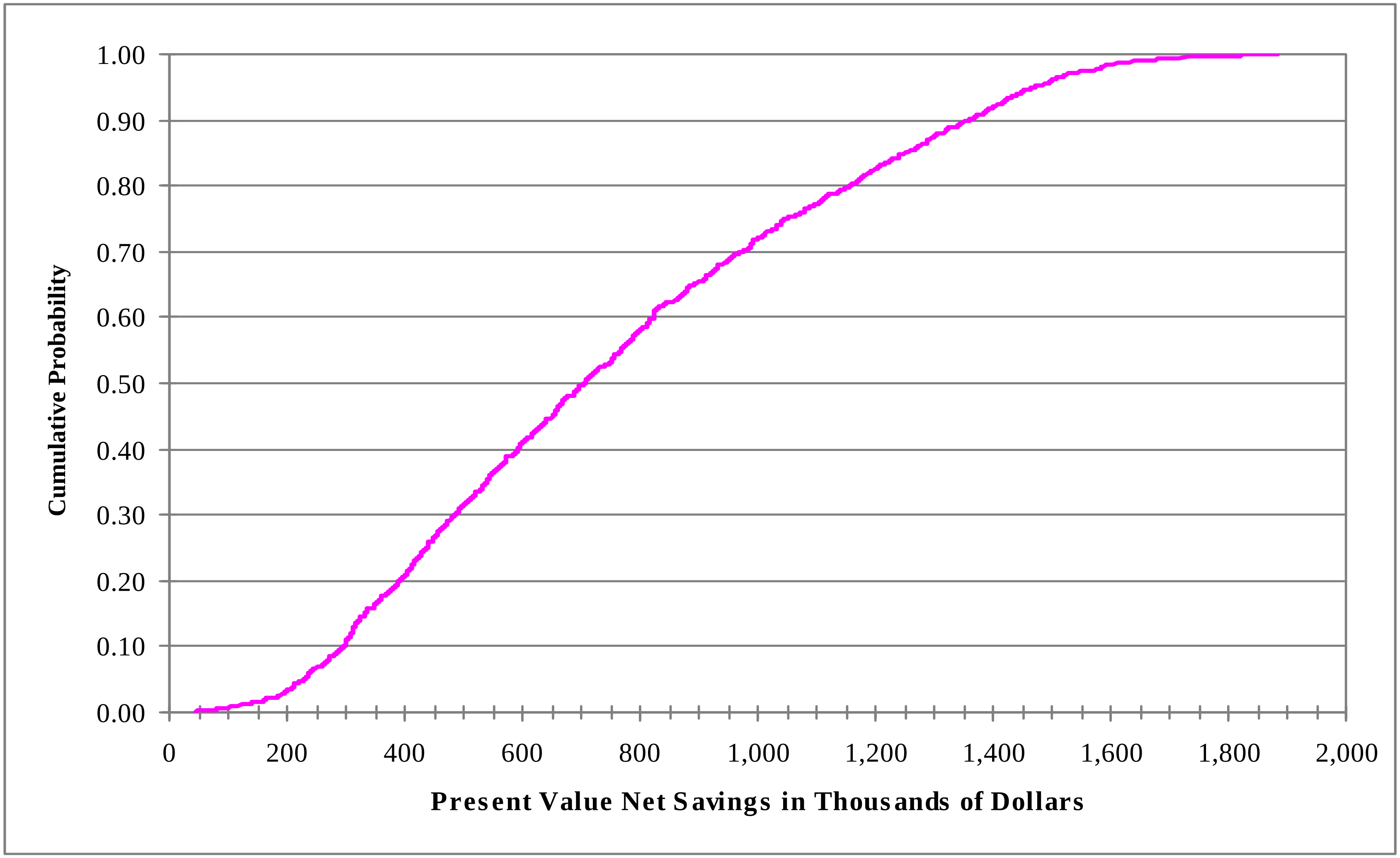

Figure 5-3. Savings-to-Investment Ratio Due to Changes in All of the Variables

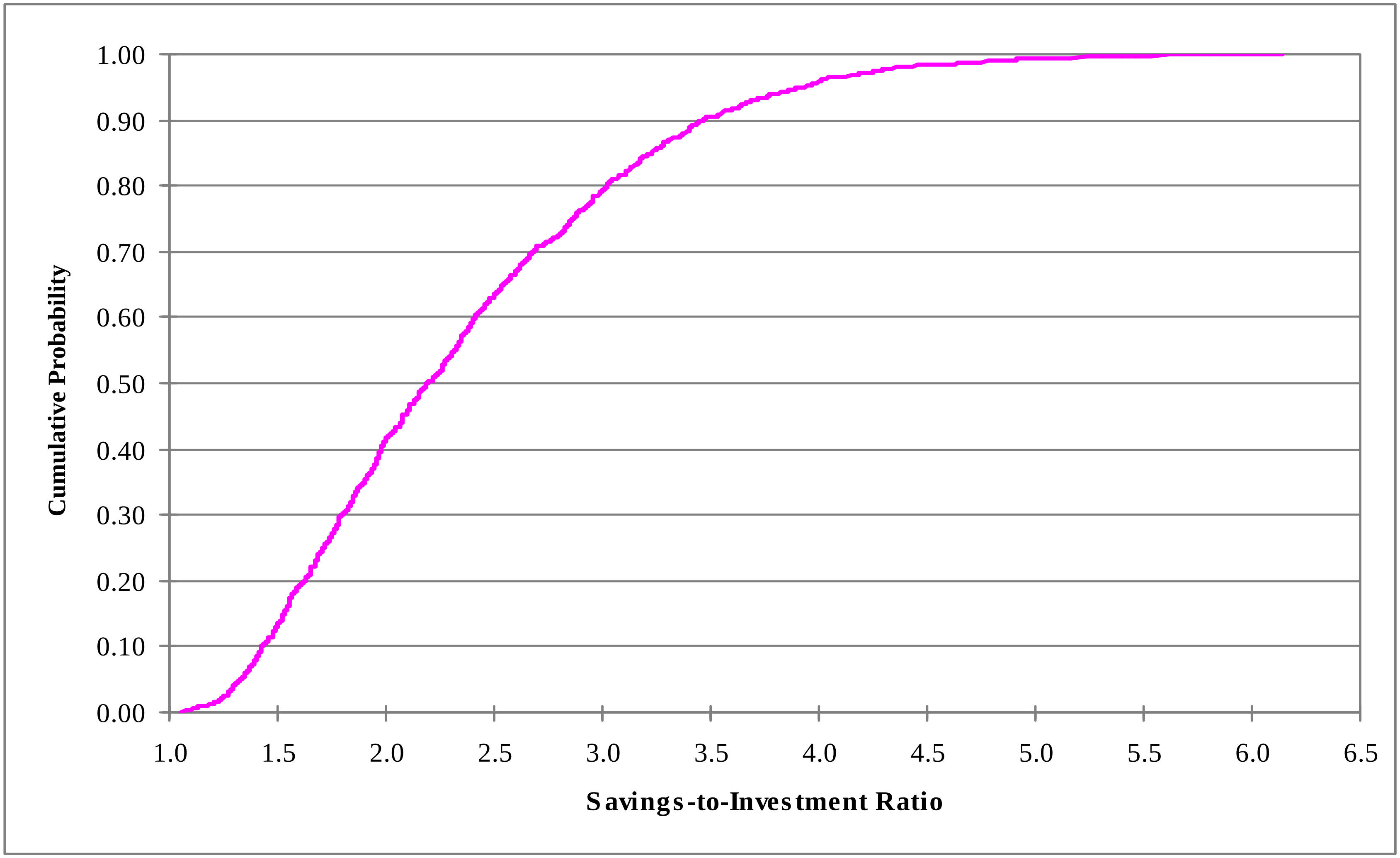

Figure 5-4. Adjusted Internal Rate of Return Due to Changes in All of the Variables

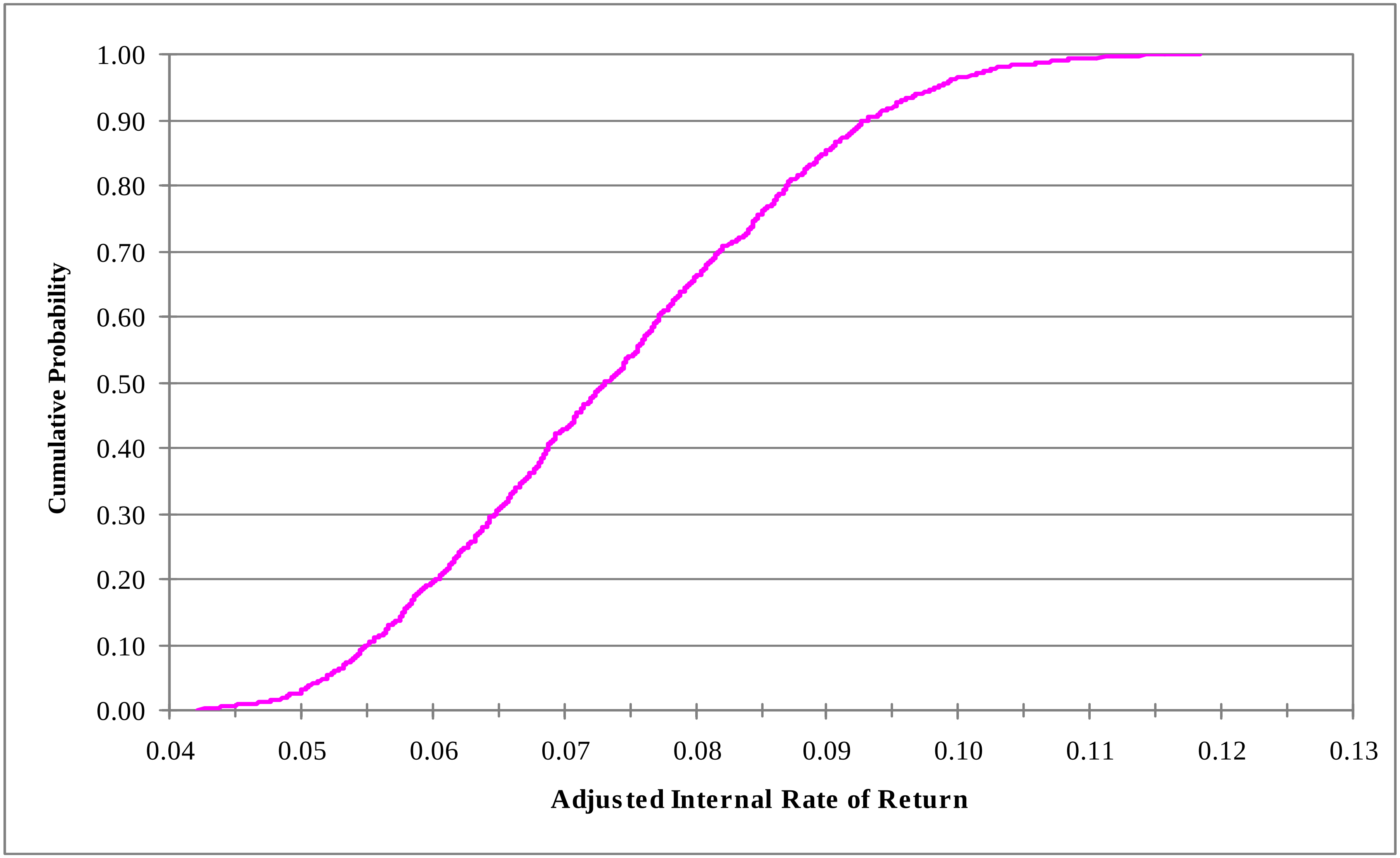

Figure 5-4 shows how the adjusted internal rate of return, AIRR, on the investments associated with the Proposed Alternative varies when all 21 variables are varied in combination. In analyzing Figure 5-4, it is useful to keep in mind that the value of AIRR resulting from the baseline analysis was 0.072. As was seen in Table 11, both the mean (0.074) and median (0.073) values of the 1,000 observations were nearly equal. Due to the way in which the AIRR is calculated, Figure 5-4 exhibits a pattern different from those seen in the other figures.[40] The CDF for the AIRR has both a fairly long lower tail as well as a long upper tail and appears to be nearly symmetrical. This helps to explain why the mean and median values in the sensitivity analysis are close to the value computed in the baseline analysis.

If the AIRR exceeds the discount rate, then the Proposed Alternative is a more cost-effective renovation strategy than the Base Case. In this case, the discount rate is defined as the minimum acceptable rate of return for an investment to be economically acceptable; it is also equal to the hurdle rate of return. Since the discount rate is 4 % and the minimum observed AIRR value from the Monte Carlo simulation is 4.2 %, all computed values of the AIRR exceed that hurdle rate. Thus, the Proposed Alternative is the most cost-effective investment choice.

The types of cost information presented in the baseline analysis and the sensitivity analysis have differed thus far. This stems from the fact that the focus of the baseline analysis was on a detailed representation of the cost data based on the cost-accounting framework. Up to this point, the focus of the sensitivity analysis was to rigorously evaluate the effects of uncertainty on the economic measures. Thus, the results of the sensitivity analysis, as presented in Tables 5-3 through 5-8 and Figures 5-1 through 5-4, treated the cost data at an aggregated level. However, the results of the Monte Carlo simulation enable more detailed analyses to be conducted. For example, a table in the same format as Table 5-7 could be prepared which builds on the cost classification presented in Table 4-11. Such a table would be useful in analyzing how different stakeholder groups were affected by a particular investment strategy or how costs vary across budget categories.

Tables 5-9 and 5-10 provide such a snapshot. Specifically, they summarize life-cycle cost information from the Monte Carlo simulations using the same format as Table 4-11. Both tables are divided into two parts. Part A reports key statistical measures for the Base Case. Part B reports key statistical measures for the Proposed Alternative. The two tables focus on different “data slices,” however, in order to illustrate how the sensitivity analysis complements the baseline analysis. Table 5-9 covers the same material that was reported in Table 4-11. Table 5-10 provides additional detail on all event-related costs.

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[40] Although the values for AIRR are a monotonic transformation of the values for SIR, the shapes of the two CDFs are quite dissimilar. This is because the AIRR is functionally related to $(SIR)^{1/25}$. This relationship is highly non-linear, explaining why the two CDF traces are so dissimilar.

Table 5-9. Statistical Measures by Cost Classification and Cost Type Due to Changes in All of the Input Variables

Part A. Base Case

Cost Classification	Cost Type	Statistical Measures for the Base Case						
		Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
Bearer:	Owner/Manager	2,538.714	2,909.572	3,339.187	3,880.696	4,797.152	3,426.061	603.035
	Occupant/User	1,336.802	1,648.684	1,992.238	2,451.522	3,175.978	2,077.558	497.130
	Third Party	422.708	535.835	681.143	868.386	1,157.819	712.464	202.440
Category:	Capital Investment	1,042.323	1,136.640	1,170.961	1,207.663	1,343.717	1,172.836	49.685
	O&M	2,783.707	3,371.207	4,152.394	5,117.372	6,588.994	4,310.030	1,068.671
	Other	430.409	550.434	701.302	892.625	1,204.773	733.217	208.364
Component:	Building/Facility Elements	2,176.572	2,503.133	2,852.649	3,293.802	4,007.353	2,929.053	493.070
	Building/Facility Site Work	136.109	145.872	156.115	169.980	192.043	158.714	14.828
	Non-Elemental	1,972.161	2,435.590	3,009.532	3,730.476	4,877.460	3,128.315	794.973

Table 5-9. Statistical Measures by Cost Classification and Cost Type Due to Changes in All of the Input Variables (continued)

Part B. Proposed Alternative

Cost Classification	Cost Type	Statistical Measures for the Alternative						
		Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
Bearer:	Owner/Manager	2,734.617	3,165.627	3,489.845	3,921.559	4,669.915	3,571.421	476.937
	Occupant/User	995.680	1,243.041	1,532.129	1,891.290	2,436.117	1,589.822	394.109
	Third Party	189.734	237.344	281.978	333.799	426.369	289.388	60.081
Category:	Capital Investment	1,567.308	1,716.373	1,771.406	1,828.779	1,959.304	1,772.030	81.870
	O&M	2,132.068	2,630.246	3,253.768	4,011.710	5,216.230	3,383.029	853.437
	Other	192.555	241.878	287.215	341.011	440.176	295.572	61.787
Component:	Building/Facility Elements	2,375.873	2,764.691	3,055.764	3,436.134	4,048.389	3,114.883	418.346
	Building/Facility Site Work	229.685	238.056	247.254	258.308	276.205	248.992	12.399
	Non-Elemental	1,355.974	1,645.834	2,012.984	2,465.556	3,170.004	2,086.757	500.665

Table 5-10. Statistical Measures by Cost Category and Bearer for Event–Related Cost Items Due to Changes in All of the Input Variables

Part A. Base Case

Cost Category	Bearer	Event-Related Cost Item	Statistical Measures for the Base Case						
			Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
Capital Investment	**Owner/ Manager**	Damage to Data Center	18.714	43.212	59.640	80.047	139.537	63.216	25.389
O&M	**Occupant/ User**	Business Interruption	32.092	71.689	97.920	128.450	229.019	103.689	41.349
		Record Reconstruction	104.961	105.231	106.529	108.988	112.525	107.275	2.252
Other	**Owner/ Manager**	Non-fatal Injuries	3.061	7.101	9.711	13.038	24.149	10.377	4.203
	Occupant/ User	Non-fatal Injuries	3.061	7.101	9.711	13.038	24.149	10.377	4.203
	Third Party	Non-fatal Injuries	3.061	7.101	9.711	13.038	24.149	10.377	4.203
		Denial of Service	13.465	28.038	39.554	52.709	97.370	41.567	16.637
		Identity Theft	399.563	494.094	626.434	805.262	1,049.672	660.520	188.481

Table 5-10. Statistical Measures by Cost Category and Bearer for Event–Related Cost Items Due to Changes in All of the Input Variables (continued)

Part B. Proposed Alternative

Cost Category	Bearer	Event-Related Cost Item	Statistical Measures for the Alternative						
			Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
Capital Investment	**Owner/ Manager**	Damage to Data Center	4.597	8.371	11.043	14.284	25.780	11.733	4.347
O&M	**Occupant/ User**	Business Interruption	11.329	22.456	29.182	37.571	71.250	30.892	11.358
		Record Reconstruction	28.500	28.653	29.094	29.853	30.903	29.297	.712
Other	**Owner/ Manager**	Non-fatal Injuries	1.065	2.253	2.916	3.782	6.903	3.092	1.136
	Occupant/ User	Non-fatal Injuries	1.065	2.253	2.916	3.782	6.903	3.092	1.136
	Third Party	Non-fatal Injuries	1.065	2.253	2.916	3.782	6.903	3.092	1.136
		Denial of Service	5.321	10.011	13.066	17.116	33.411	13.966	5.146
		Identity Theft	105.838	131.710	168.065	217.354	284.909	177.542	51.914

Table 5-9 employs the cost-accounting framework to summarize life-cycle costs by cost classification and by cost type. The three cost classifications are concerned with the bearer, the budget category, and the building component. Associated with each cost classification are its cost types. The cost types specify who bears which costs, how costs are allocated among three widely accepted budget categories, and how costs are allocated among key building components. Each individual cost item has associated with it a cost type for each cost classification. Thus, the combined costs across a given cost classification (e.g., bearer) equal the life-cycle cost of the investment alternative under analysis.

Each statistical measure reported in Table 5-9 (e.g., 25^{th} percentile), when aggregated across a cost classification (e.g., bearer), approximates but does not necessarily equal the corresponding statistical measure for the life-cycle costs of the Base Case, LCC_{BC}, and the Proposed Alternative, LCC_{Alt}, recorded in Table 5-7. This is because Table 5-9 disaggregates the life-cycle cost total into its constituent parts (e.g., capital investment costs, O&M costs, and other costs) and calculates statistical measures for each constituent part. This approach provides an in-depth snapshot of how the cost of each constituent part varies. Table 5-9 uses the same statistical measures as Table 5-7.

Part A of Table 5-9 summarizes life-cycle cost information on the Base Case. Reference to the table reveals that the value of each statistical measure—expressed in thousands of 2003 dollars—varies considerably across cost types. The mean exceeds the median across all cost types, reinforcing the effects of high values on the mean as noted in the higher-level cost summaries presented in Tables 5-7 and 5-8 and in Figure 5-1. The median value tends to exceed slightly the baseline value for the corresponding cost type. For example, the median value for capital investment is $1,171K, whereas the baseline value is $1,168K (see Table 4-11). The last column of the table records the standard deviation. The cost type with the highest standard deviation is O&M costs, followed by non-elemental costs. The cost types with the lowest standard deviations are capital investment costs and building/facility site work. Because the differences in the calculated value of the standard deviation are so large across cost types, it is instructive to "drill down" on potential sources of that variability. This approach is taken for event-related cost items in Table 5-10.

Part B of Table 5-9 summarizes life-cycle cost information on the Proposed Alternative. Reference to the table reveals that the value of each statistical measure—expressed in thousands of 2003 dollars—varies considerably across cost types. The mean exceeds the median across all cost types, reinforcing the effects of high values on the mean as noted in the higher-level cost summaries presented in Tables 5-7 and 5-8 and in Figure 5-1. The median value tends to exceed slightly the baseline value for the corresponding cost type. For example, the median value for O&M costs is $3,254K, whereas the baseline value is $3,201K (see Table 4-11). The last column of the table records the standard deviation. The cost type with the highest standard deviation is O&M costs, followed by non-elemental costs. The cost types with the lowest standard deviations are other costs, third-party costs, and building/facility site work. Note that with one important exception, the standard deviation for each cost type recorded for the Proposed Alternative is less than the corresponding standard deviation for the Base Case. The one exception is concerned with capital investment costs. As noted earlier, because the differences in the calculated value of the standard deviation are so large across cost types, it is instructive to "drill down" on potential sources of that variability. This approach is taken for event-related cost items in Table 5-10.

Table 5-10 builds on the material presented in Table 5-9. Table 5-10 records distributional information on all event-related cost items. The table records the cost category and the bearer in the first two columns. Each event-related cost item is recorded in the third column.

Part A of Table 5-10 covers the Base Case; it builds on the material presented in Part A of Table 5-9. Referring to Table 5-10, we see that the mean in every case exceeds the median—just as was observed in Table 5-9. The median value for each event-related cost item is fairly close to the corresponding baseline value (see event-related entries in Tables 4-5, 4-6, and 4-7). The last column of the table records the standard deviation. With the exception of the identity theft cost item, the standard deviations are much smaller than the values recorded in Table 5-9. Comparisons between the entries in Part A of Tables 5-9 and 5-10 reveal that the large variations in O&M costs and non-elemental costs are not linked to event-related costs items.[41] On the other hand, almost all of the variation in other costs and third-party costs are due to the identity theft cost item.

Part B of Table 5-10 covers the Proposed Alternative; it builds on the material presented in Part B of Table 5-9. Referring to Table 5-10, we see that the mean in every case exceeds the median—just as was observed in Table 5-9. The median value for each event-related cost item is fairly close to the corresponding baseline value (see event-related entries in Tables 4-8, 4-9, and 4-10). The last column of the table records the standard deviation. The standard deviations are much smaller than the values recorded in Table 5-9. Comparisons between the entries in Part B of Tables 5-9 and 5-10 reveal that the large variations in O&M costs and non-elemental costs are not linked to event-related costs items.[42] Note that the relatively high value of the standard deviation of capital investment costs is due to variations in the costs of the enhanced renovation (see Table 5-4[43]) rather than the event-related cost item damage to the data center. Comparisons between Part A and Part B of Table 5-10, reveal that the deviations of event-related cost items for the Proposed Alternative are much smaller than the corresponding values for the Base Case. This helps to reinforce the choice of the Proposed Alternative as the most cost-effective risk mitigation strategy.

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[41] Due to the impact of variations in the discount rate, the input cost site security was the principal component of the high value of the standard deviation for O&M costs, non-elemental costs, and owner/manager costs for the Base Case.

[42] As was the case for the Base Case, due to the impact of variations in the discount rate, the input cost site security was the principal component of the high value of the standard deviation for O&M costs, non-elemental costs, and owner/manager costs for the Proposed Alternative.

[43] Note that the calculated value for the standard deviation of LCC_{Alt} for the enhanced renovation recorded in Table 5-4 is due to changes in the value of that variable alone, rather than for all variables simultaneously.

5.4 How the Sensitivity Analysis Links to the Software Product

The sensitivity analysis links directly to four key features of the software product. These features are illustrated in Tables 5-1 through 5-10 and in Figures 5-1 through 5-4; they are concerned with: (1) the cost-accounting framework; (2) selected data inputs for both deterministic and probabilistic sensitivity analyses; (3) selected output reports; and (4) the "drill down" on the "Cost Summary" screen of the software product.

The software product employs the same cost-accounting framework as described in Section 2.3. This promotes a close coupling between the sensitivity analysis and the baseline analysis. The "roll ups" to the cost types and cost classifications for individual cost items are identical to those used in the baseline analysis. Thus, any changes in life-cycle cost are traceable to variations in input variables about their baseline values. Such an approach promotes in-depth analyses via the "drill down" feature described at the end of this section.

Table 5-1 records the types of cost-related information requested of the software product's user for both deterministic and probabilistic sensitivity analyses. For deterministic sensitivity analyses, Table 5-1 records the minimum and maximum setting for each variable of interest. For probabilistic sensitivity analyses, Table 5-1 records both the minimum and maximum setting along with the appropriate probability distribution to be used in any Monte Carlo simulations. The input screens for both types of sensitivity analysis are designed to collect information on both the variables of interest and the type of analysis (e.g., single-variable deterministic).

Tables 5-2 through 5-8 and Figures 5-1 through 5-4 are indicative of selected sets of output reports from the software product. Table 5-2 is indicative of the Most Significant Factors tab in the software product. This feature identifies those factors which have the greatest impact on life-cycle cost. The output from the software product will differ slightly from the material contained in Table 5-2, because Table 5-2 is constructed via a two-stage process that is based on net savings rather than a pure measure of life-cycle costs. Figure 5-1 is a standard output from the software product whenever a Monte Carlo simulation is performed. The user will also have the option to obtain additional graphical reports for economic measures other than life-cycle cost (e.g., Figures 5-2 through 5-4). Tabular summaries for Monte Carlo simulations, either singly (see Tables 5-3 through 5-6) or in combination (see Table 5-7) will also be available to the user of the software product.

The software product is designed to help the user "drill down" on how individual cost items are distributed across Bearer, Budget Category, and Building Component. The software product drills down according to a probabilistic version of the Cost Summary screen (see Table 4-11 and its supporting tables). This feature is illustrated via a two-stage analysis. The first stage drills down from life-cycle cost (see Table 5-7) to the individual cost categories and cost types; it is illustrated in Table 5-9. The second stage drills down to the individual cost items to determine how they contribute to variations in life-cycle cost; it is illustrated in Table 5-10. This approach gives users a snapshot of all of the costs entering the analysis, expressed in present value terms, which “roll up” into the life-cycle costs recorded in the Cost Summary screen.

It is also worth noting that the information presented in Tables 5-1 through 5-10 and in Figures 5-1 through 5-4 may be used as a test problem for prospective users of the software product. Prospective users of the software product should first attempt to reproduce the computed values for PVNS recorded in Table 5-2. These values are deterministic and will highlight any specification errors or deviations from the minimum and maximum values recorded in Table 5-1. Next, prospective users should perform a Monte Carlo simulation using the values and the distributions recorded in Table 5-1. Although the computed values for the statistical measures (e.g., 25th percentile) will differ from one Monte Carlo simulation to another, differences between median values should be fairly small. Thus, the users of the software product have a convenient frame of reference through which they can gain familiarity with the sensitivity analysis features of the software product.

6 Summary and Suggestions for Further Research

6.1 Summary

This report illustrates how to apply the life-cycle cost method to a prototypical data center renovation project. The building owners are evaluating two renovation strategies: the Base Case, which employs pre-9/11 levels of security; and the Proposed Alternative, which recognizes the increased potential for a cyber attack and a CBRE attack. Two basic types of analysis are presented: a baseline analysis and a sensitivity analysis employing Monte Carlo simulation. The two types of analysis complement and reinforce each other. A detailed cost accounting framework is used to classify costs by bearer, budget category, and building component for the two renovation strategies.

The material presented in the baseline analysis (see Chapter 4) demonstrates how the cost accounting framework promotes better-informed decision making by clearly identifying the most cost-effective renovation strategy. The cost data presented in Tables 4-5 through 4-11 represent a simple but concise statement of who bears which costs, how much they bear, and how these costs are distributed.

The cost information presented as part of the baseline analysis demonstrated how data used to calculate life-cycle costs could also be used to compute three additional measures: (1) the present value of net savings (PVNS); (2) the savings-to-investment ratio (SIR); and (3) the adjusted internal rate of return (AIRR). These economic measures are all useful in evaluating whether or not to undertake a particular investment, since each measure provides a different perspective. The PVNS measures the overall magnitude of cost savings. The SIR measures the cost savings per unit of capital investment. The AIRR is the annual percentage yield from the capital investment over the study period. Exhibit 6-1 summarizes the baseline analysis. It provides a brief description of each renovation strategy and covers the background, approach, and results of the economic evaluation. Exhibit 6-1 utilizes the summary format introduced in Chapter 2 (see Exhibit 2-1); it provides a concise statement of why the Proposed Alternative is the “preferred” choice with a PVNS of $682K.

In the sensitivity analysis (see Chapter 5), each economic measure is first rigorously analyzed. Charts and tables are produced to demonstrate how changing assumptions, input data, and the two sets of attack scenarios affect each economic measure. The results of the sensitivity analysis reinforced how to choose the most cost-effective risk mitigation plan. The second part of the sensitivity analysis established a direct linkage to several of the more detailed tables presented in the baseline analysis. Specifically, Tables 5-9 and 5-10 were used to “drill down” on the individual cost categories, cost types, and event-related cost items. This approach enabled the sources of variability to be identified and quantified, thus producing a risk mitigation plan that identifies the most cost-effective investment alternative as well as incorporates information on specific event-related risks.

Exhibit 6-1. Summary of the 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 (3,716 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 occupants of the data center are part of the same parent company, but not part of the same corporate division responsible for facilities construction and renovation.

The building owners employ two different renovation strategies. The first, referred to as the Base Case, employs upgrades which are consistent with pre-9/11 levels of security. Thus, the Base Case represents maintenance of the *status quo*. The second, referred to as the Proposed Alternative, recognizes 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 capture 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 has been planned for some time to upgrade the data center's HVAC, telecommunications and data processing systems and to address a number of generic security concerns.
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) and for the Proposed Alternative (Enhanced Renovation), 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 > discount or hurdle rate 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 or hurdle rate 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.
- However, both the Base Case and the Proposed Alternative have similar types of outcome costs.

Exhibit 6-1. Summary of the Data Center Case Study (continued)

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	$1,168K	$1,772K

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

PV of Non-Investment Costs	**Base Case**	**Proposed Alt.**
O&M Costs	4,082K	3,201K
Other Costs	687K	282K
	$4,769K	$3,483K

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

LCC	**Base Case**	**Proposed Alt.**
PV of Investment Costs	1,168K	1,772K
PV of Non-Investment Costs	4,769K	3,483K
	$5,937K	$5,255K

PVNS from Proposed Alternative $682K

Savings-to-Investment Ratio (SIR)

PV of Non-Investment Savings $1,286K
Divided by PV of Incr. Investment 604K
SIR = 2.13

Adjusted Internal Rate of Return (AIRR)

$(1+0.04)\ 2.13^{1/25} - 1 = 0.072$

AIRR = 7.2 %

which exceeds the hurdle rate of 4.0 %

3.b Key Results:

- **LCC**
  Base Case $5,937K
  Proposed Alt. $5,255K
- **PVNS from Alt.** $682K
- **SIR** 2.13
- **AIRR** 7.2 %

3.c Traceability:

Life-cycle costs and supplementary measures were calculated according to ASTM standards E 917, E 964, E 1057, and E 1074.

The data center case study highlights the merits of the life-cycle cost method and why we have chosen this method as the core component of our decision methodology. The case study also provides a snapshot of the types of data inputs and cost summaries that our software product will produce, and serves as a valuable reference point for checking the computational algorithms in the software product.

6.2 Suggestions for Further Research

The background work for this report uncovered additional areas of research that might be of value to government agencies and private-sector organizations concerned with homeland security-related issues. These areas of research are concerned with: (1) the specification of mitigation strategies with particular emphasis on spillover effects; (2) the construction of scenarios for modeling sequential investment decisions; and (3) evaluations based on multiattribute decision analysis.

The data center case study illustrated an example of a beneficial spillover. In this case, the improved indoor air quality and reduced energy consumption associated with the Proposed Alternative's HVAC upgrade resulted in a significant reduction in life-cycle cost. In comparing investment alternatives, it is important to recognize that spillovers—either positive or negative—can tip the balance from one alternative to another. Consequently, every effort should be made to identify spillovers and quantify their impacts. This is especially true for cases where a particular mitigation strategy may address multiple hazards.

Many investment decisions are sequential in nature. The data center case study included sequential elements related to capital replacements. However, additional research on scenario construction is needed to better capture the sequential nature of decision making in a life-cycle cost context. Because the sequence in which investment decisions are made impacts not only capital costs but O&M and other costs as well, research on scenario construction would help the users of the software product to identify those investment sequences which have the most favorable impact on life-cycle cost.

Many investment alternatives differ in characteristics that decision makers consider important but that are not readily expressed in monetary terms. Because the standardized evaluation methods employed in this report consider only monetary benefits and monetary costs associated with alternative investment choices, their application does not reflect the importance of these non-financial characteristics to the decision maker. When non-financial characteristics are important, decision makers need a method that accounts for these characteristics (also called attributes) when choosing among alternative investments. A class of methods that can accommodate non-monetary benefits and costs is multiattribute decision analysis.[44]

[44]For more information on multiattribute decision analysis, see Norris, Gregory A., and Harold E. Marshall. 1995. *Multiattribute Decision Analysis Method for Evaluating Buildings and Building Systems.* NISTIR 5663. Gaithersburg, MD: National Institute of Standards and Technology.

The analytical hierarchy process (AHP) is one of a set of multiattribute decision analysis methods that considers non-financial characteristics in addition to common economic evaluation measures when evaluating project alternatives. The AHP has several important strengths: (1) it is well-known and well-reviewed in the literature; (2) it includes an efficient attribute weighting process; (3) it incorporates hierarchical descriptions of attributes; (4) its use is facilitated by available software; and (5) it has been accepted by ASTM as a standard practice for investments related to buildings and building systems.[45]

The AHP and its associated software represent a powerful and versatile management tool. How to apply this management tool most productively to homeland security-related issues suggests additional research on how decision makers view non-financial outcomes associated with low-probability, high-consequence events.

[45] ASTM International. 2002. "Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems." E 1765. *Annual Book of ASTM Standards: 2002*. Vol. 04.12. West Conshohocken, PA: ASTM International.

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