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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, Maryland 20899

Benefits and Costs of Research: A Case Study of Cybernetic Building Systems

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U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

Technology Administration
Gary R. Bachula, Acting Under Secretary for Technology

National Institute of Standards and Technology
Raymond G. Kammer, Director

Abstract

The National Institute of Standards and Technology (NIST) is improving its resource allocation process by doing "microstudies" of its research impacts on society. This report is one of a series of microstudies prepared by NIST's Building and Fire Research Laboratory (BFRL).

This report focuses on a critical analysis of the economic impacts of past, ongoing, and planned BFRL research for developing and deploying cybernetic building systems (CBSs) in office buildings. Building systems targeted for incorporation into CBS products and services include energy management, fire and security, fault detection and diagnostics, the real-time purchase of electricity, and the aggregation of building stock for multi-facility operations. A CBS is defined as a multi-system configuration that is able to communicate information and control functions simultaneously and seamlessly at multiple levels. Pressure to increase building systems performance and reduce costs has created a potential market for CBS products and services. BFRL is collaborating with industry on the development of CBS products and services and is providing a forum for conducting interoperability testing.

This case study of BFRL's CBS-related research, development, and deployment effort illustrates how to apply in practice a series of standardized methods to evaluate and compare the economic impacts of alternative research investments. It is presented in sufficient detail to understand the basis for the economic impact assessment and to reproduce the results. It is based on past, ongoing, and planned research efforts. Thus, it includes CBS-related investment costs that have already occurred along with estimates of future investment costs and cost savings due to the use of CBS products and services.

The results of this study demonstrate that the use of CBS products and services will generate substantial cost savings to the owners, managers, and occupants of office buildings across the nation. The present value of cost savings nationwide expected from the use of CBS products and services in office buildings exceeds $1.1 billion ($1,176 million in 1997 dollars). Furthermore, because of BFRL's role as a facilitator and developer of key CBS enabling technologies, CBS products and services are expected to become available commercially in 2003. Without BFRL's participation, the commercial introduction of CBS products and services would likely be delayed until 2010. Consequently, potential cost savings accruing to the owners, managers, and occupants of office buildings over the period 2003 until 2010 would have been foregone. These cost savings are $90.7 million in 1997 dollars. These cost savings measure the return on BFRL's CBS-related investment costs of approximately $11.5 million.

Keywords

BACnet; benefit-cost analysis; building economics; cybernetic building systems; economic analysis; energy conservation; fire panels; fire safety; impact evaluation; life-cycle costing; sensors; research impacts

Preface

This study was conducted by the Office of Applied Economics in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). The study is designed to estimate the economic impacts resulting from BFRL research and to estimate the return on BFRL's research investment dollars. The intended audience is the National Institute of Standards and Technology as well as other government and private research groups that are concerned with evaluating how efficiently they allocated their past, present, and future research budgets.

The measurement of economic impacts of research is a major interest of BFRL and of NIST. Managers need to know the impact of their research programs in order to achieve the maximum social benefits from their limited budgets. The standardized methods for measuring economic impacts employed in this study are essential to support BFRL's effort to evaluate the cost effectiveness of completed and ongoing research projects. As additional experience is gained with the application of these standardized methods, their use will enable BFRL to select the "best" among competing research programs for future funding, to evaluate how cost effective are existing research programs, and to defend or terminate programs on the basis of their economic impact. This need for measurement methods exists across programs in BFRL, in NIST, and in other research laboratories.

Acknowledgments

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List of Acronyms

Acronym	Definition
AIRR	Adjusted Internal Rate of Return
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
ATM	Asynchronous Transfer Mode
BACnet	Building Automation and Control Networks
BCR	Benefit-to-Cost Ratio
BFRL	Building and Fire Research Laboratory
BOMA	Building Owners and Managers Association
CBECS	Commercial Building Energy Consumption Survey
CBS	Cybernetic Building System
CDF	Cumulative Distribution Function
CORBA	Common Object Request Broker Architecture
CPI	Consumer Price Index
DDC	Direct Digital Control
DDE	Dynamic Data Exchange
DOE	Department of Energy
FDD	Fault Detection and Diagnostic
GSA	General Services Administration
HVAC	Heating, Ventilation, and Air-Conditioning
IAQ	Indoor Air Quality
IFMA	International Facilities Management Association
IREM	Institute of Real Estate Management
LCC	Life-Cycle Cost
MARR	Minimum Attractive Rate of Return
MEL	Manufacturing Engineering Laboratory
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NSTC	National Science and Technology Council
OAE	Office of Applied Economics
OMB	Office of Management and Budget
PVB	Present Value of Benefits
PVC	Present Value of Non-Investment Costs
PV$\underline{C}$	Present Value of Combined Costs
PVI	Present Value of Investment Costs
PVNB	Present Value of Net Benefits
PVNS	Present Value of Net Savings
PVS	Present Value of Savings

SIC	Standard Industrial Classification
SIR	Savings-to-Investment Ratio
TV	Terminal Value
VAV	Variable Air Volume
VCBT	Virtual Cybernetic Building Testbed
VRML	Virtual Reality Modeling Language
VTS	Visual Test Shell

Executive Summary

This report is the third in a series of microstudies prepared by NIST's Building and Fire Research Laboratory (BFRL).[i, ii] It focuses on a critical analysis of the economic impacts of past, ongoing, and planned BFRL research for developing and deploying cybernetic building systems (CBSs) in office buildings. Pressure to increase building systems performance and reduce costs has created a potential market for CBS products and services. BFRL is collaborating with industry on the development of CBS products and services and is providing a forum for conducting interoperability testing. A CBS is defined as a multi-system configuration that is able to communicate information and control functions simultaneously and seamlessly at multiple levels.

This case study of BFRL's CBS-related research, development, and deployment effort illustrates how to apply in practice a series of standardized methods to evaluate and compare the economic impacts of alternative research investments. It is presented in sufficient detail to understand the basis for the economic impact assessment and to reproduce the results. It is based on past, ongoing, and planned research efforts. Thus, it includes CBS-related investment costs that have already occurred along with estimates of future investment costs and cost savings due to the use of CBS products and services in office buildings.

Chapter 2 presents the five economic evaluation methods (i.e., economic measures) that are most appropriate for measuring the benefits (cost savings) impacts of research programs: (1) present value of net benefits (PVNB); (2) present value of net savings (PVNS); (3) benefit-to-cost ratio (BCR); (4) savings-to-investment ratio (SIR); and (5) adjusted internal rate of return (AIRR). The PVNB (PVNS) measures the overall magnitude of the benefits (cost savings) net of the costs of undertaking the research. The BCR (SIR) measures the benefits (cost savings) per unit cost of the research. The AIRR is the annual percentage yield from a project over the study period, taking into account the reinvestment of interim receipts. All five methods apply to Accept/Reject decisions. Both PVNB and PVNS are appropriate for Design/Size decisions (selecting one among mutually exclusive alternatives). BCR, SIR, and AIRR are appropriate for ranking alternatives under a budget constraint. A format for summarizing economic impacts of research investments is presented in Exhibit 2.1.

Chapter 3 describes BFRL's CBS-related research, development, and deployment effort and each of its six key areas of research. The CBS efforts within BFRL are aimed at producing a suite of products and services that integrate a wide variety of building

[i] The first report focuses on two building technology applications: (1) ASHRAE Standard 90-75 for residential energy conservation; and (2) 235 shingles, an improved asphalt shingle for sloped roofing. See 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.
[ii] The second report focuses on a fire technology application: the Fire Safety Evaluation System. See Chapman, Robert E., and Stephen F. Weber. 1996. *Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System*. NISTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology.

systems. Building systems targeted for incorporation into CBS products and services include energy management (e.g., heating, ventilation, and air-conditioning (HVAC) and lighting), fire and security, fault detection and diagnostics, the real-time purchase of electricity, and the aggregation of building stock for multi-facility operations. How these systems communicate, interact, share information, make decisions, and perform in a "synergistic" and reliable manner is at the heart of BFRL's CBS program.

Chapter 4 provides a snapshot of the US construction industry. As such, it provides the context within which the scope and size of the market for CBS products and services is defined. Information is first presented on the value of construction put in place to show the size of the construction industry and each of its four sectors. The four sectors are residential, commercial/institutional, industrial, and public works. Information on the commercial/institutional sector is then presented to focus on its importance within the overall construction industry and to define its key components. Office buildings are shown to be a key component of the commercial/institutional sector and are considered the most likely market for CBS products and services. Special emphasis is then placed on detailing the key characteristics of office buildings (e.g., building floorspace and year of construction) to define the scope and size of the market for CBS products and services in office buildings. Detailing the key characteristics of office buildings is crucial, because investments in CBS products and services affect additions, alterations, and maintenance and repair activities as well as new construction activities.

A strategy for identifying, collecting, and measuring CBS-related benefits and costs is presented in Chapter 5. The strategy identifies key stakeholders (e.g., building owners and managers), presents comprehensive lists of CBS-related benefits and costs, and documents the relationships between benefits, costs, and stakeholders. The strategy was developed through an iterative process. First, information was solicited from all of the members of the BFRL CBS team. A brainstorming session was used to develop candidate lists of key stakeholder classes and general types of CBS-related benefits and costs. Second, the lists were refined and organized into a suite of "classification" hierarchies. Third, the classification hierarchies were distributed to each of the BFRL CBS project leaders and, upon their review of the classification hierarchies, critiqued in a series of meetings. The meetings with the BFRL CBS project leaders also sought to identify subject matter experts for follow-on discussions. Finally, subject matter experts from industry and government were interviewed. These interviews were used to finalize the analysis strategy and the classification hierarchies as well as to collect information on current industry practices and to identify additional data sources.

Chapter 6 describes the data and assumptions used to evaluate the economic impacts of installing CBS products and services in office buildings. The goal of Chapter 6 is fourfold. First, it establishes the sources and validity of the data used in the CBS economic impact assessment. Second, it defines the base case and the CBS alternative. Third, it produces estimated values for key sets of benefits and costs. Fourth, it documents the process by which key assumptions were established, including how the values of key parameters were set. For example, the study period over which costs and savings are measured consists of the 25 years from 1991 through 2015. The base year is

1997, and all dollar amounts are calculated in present value 1997 dollars. The discount rate is 7 percent (real), which is the OMB discount rate in effect for government projects in 1997.

The CBS economic impact assessment was carried out in two stages. In the first stage, a baseline analysis was performed. In the baseline analysis, all input variables used to calculate the economic measures are set at their likely values. It is important to recognize that the term baseline analysis is used to denote a complete analysis in all respects but one; it does not address the effects of uncertainty. In the second stage, nine input variables were varied both singly and in combination according to an experimental design. Monte Carlo simulations are employed to evaluate how changing the value of these variables affects the calculated values of the economic measures.

In Chapter 7 (see Exhibit 7-1), the results of the baseline analysis demonstrate that the use of CBS products and services will generate substantial cost savings to the owners, managers, and occupants of office buildings across the nation. The present value of cost savings nationwide expected from the use of CBS products and services in office buildings exceeds $1.1 billion ($1,176 million in 1997 dollars). Furthermore, because of BFRL's role as a facilitator and developer of key CBS enabling technologies, CBS products and services are expected to become available commercially in 2003. Without BFRL's participation, the commercial introduction of CBS products and services would likely be delayed until 2010, and potential cost savings accruing to the owners, managers, and occupants of office buildings over the period 2003 until 2010 would have been foregone. These cost savings are $90.7 million in 1997 dollars. These cost savings measure the return on BFRL's CBS-related investment costs of approximately $11.5 million. Stated in present value terms, every public dollar invested in BFRL's CBS-related research, development, and deployment effort is expected to generate $7.90 in cost savings to the public. The estimated annual percentage yield from BFRL's CBS-related investments over the 25-year study period is 16.2 percent.

Chapter 8 covers the sensitivity analysis. The objective of the sensitivity analysis was to evaluate how uncertainty in the values of each of the nine input variables, both singly and in combination, translates into changes in each of the six economic measures. The six economic measures evaluated in the sensitivity analysis are: (1) the present value of savings nationwide, PVS_{ALL}; (2) the present value of savings due to BFRL, PVS_{BFRL}; (3) the present value of BFRL's CBS-related investment costs, PVC_{BFRL}; (4) the present value of net savings due to BFRL, $PVNS_{BFRL}$; (5) the savings-to-investment ratio on BFRL's CBS-related investments, SIR_{BFRL}; and (6) the adjusted internal rate of return on BFRL's CBS-related investments, $AIRR_{BFRL}$. The major advantage of the sensitivity analysis is that it produces results that can be tied to probabilistic levels of significance for each economic measure (e.g., the probability that $PVNS_{BFRL}$ is greater than or equal to zero, SIR_{BFRL} is greater than or equal to 1.0, or $AIRR_{BFRL}$ is greater than or equal to the discount rate, each of which would indicate that BFRL's CBS-related investments were cost effective).

The results of the sensitivity analysis serve to validate the results of the baseline analysis. For example, the Monte Carlo simulation in which all nine of the input variables were varied in combination produced 1,000 observations for each of the six economic measures. The median value for each economic measure was almost identical to the value calculated in the baseline analysis for that measure. Note, however, that results from this Monte Carlo simulation reveal that the present value of net savings due to BFRL, $PVNS_{BFRL}$, can be negative. This implies that there is some non-zero probability that BFRL's CBS-related investments are not cost effective. On the opposite extreme, however, $PVNS_{BFRL}$ may reach nearly $1.4 billion in 1997 dollars.

The fact that the range of values for an economic measure is so wide prompted an in-depth examination of the results of this Monte Carlo simulation for three of the six economic measures. These measures are particularly helpful in understanding BFRL's contribution, since each measure provides a different perspective. The first, the present value of net savings due to BFRL, is a magnitude measure; it shows a dollar value to the public net of BFRL's CBS-related investments. The second, the savings-to-investment ratio on BFRL's CBS-related investments, is a multiplier; it shows, in present value terms, how many dollars the public receives for each public dollar spent. The third, the adjusted internal rate of return on BFRL's CBS-related investments, is a rate of return; it shows the return on the public monies going into the development of CBS products and services throughout the 25-year study period.

For each of the three economic measures, less than 60 observations out of 1,000 were responsible for the observed "uneconomical" outcome. Stated another way, there is at least a 94 percent chance that BFRL's CBS-related investments are cost effective. This underscores the importance of using multiple measures that ensure consistency in decision making.

Chapter 9 discusses additional areas of research that might be of value to government agencies and other institutions that are concerned with an efficient allocation of their research budgets. These areas of research are concerned with: (1) the development of a standard classification of research benefits and costs; (2) factors affecting the diffusion of new technologies; (3) conducting prospective evaluations with scheduled follow-ups; and (4) evaluations based on multiattribute decision analysis.

1. Introduction

1.1 Background

The pressures of competing in the global marketplace are affecting nearly every U.S. business. Now more than ever, U.S. businesses are finding that they must continuously improve their products and services if they are to survive and prosper. Research, with its potential for incremental and breakthrough improvement is of central importance to most businesses' continuous improvement efforts. A key component of the competitiveness problem is the "inability of American companies (or, more accurately, the U.S.-based portions of what are fast becoming global technology firms) to transform discoveries quickly into high-quality products and into processes for designing, manufacturing, marketing, and distributing such products."[1]

Increasingly, the winners in the competitiveness race are those businesses that most rapidly make use of the fruits of research (e.g., new data, insights, inventions, and prototypes). Efforts underway at the National Institute of Standards and Technology (NIST) and elsewhere in the U.S. focus on speeding up the commercial application of basic and applied research results. *The purpose of this report is to respond to the follwing question: "how do we measure the results of our investments in technology development and application?"*[2] A case study approach is used to illustrate how standardized evaluation methods may be used to measure the economic impacts of such investments.

NIST's research laboratories serve all sectors of U.S. industry through focused research programs. Each laboratory has strong working relationships with industrial, trade, and professional organizations in its areas of technology concentration. The program of NIST's Building and Fire Research Laboratory (BFRL) is guided by a prioritized research agenda developed by experts from the building and fire communities. Its performance prediction and measurement technologies enhance the competitiveness of U.S. industry and public safety. Specifically, BFRL is dedicated to improving the life-cycle quality and economy of constructed facilities. BFRL studies structural, mechanical, and environmental engineering, fire science and fire safety engineering, building materials, and computer integrated construction practices.

To further strengthen its ties to industry, BFRL is participating in the Subcommittee on Construction and Building of the National Science and Technology Council (NSTC). The NSTC, a cabinet-level group charged with setting federal technology policy, coordinates research strategies across a broad cross-section of public and private interests. The Subcommittee on Construction and Building coordinates and defines

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[1]Reich, Robert W. 1989. "The Quiet Path to Technological Preeminence." *Scientific American* (October): pp. 41-47.

[2]Good, Mary, and Arati Prabhakar. 1994. "Foreword." In Mark Bello and Michael Baum, *Setting Priorities and Measuring Results at the National Institute of Standards and Technology*. Gaithersburg, MD: National Institute of Standards and Technology.

priorities for federal research, development, and deployment related to the industries that produce, operate, and maintain constructed facilities, including, buildings and infrastructure.[3]

BFRL has long recognized the value of measuring the impacts of its research program. Previous studies have shown that even modest research efforts within BFRL are capable of producing significant impacts.[4] One reason for such outcomes is the unique mix of research facilities and skills possessed by BFRL and its staff. Through many years of active collaboration with its various user communities, BFRL's research findings are highly regarded when new construction, building, and disaster mitigation technologies are considered for introduction into the U.S. market.

1.2 Purpose

This report is the third in a series of impact studies prepared by BFRL. It focuses on the research, development, deployment, and adoption and use of Cybernetic Building Systems (CBSs) in office buildings. The first report focuses on two building technology applications: (1) ASHRAE Standard 90-75 for residential energy conservation; and (2) 235 shingles, an improved asphalt shingle for sloped roofing.[5] The second report focuses on a fire technology application: the Fire Safety Evaluation System for health care facilities.[6]

The CBS research and development effort within BFRL is aimed at producing a suite of products that integrate a wide variety of building systems. How these systems communicate, interact, share information, make decisions, and perform in a "synergistic" and reliable manner is at the heart of BFRL's CBS research and development effort.

This report employs standardized methods to evaluate the expected economic impacts of the adoption and use of CBS products and services in office buildings. This "case study" approach illustrates how to apply in practice standardized methods to evaluate and compare the economic impacts of research investments. The standardized methods for measuring economic impacts employed in this study are essential to support BFRL's effort to evaluate the cost effectiveness of planned, on going, and completed research projects. This need for measurement methods exists across programs in BFRL, in NIST, and in other research laboratories.

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[3]Seven goals to enhance the competitiveness of the U.S. construction industry are explicit in the mission of the Subcommittee. For a detailed description of these goals and how the Subcommittee on Construction and Building will approach them, see Wright, Richard N., Arthur H. Rosenfeld, and Andrew J. Fowell. 1995. *Construction and Building: Federal Research and Development in Support of the U.S. Construction Industry*. Washington, DC: National Science and Technology Council.

[4]Marshall, Harold E., and Rosalie T. Ruegg. 1979. *Efficient Allocation of Research Funds: Economic Evaluation Methods with Case Studies in Building Technology*. NBS Special Publication 558. Gaithersburg, MD: National Bureau of Standards.

[5]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.

[6] Chapman, Robert E., and Stephen F. Weber. 1996. *Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System*. NISTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology.

1.3 Scope and Approach

This report takes a long-run view of research planning and evaluation. The focus is on specific benefits and costs of research investments, with little attention being given to institutional considerations and other constraining factors. Examples of such constraining factors which research managers are likely to find important are the compatibility of research projects with the organization's mission and the ability to perform those projects within budget constraints.

This report has eight chapters in addition to the Introduction. The body of this report, Chapters 3 through 8, consists of a case study of CBSs in office buildings. The approach taken in this report is to present all CBS-related information in sufficient detail *both to understand* the basis for the economic impact assessment *and to reproduce* the results of the economic impact assessment. The CBS case study is *ex ante* in that it is based on both past and on going and planned research efforts.

The CBS case study provides estimates of the economic impacts from BFRL research efforts aimed at the development and introduction of a suite of CBS products and services for office buildings. The methodology and the standardized methods employed in the study to measure the CBS's economic impacts are described in Chapter 2. Standardized methods are used to define the key measures of the economic impacts of research investments. A format for summarizing the economic impacts of research investments is also presented. Chapter 3 describes BFRL's CBS-related research and development effort. Both the overall CBS research and development effort and the six key areas of research, which are its constituent parts, are described. Chapter 4 provides an overview of the construction industry. The overview provides the context within which the market for CBS products and services is defined. A strategy for measuring CBS-related benefits and costs is presented in Chapter 5. The strategy identifies key stakeholders (e.g., building owners and managers), presents comprehensive lists of CBS-related benefits and costs, and documents the relationships between benefits, costs, and stakeholders. Assumptions about those years over which costs and savings are tabulated, the appropriate discount rate, and the rate and level of adoption of CBS products and services in office buildings are necessary to measure the economic impacts of CBSs. These assumptions, and the supporting data upon which these assumptions are based, are described in Chapter 6. In addition, Chapter 6 develops estimates of the key benefits and costs that are the focus of the *ex ante* impact assessment. These "significant few" benefits and costs are well-defined subsets of the comprehensive lists presented in Chapter 5. Estimates of the cost savings from using CBS products and services in office buildings are the focus of Chapter 7. In addition, that part of dollar savings that appears attributable specifically to BFRL's research and development effort is estimated. A two-page summary of the CBS case study is given in Section 7.1. Chapter 8 includes a sensitivity analysis to provide the reader with additional background and perspective on the economic impacts of BFRL's CBS-related research and development effort. 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 measures of the economic impacts of CBSs.

Chapter 9 concludes the report with a summary and suggestions for further research.

2. A Methodology for Analyzing Economic Impacts

This chapter focuses on laying out a methodology for conducting and summarizing an economic impact assessment. The methodology is based on two types of analysis, five measures of economic performance, and a format for summarizing the results of an economic impact assessment. The two types of analysis are baseline analysis and sensitivity analysis. They are described in Section 2.1. The five measures of economic performance are present value of net benefits, present value of net savings, benefit-to-cost ratio, savings-to-investment ratio, and adjusted internal rate of return. They are described in Section 2.2. The format for summarizing the results of the economic impact assessment is described in Section 2.3.

2.1 Types of Analysis

2.1.1 Baseline Analysis

The starting point for conducting an economic impact assessment is referred to as the baseline analysis. In the baseline analysis, all data (i.e., all input variables and any functional relationships among these variables) entering into the benefit, cost, and savings 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 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.[7] Throughout this report, likely value and baseline value are used interchangeably. Baseline data represent a fixed state of analysis based on likely values. For 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., present value of net benefits, present value of net savings, benefit-to-cost ratio, 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

[7] Two common measures of central tendency are the 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 cases 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.

applications. Office of Management and Budget *Circular A-94* recommends sensitivity analysis to federal agencies as one technique for treating uncertainty in input variables. Therefore, a sensitivity analysis complements the baseline analysis by evaluating the changes in output measures when selected key sets of data vary about their likely (i.e., 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[8] and the subsequent video[9] and workbook.[10]

2.2 Overview of Evaluation Methods

Several methods of economic evaluation are available to measure the economic performance of a research program, a new technology, a building, a building system, or like investment, over a specified time period. These methods include, but are not limited to, present value of net benefits, present value of net savings, benefit-to-cost ratio, savings-to-investment ratio, and the adjusted internal rate of return. These methods differ in the way in which they are calculated and, to some extent, in their applicability to particular types of investment decisions. The five methods described in this section are based on ASTM standard practices.[11] Detailed descriptions of each of the standardized methods are given in Chapman and Fuller.[12] Readers interested in an excellent, in-depth survey covering these as well as other methods are referred to Ruegg and Marshall.[13]

In order to describe each of the five 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:

$a*$ = the alternative under analysis;

t = a unit of time, where $-t^a$ is the earliest point (i.e., beginning of the study period) before the base year (i.e., t=0) and T is the last point after the base year (i.e., end of the study period);

L = the length of the study period (e.g., $t^a + T$);

B_t^{a*} = the benefits for alternative $a*$ in year t;

[8]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.
[9]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.
[10]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.
[11]American Society for Testing and Materials (ASTM). Third Edition, 1994. *ASTM Standards on Building Economics*. Philadelphia, PA: American Society for Testing and Materials.
[12]Chapman and Fuller, *Two* Case *Studies in Building Technology*, pp. 27-37.
[13]Ruegg, Rosalie T. and Harold E. Marshall. 1990. *Building Economics: Theory and Practice.* New York: Chapman and Hall.

I_t^{a*} = the investment costs for alternative $a*$ in year t;

C_t^{a*} = the non-investment costs for alternative $a*$ in year t;

$\underline{\mathbf{C}}_t^{a*}$ = the combined cost for alternative $a*$ in year t (i.e., $\underline{\mathbf{C}}_t^{a*} = I_t^{a*} + C_t^{a*}$);

S_t^{a*} = the savings for alternative $a*$ in year t;

d = the discount rate.

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) to adjust all benefits, costs, and savings—past, present, and future—to the base year (i.e., t=0). The dollar denominated quantities defined above and their associated present value terms are: the present value of benefits (*PVB*), the present value of investment costs (*PVI*), the present value of non-investment costs (*PVC*), the present value of combined costs (*PV*<u>***C***</u>), and the present value of savings (*PVS*).

2.2.1 Present Value of Net Benefits and Present Value of Net Savings

The present value of net benefits (PVNB) method is reliable, straightforward, and widely applicable for finding the economically efficient choice among alternatives (e.g., building systems). It measures the amount of net benefits from investing in a given alternative instead of investing in the foregone opportunity (e.g., some other alternative or maintenance of the *status quo*).

PVNB is computed by subtracting the time-adjusted costs of an investment from its time-adjusted benefits. If PVNB is positive, the investment is economic; if it is zero, the investment is as good as the next best investment opportunity; if it is negative, the investment is uneconomical. Emphasis is on economic efficiency because the method is appropriate for evaluating alternatives that compete on benefits, such as revenue or other advantages that are measured in dollars, in addition to costs.

The present value of net savings (PVNS) method is the PVNB method recast to fit the situation where there are no significant benefits in terms of revenue or the like, but there are reductions in future costs (e.g., reductions in the cost of ownership to consumers).[14] By treating savings like revenue benefits, the PVNB method may be reformulated as the PVNS method.

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[14]If there are any benefits, say in the form of revenues or other positive cash flows; add them to the cost savings associated with the alternative under analysis.

The PVNB for a given alternative, a^*, may be expressed as:

$$PVNB^{a^*} = PVB^{a^*} - PV\underline{\mathbf{C}}^{a^*}$$
$$= \sum_{t=-t^a}^{T} \left(B_t^{a^*} - \underline{\mathbf{C}_t^{a^*}} \right) / (1 + d^t) \qquad 2.1$$

If there are no important benefits in terms of revenue or the like, but there are reductions in future costs, then, the PVNS for a given alternative, a^*, may be expressed as:

$$PVNS^{a^*} = \left(PVS^{a^*} \right) - PVI^{a^*}$$
$$= \sum_{t=-t^a}^{T} \left(S_t^{a^*} - I_t^{a^*} \right) / (1 + d)^t \qquad 2.2$$

If the decision maker anticipates revenues from the investment, then use the PVNB measure. If the decision maker expects costs to be reduced, then use the PVNS measure. The PVNS measure is one of the methods used in the Cybernetic Building System (CBS) case study (see Chapters 7 and 8).

2.2.2 Benefit-to-Cost Ratio and Savings-to-Investment Ratio

The benefit-to-cost ratio (BCR) and the savings-to-investment ratio (SIR) are numerical ratios whose sizes indicate the economic performance of an investment. The BCR is computed as benefits, net of future non-investment costs, divided by investment costs. The SIR is savings divided by investment costs. The SIR is the BCR method recast to fit the situation where the investment's primary advantage is lower costs. SIR is to BCR as PVNS is to PVNB.

A ratio less than 1.0 indicates an uneconomic investment; 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, 4.75 means that the investor (e.g., the general public for a public-sector research program) can expect to receive $4.75 for every $1.00 invested (e.g., public funds expended), over and above the required rate of return imposed by the discount rate.

The BCR for a given alternative, a^*, may be expressed as:

$$BCR^{a^*} = \left(PVB^{a^*} - PVC^{a^*} \right) / PVI^{a^*}$$
$$= \frac{\sum_{t=-t^a}^{T} \left(B_t^{a^*} - C_t^{a^*} \right) / (1 + d)^t}{\sum_{t=-t^a}^{T} I_t^{a^*} / (1 + d)^t} \qquad 2.3$$

The SIR for alternative *a** may be expressed as:

$$SIR^{a^*} = PVS^{a^*} / PVI^{a^*}$$

$$= \frac{\sum_{t=-t^a}^{T} S_t^{a^*} / (1+d)^t}{\sum_{t=-t^a}^{T} I_t^{a^*} / (1+d)^t} \qquad 2.4$$

As was the case for the PVNB and PVNS measures, use the BCR if the decision maker anticipates revenues from the investment, and use the SIR if the decision maker anticipates costs to be reduced. The SIR measure is the second method used in the CBS case study (see Chapters 7 and 8).

2.2.3 Adjusted Internal Rate of Return

The adjusted internal rate of return (AIRR) is the 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**, 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**, is denoted as TV^{a^*}.

The reinvestment rate in the AIRR calculation is equal to the minimum attractive rate of return (MARR), the opportunity cost of capital, 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 (e.g., benefits, non-investment costs, savings) 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**, applied to the terminal value, TV^{a^*}, 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.[15] The most convenient procedure for calculating the AIRR is based on its relationship to the BCR (SIR). This

[15]Chapman and Fuller, *Two Case Studies in Building Technology*, pp. 35-37.

procedure results in a closed-form solution for *r**. The AIRR—expressed as a decimal—is that value of *r** for which:

$$\begin{aligned} r^* &= (1+d)(BCR^{a^*})^{\frac{1}{L}} - 1 \\ &= (1+d)(SIR^{a^*})^{\frac{1}{L}} - 1 \end{aligned} \qquad 2.5$$

The AIRR measure is the third method used in the CBS case study (see Chapters 7 and 8).

2.2.4 Summary of Methods[16]

The methods presented in the previous sections provide the basis for evaluating the economic performance of research investments. 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 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 in a research environment. 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 research project/program be configured? The third type of decision builds on the second and introduces an important concept, interdependence. Many research projects/programs are multidisciplinary and are analogous to a portfolio. In addition, there may be both economies of scale (e.g., spreading out the use of specialized equipment) and of scope

[16]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).

(e.g., packaging of staff talents). Consequently, for a given set of skills, laboratory facilities, candidate projects, and implied interdependencies, the problem becomes how to choose that combination of projects which maximizes PVNB (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 PVNB (PVNS) method is appropriate in three of the four cases. Only in the presence of a budget constraint is the use of PVNB (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

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

In summary, there are several reasons why multiple measures of economic performance are necessary. First and foremost, managers want to know if a particular research project is economic. Reference to Table 2-1 shows that all of the evaluation methods address this type of decision. Furthermore, these evaluation methods may be used *ex ante* for emerging technologies as well as *ex post* for past research projects. 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 PVNB (PVNS) method emerges as the principle means for evaluating a project's or program's merits.[17] Finally, the tightening budget picture involves setting priorities. Consequently, decision makers need both measures of magnitude, provided by PVNB (PVNS), and of return, provided by either the BCR (SIR) or the AIRR, to assess economic performance. Multiple measures, when used appropriately, ensure consistency in both setting priorities and selecting projects for funding. The results from the CBS case study presented in Chapters 7 and 8 illustrate the importance of multiple measures of economic performance.

[17]If incremental values of the BCR (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.

2.3 Presentation and Analysis of the Results of an Economic Impact Assessment

The presentation and analysis of the results of an economic impact assessment 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. The purpose of this section is to outline a generic framework for economic impact studies that meets the two previously cited conditions. The generic framework is built upon the following three factors: (1) the significance of the research effort; (2) the analysis strategy; and (3) the calculation of key benefit and cost measures. A specific framework, tailored to BFRL, is given in Exhibit 2-1; it is also used as the basis for summarizing the CBS case study (see Section 7.1).

The discussion that follows relates the three factors for the generic framework referenced above to the specific framework given in Exhibit 2-1. Exposition of the generic framework serves two purposes. First, it provides a means for organizing the way to present material associated with an in-depth economic impact assessment. 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 research managers (e.g., laboratory directors) as the basis for statements on the benefits of the research project or program to the public. A two-page summary of the CBS case study is provided at the beginning of Chapter 7.

2.3.1 Significance of Research Effort

This section of an economic impact assessment sets the stage for the results that follow. The goal at this point is to clearly describe:

(1) why the research is important and how the organization conducting the research became involved; and

(2) why some or all of the changes brought about were due to the research organization’s contribution.

Emphasis is placed on providing dollar estimates to define the magnitude of the problem. If any non-financial characteristics are of key importance to senior management, list and describe them briefly. A clear tie into the research organization’s mission or vision is included to demonstrate why the organization conducting the research is well qualified and well positioned to participate in the research effort. The section concludes with a statement of the research organization’s contribution.

Exhibit 2-1. Format for Summarizing the Economic Impacts of BFRL Research Efforts

<table>
<tr>
<td>1.a Significance of Research Effort:

Describe why the research is important and how BFRL became involved.

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

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

Describe how the present value of total benefits (savings) to the nation stemming from all contributions to the research effort was determined.

Describe how the present value of total costs to the nation stemming from all contributors to the research effort was determined.

Describe how the present value net benefits (savings) to the nation was determined.

Describe how the present value of total benefits (savings) attributable to BFRL's research effort was determined.

Describe how the present value of total costs attributable to BFRL's research effort was determined.

Describe how the present value of net benefits (savings) attributable to BFRL's research effort was determined.

Describe how any additional measures were calculated and how BFRL's contribution was determined.

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) other.</td>
</tr>
<tr>
<td>3.a Calculation of Benefits, Costs, and Additional Measures:

Total Benefits (Savings):
Report the present value of the total benefits (savings) attributable to BFRL's research effort.

Total Costs:
Report the present value of the total costs attributable to BFRL's research effort.

Net Benefits (Savings):
Report the present value of net benefits (savings) attributable to BFRL's research effort.

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 Benefits (PVNB) or the Present Value of Net Savings (PVNS) attributable to BFRL and at least one of the following:

❖ Benefit-to-Cost Ratio (BCR) or Savings-to-Investment Ratio (SIR)
❖ Adjusted Internal Rate of Return (AIRR)</td>
</tr>
</table>

2.3.2 Analysis Strategy

This section of an economic impact assessment 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; and (c) the discount rate or minimum acceptable rate of return used.

Special emphasis is placed on documenting the *sources and validity* of any data used to make estimates or projections of key benefit and 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:

(1) the present value of **total benefits (savings)** to the nation stemming from all contributors to the research effort under study was determined;

(2) the present value of **total costs** for all contributors to the research effort under study, any users of the new technology under study, and any third parties affected by either the research effort or the use of the new technology was determined;

(3) the present value of **net benefits (savings)** to the nation stemming from all contributors to the research effort under study, any users of the new technology under study, and any third parties affected by either the research effort or the use of the new technology was determined;

(4) the present value of **total benefits (savings)** attributable to the research organization's contribution was determined;

(5) the present value of **total costs** attributable to the research organization's contribution was determined;

(6) the present value of **net benefits (savings)** attributable to the research organization's contribution was determined; and

(7) any **additional measures** were calculated and how the research organization's contribution was determined.

2.3.3 Calculation of Benefits, Costs, and Additional Measures

This section of an economic impact assessment focuses on reporting the calculated values of the key benefit and cost measures, as well as any additional measures that are deemed appropriate. At this point, we note that it is essential to report the calculated value of the present value of net benefits *or the present value of net savings* attributable to the research organization's contribution and at least one of the following:

(a) the benefit-to-cost ratio *or the savings-to-investment ratio*; or

(b) the adjusted internal rate of return.

Summaries (e.g., tables, graphs, comparative statistics) of the following information should also be reported:

(1) the present value of the total benefits attributable to the research organization's contribution;

(2) the present value of the total costs attributable to the research organization's contribution;

(3) the present value of net benefits attributable to the research organization's contribution; and

(4) the values of any additional measures calculated.

3. Building and Fire Research Laboratory's (BFRL's) Research on Cybernectic Building Systems

3.1 Cybernetic Building Systems: What They Are and What They Will Do

During the next ten years, building control companies, equipment and systems manufacturers, energy providers, utilities, and design engineers will be under increasing pressure to improve performance and reduce costs. One means of accomplishing this is through the development, adoption, and use of cybernetic building systems (CBSs) that integrate more and more building systems. Building systems targeted for incorporation into CBS products and services include energy management (e.g., heating, ventilation, and air-conditioning (HVAC) and lighting), fire (e.g., detection and fire fighting), security, fault detection and diagnostics, optimal control, the real-time purchase of electricity, and the aggregation of building stock for multi-facility operations. How these systems communicate, interact, share information, make decisions, and perform in a synergistic and reliable manner needs to be addressed on an industry wide basis if CBSs are to be successful and the U.S. is to obtain a significant share of the potential global market for such systems.

A CBS is defined as a multi-system configuration able to communicate information and control functions simultaneously and seamlessly at multiple levels. The configuration must also allow for two-way communication between the building(s) in which it is installed, utilities, and energy and service providers. The multiple levels of communication and control are based on the BACnet (***B***uilding ***A***utomation and ***C***ontrol ***net***works) layered protocol architecture.[18]

BFRL is working towards a fully operational CBS being tested and deployed by 2002. To achieve this goal, BFRL is working with industry (e.g., equipment and systems manufacturers, and service providers), building professionals (e.g., owners, designers, and operators), trade associations, professional societies, standards organizations, university researchers, and other government agencies (e.g., General Services Administration and the Department of Energy). Strategic partnerships for the overall CBS research, development, and deployment effort is being patterned after the NIST BACnet Interoperability Testing Consortium. The BACnet Consortium is a cooperative research and development agreement between equipment manufacturers, facilities managers, and researchers aimed at developing interoperable building control equipment communicating with the BACnet protocol (see Section 3.2.1).

The overall CBS research, development, and deployment effort is built around six key projects (see Sections 3.2.1 through 3.2.6). In addition, the overall effort includes a full-scale demonstration of a CBS.

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[18] For an overview of BACnet, see Section 3.2.1. For a description of BACnet's layered protocol architecture, see Bushby (Bushby, Steven T. 1997. "BACnet: A Standard Communication Infrastructure for Intelligent Buildings." *Automation in Construction* (Vol. 6): pp. 529-540).

A schematic for how the six key projects fit together and how BFRL will work with industry to develop CBS products and services is shown in Figure 3-1. Each of the six key projects is represented by a rectangle in the figure. These activities are undertaken and funded primarily by BFRL. Those activities undertaken by the private sector are represented by ovals in the figure. Demonstration projects are a hybrid activity, involving a broad cross-section of participants; they are represented by the rectangle with rounded edges in the figure. Unidirectional arrows or bi-directional arrows (i.e., including a feedback mechanism) represent information flows between activities. Note that the Virtual Cybernetic Building Testbed provides the mechanism through which feedback between the upper tier of BFRL projects takes place. Figure 3-1 includes a vendor tier. Because many different vendors will develop and offer commercial products and/or services, the figure uses an ellipsis (**…**) to reflect the indeterminacy of the number of vendors in the vendor tier. Figure 3-1 shows the culmination of BFRL's efforts as the demonstration projects. Once the demonstration projects are completed, the private sector moves into a full-scale market adoption process. This process will evolve over a number of years as the CBS products and services diffuse throughout the marketplace.

Prior to the deployment of fully operational CBS products and services in 2002, BFRL will produce a series of intermediate products. These products are described briefly in the series of bullets that follow:

- Develop standard communication protocols for the open exchange of information among energy providers, utilities, energy management systems, fire detection/smoke control systems, security systems, elevator controls, and service providers.

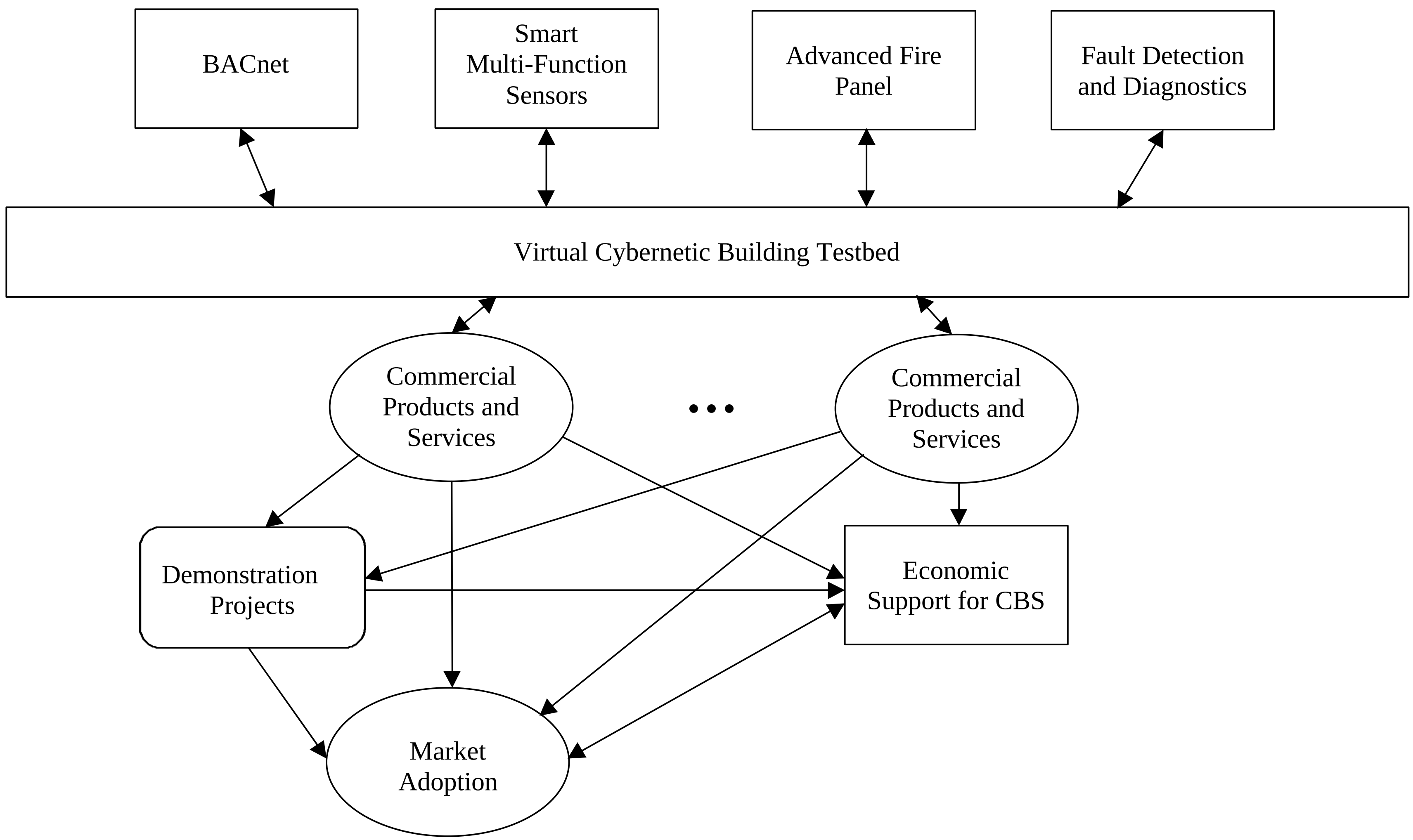
- Develop enabling technologies, such as fault detection and diagnostic methods, a hierarchical framework for control decision making, advanced operating strategies for aggregated buildings, and the application of real time fire modeling in buildings.

- Develop advanced measurement technologies, including smart multi-functional sensors.

- Develop performance measures, standards, and evaluation tools for protocol compliance testing, real time monitoring, and the evaluation and documentation of CBS interactions.

- Construct a Virtual Cybernetic Building Testbed in the laboratory to facilitate the development and evaluation of new products and systems by manufacturers and external service providers.

Figure 3-1. Flowchart of CBS Research, Development, and Deployment Effort



- Develop a Consortium of manufacturers and service providers interested in producing, testing, demonstrating, and selling CBS products and services.

- Develop interoperability testing and certification programs to facilitate the development and introduction of CBS products and services into the marketplace.

- Conduct a prospective economic impact assessment of BFRL's CBS-related research, monitor outcomes, and conduct a follow-up economic impact assessment.

- Develop and demonstrate the integration of CBS products, services, and concepts on the system/subsystem level.

3.2 Key Components of BFRL's Research on CBS

3.2.1 Building Automation and Control Networks (BACnet)

Today's direct digital control systems (DDCs) employ proprietary communication protocols that prevent systems made by different manufacturers from communicating with each other. The problem dates from the 1980s when dropping prices and rising capabilities for computer-based technologies spurred the controls industry to use digital controls. To operate these controls requires exchanging data over a network, and individual DDC manufacturers solved the communication problems in different ways. The proliferation of proprietary systems has frustrated building owners' efforts to integrate innovative products from different DDC manufacturers in ways that best suit the unique needs of their building(s). Prior to the introduction of BACnet, building owners were forced to either forego potential cost savings due to systems integration or accept a proprietary system from a single vendor that could severely limit future expansion capabilities.

BACnet is a standard communications protocol for building automation and control systems developed under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). BACnet provides a standard communications infrastructure interconnecting building automation and control devices made by different manufacturers. This makes it possible for building owners to obtain competitive upgrades to building control systems. In addition, BACnet makes possible the integration of building systems that currently stand-alone. In June 1995 BACnet was approved as an ASHRAE standard and, later, as an American national standard by the American National Standards Institute (ANSI). It has been selected as a European Community pre-standard by the European Committee for Standardization. Today, there are over 4,000 installed systems running BACnet in at least 16 countries.

In 1996, the largest federal building west of the Mississippi River, the Phillip Burton Federal Office Building in San Francisco, was selected by the General Services

Administration (GSA) for the first large-scale demonstration of BACnet among multiple vendors.[19] BFRL provided technical assistance to GSA for this project including technical review of the control system design and specifications, laboratory testing of the BACnet capabilities of the products to be used in the building, and on site commissioning support. BFRL has also been collecting and analyzing network traffic data to document how BACnet performs in large control systems. Phase II of the project, retrofit of the control systems for the air handling units and over 1300 variable air volume (VAV) box controllers, was completed in 1998 and the multi vendor BACnet control system is fully operational. Phase III when underway will expand the BACnet system to a new central plant facility and connect the control system in this building with other GSA buildings. This will provide centralized access to energy consumption and system performance data, and prepare GSA for aggregating utility loads in a deregulated marketplace.

BACnet work is expanding beyond the HVAC realm. BFRL is working with the National Electrical Manufacturers Association (NEMA) and the National Fire Protection Association (NFPA) to extend BACnet to fire protection products. NEMA has endorsed BACnet as the industry's recommended method of integrating security and fire alarm systems with other building control systems. The first commercial BACnet fire system products will be introduced within the next two years. New features are being added to the protocol that will enhance the use of BACnet in life-safety systems. For example, some day “smart elevators” may be able to tap into HVAC control and fire detection systems so, if there is a fire, elevators can be used to help evacuate people in a safe and efficient manner.

To date, BFRL has entered into cooperative research and development agreements with 22 partners to develop interoperable building control equipment that communicates using the BACnet protocol. The objective of the consortium is to assist the member companies in developing products that conform to the BACnet standard and to develop conformance-testing tools and procedures that can be used to establish an industry-run certification program. BFRL has developed test methods and software testing tools and provided facilities for member consortium companies to bring their prototype products together for testing.

The Visual Test Shell (VTS) is a BFRL developed software tool for testing building control products for conformance to the BACnet standard. VTS is now being used by manufacturers who are developing BACnet products. The testing procedures implemented in VTS have become the basis for a draft addendum to the BACnet standard that defines a conformance test suite. A revised version of this tool, which runs in a Windows95 or WindowsNT environment, was released in 1998. Development of the testing tool will continue in parallel with an ASHRAE addendum to the BACnet standard which will define conformance-testing procedures for BACnet.

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[19] Applebaum, Martin A., and Steven T. Bushby. 1998. “The 450 Golden Gate Project: The World’s First Large-Scale Use of BACnet.” *ASHRAE Journal* (July): pp. 23-30.

3.2.2 Smart Multi-Function Sensors

The United States currently spends billions of dollars annually to install and maintain systems in buildings to assure safety from unwanted fires. A major opportunity for cost savings is to reduce both these expenditures and fire-related losses through the introduction of new products. Smart multi-function sensors will permit fire and indoor air quality (IAQ) sensor designers to demonstrate the feasibility of new concepts, to provide the critical link between sensor input and output required for meaningful numerical simulations, and to improve the reliability and performance of fire detection systems.

Test protocols and certification processes have been developed to accommodate specific fire sensor technologies. In the past, the sources used in these test methods were optimized for a unique fire or smoke property to quantify detector response. Very little has been done to determine the impact of test methods on the development of innovative IAQ sensors. To improve detection sensitivity and reduce inappropriate responses, the industry has developed new sensor designs based on the measurement of different aspects of the fire source, or on specific combinations of sensors that can help in distinguishing a real fire from an interfering background signal. Existing test methods are unable to evaluate and quantify the performance of the new sensing systems needed for monitoring and predicting the changing environment as part of a CBS.

BFRL is working with the IAQ and fire sensing industries to identify the state of the technology, the opportunities for sharing information among fire and other building control systems, and the advantages and barriers hindering the adoption of emerging technologies (e.g., micro-electronic gas sensor arrays and wireless communication sensing). Emerging sensing technologies for duct and ceiling air velocity and pressure differences between adjacent rooms will also be examined. Efforts will be aimed at demonstrating the advantages of multi-function sensors (e.g., using the output of an existing CO_2/IAQ sensor to help define the fire/non-fire state or the movement of fire gases) and multi-sensor (e.g., using the output from CO, temperature, and smoke sensors to distinguish nuisance sources from threatening fires). This will include the use of such sensors for improving the reliability and performance of fire detection systems through earlier detection of small fires, and the reduction in both false negatives (i.e., reported fires that do not exist) and false positives (i.e., unreported fires). A standard means for evaluating the response of fire and IAQ sensors, including exposure to nuisance sources, will be developed and offered for adoption to industry. Water vapor condensation is thought to be a major source of false negatives, but is also a useful marker for the environmental state. A means for assessing a sensor’s response to water vapor will be explored. Full-scale room tests will be conducted to determine the environment adjacent to the detector, and the fire-emulator/detector-evaluator will be programmed to reproduce those conditions.

3.2.3 Advanced Fire Detection and Alarm Panels

As noted earlier, the United States currently spends billions of dollars annually to install and maintain systems in buildings to assure safety from unwanted fires. A major opportunity for cost savings is to reduce both these expenditures and fire-related losses through the introduction of new products. Advanced fire detection and alarm panels have the potential to revolutionize the way building fires are detected, located, and fought by fire-fighting personnel.

Advanced fire detection and alarm panels, when fully developed and deployed, will isolate the location of a fire in a building and predict the short and long term behavior and effects of fire growth and smoke spread in the building. Development and deployment of the advanced fire detection and alarm panels will be facilitated through a strategic coalition with the detection industry, the National Electrical Manufacturers Association, and the National Fire Protection Association.

To date, BFRL has developed an advanced model of fire growth and smoke spread in buildings. As sensor use in buildings becomes more widespread, it is possible to use this information as input to the BFRL model to detect and predict the evolution of a fire in a building. Work is currently underway to orient the BFRL model so the inputs are based on building plans, the contents of the buildings, and sensor data. As a result, model inputs can be specified both for current building systems and for more advanced systems (e.g., those using the BACnet protocol). As the sensor suite becomes more extensive and provides more information, model predictions can be refined to provide greater detail and more reliable predictions for longer time intervals.

The advanced fire detection and alarm panels and their associated models and algorithms will provide continuous estimates of the state of a building, enabling smart sensing to reduce false alarms and to produce both short and long term predictions for purposes of escape and rescue. For very large facilities, this would enable a measured response so those incidents can be isolated and contained without general interruption of business. It is important to verify the algorithms developed for the advanced fire detection and alarm panels and to test them under a variety of adverse conditions to minimize false negative reports. Elimination of both false negatives and false positives will be a high priority. The algorithms employed will use sensor data to start the predictive models, and then refine the prediction, as additional information becomes available. An important aspect of this approach is the knowledge of what information sensors are reporting. For example, analog information is available from the sensors, but a better understanding is needed of how different sensors respond to the ambient environment. This effort will require development of a standard test method to obtain these data for use in the sensor-driven models and to quantify the response of single and multi-function building sensors to thermal, flow, gas, and particulate loadings.

3.2.4 Fault Detection and Diagnostic Systems with Hierarchical Controls

Today's building energy management systems have the capability to monitor and log operating data for thousands of measurement and control points. These capabilities routinely exceed the capabilities of building owners and operators to process and understand the data. Consequently, HVAC equipment frequently operates under the influence of faults that go undetected. The faults lead to energy waste, occupant discomfort, and shorter equipment life. Building energy management systems need to be equipped with intelligent fault detection and diagnostic (FDD) tools to enable building operators to ensure that HVAC systems are operating as expected. These FDD tools will detect problems (i.e., faults) as they occur, determine what component or system is failing or has failed, and recommend maintenance and repair procedures. These FDD tools can then be incorporated into either the building energy management system, the building equipment, or into stand-alone systems dedicated to fault detection and diagnostics.

In 1998, BFRL completed the development of a prototype FDD Test Shell. The FDD Test Shell is a platform based on Microsoft Windows dynamic data exchange (DDE) that facilitates the integration of FDD modules (e.g., data, reference models, and possibly multiple FDD methods) developed in any application development environment that supports DDE. The FDD Test Shell can accept data from an experimental rig, a simulation model, or a file containing columns of data. Part of this data might be used to drive reference model modules that provide expected values of variables or parameters to the FDD Test Shell. The differences (i.e., residuals) between the data and the reference model values are computed automatically and made available to FDD methods that operate on the residuals and present results on their individual user interfaces. FDD methods can also access the unprocessed data provided to the Test Shell by the data source. The modular architecture provides a structured way for researchers to share data, models, and methods. Annex 34 participants[20] have adopted the FDD Test Shell as a working tool, and seven countries, including 11 separate institutions, have committed to use the FDD Test Shell or to test their FDD methods with shared data sets.

During 1999, BFRL will extend the FDD Test Shell to include a module for evaluating and comparing the output of FDD methods. In addition, a front-end program will be written that will allow BFRL's HVACSIM$^+$ program[21] to be a data source for the FDD Test Shell. Finally, effort will begin on integrating FDD methods into a hierarchical framework that coordinates operational information from various subsystems (e.g., VAV boxes and air handling units). In its completed form, the FDD Test Shell is envisioned as a platform that will accept data from various sources, allow different modules to be written in a variety of programming languages, and synthesize information obtained from the various FDD methods in a logical manner.

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[20] International Energy Agency Annex 34 Committee on Computer-Aided Evaluation of HVAC System Performance: The Practical Application of Fault Detection and diagnostics Techniques in Real Buildings.

[21] Park, Cheol, Daniel R. Clark, and George E. Kelly. 1985. "An Overview of HVACSIM$^+$, A Dynamic Building/HVAC/Control Systems Program." *Proceedings of the 1st Annual Building Energy Simulation Conference*: pp.175-185.

By 2002, the knowledge gained by integrating and synthesizing multiple FDD methods in the FDD Test Shell will be used to develop a hierarchical architecture for CBSs that will allow various CBS functions (e.g., energy management, fire detection, elevator control, system optimization, building aggregation, and the real time purchase of electricity) to work together. Both expert systems and fuzzy logic will be studied to address the problem of "command fusion" (i.e., command coordination). The latter approach converts command fusion into a logic of graded preferences with each control function portrayed as an agent expressing "preferences" that suggest which command to apply. Fuzzy operators are used to combine the various preferences and to generate a single control choice based on multiple trade-offs. Fuzzy logic can also be used to develop "meta-rules" to describe and implement strategies for high-level control arbitration.

BFRL is initiating work with industrial partners and other control manufacturers to verify the proper performance of prototype FDD products. In conjunction with this testing, BFRL will begin an FDD demonstration project at the Phillip Burton Federal Office Building or other suitable site. By 2001, FDD methods are expected to begin to be implemented in energy management and control system products. By 2002, some of these methods are projected to begin to be implemented in other building control products.

3.2.5 Virtual Cybernetic Building Testbed

With the increasing pressure to integrate more and more building control systems and services, there is a need to be able to test and evaluate the complex interactions that are likely under both normal and adverse (e.g., emergency) operating situations. In addition, there is a need to assist control manufacturers and service providers in the development, testing, and certification of new products. Due to the complexity of the systems involved and the need to maintain a comfortable and safe building occupant environment at all times, these tasks can not be accomplished using real buildings. However, these tasks can be done through simulation/emulation. The establishment of a Virtual Cybernetic Building Testbed (VCBT) will enable manufacturers to bring the actual control products under development, obtain assistance in testing and evaluating their performance, and perform interoperability tests with other manufacturers.

When fully deployed in 2001, the VCBT will consist of a variety of simulation models emulating the performance of a typical CBS. The simulation models will be interfaced with real state-of-the-art and prototype BACnet compliant control systems to provide a hybrid software/hardware testbed. The testbed will be used by NIST researchers, control manufacturers, service companies, and software developers to develop and evaluate control strategies and control products that use the BACnet communication protocol. The VCBT is designed to emulate the performance of both fault free and fault containing building heating and cooling equipment, different HVAC systems, and the building shell. In addition, lighting, vertical transport systems, and other services would be emulated. An advanced graphical user interface is being developed along with remote accessibility

to the VCBT through various communication interfaces, including telephone and the Internet.

The VCBT will combine BFRL's extensive experience with the modeling and simulation of buildings, HVAC systems, controls, and fires with the Manufacturing Engineering Laboratory's (MEL’s) expertise in the area of systems integration, object oriented programming, the use of a Common Object Request Broker Architecture (CORBA), advanced information models and data bases, and the Virtual Reality Modeling Language (VRML). It will make use of MEL's ATM (asynchronous transfer mode) network to exchange information among the various VCBT components in real time and will allow for both on-site and remote use of the VCBT by NIST customers.

The development and deployment of the VCBT is divided into four phases. Phase I, which was completed in 1998, involves the development of an HVAC emulator to simulate the performance of a VAV air handling unit, three VAV boxes, and three building zones using BFRL's HVACSIM$^+$ program. Phase II, which will be completed in September 1999, involves development of a building shell emulator, a fire emulator, a more complex HVAC emulator, a building/HVAC Product Model, and a VRML based interactive VCBT display. The various VCBT components, which will be in different NIST locations, will use the CORBA paradigm to provide a real time, distributed emulation environment based on message passing between objects and client-server programming. The last two phases will involve the enhancement of the VCBT front-end and the expansion of the VCBT to include the emulation of additional building services, fault containing systems, and other services likely to be provided by outside service companies.

The VCBT will be used by researchers at NIST and other organizations to study the complex interactions that occur as a result of integrating different building services and systems. Of particular interest is the impact of integrating fire detection, smoke control, transportation, HVAC, and energy management systems on life safety. The extension of the BACnet protocol to cover lighting, fire detection, transportation, and other services will be facilitated by the availability of the VCBT as a testbed for testing and evaluating changes to the BACnet standard. The VCBT will also be used by manufacturers of building controls and future CBS products to develop and test algorithms, evaluate the performance of new products, and perform interoperability testing with other manufacturers. The existence and use of the VCBT by newly developing service companies will facilitate the development of new building services, such as fault detection and diagnosis, automated commissioning, building system optimization, and predictive maintenance.

The VCBT will allow BFRL and ASHRAE to more quickly and reliably extend the BACnet standard to cover non-HVAC services. By helping building researchers better understand the interaction between different building control systems, the VCBT will facilitate the development of new national and international standards for integrating these systems in a manner that will enhance life safety, increase reliability, and result in more efficient operation and enhanced building system performance.

3.2.6 Economic Support for Cybernetic Building Systems

CBS products and services are one means to improve the performance of building systems and to reduce the costs of these systems. But investments in and the use of CBS products and services will be forthcoming only if industry perceives that the economic benefits outweigh the costs of using such products and services. Being able to demonstrate net economic savings from using CBS products and services will encourage their acceptance and use. Economic support for the overall CBS effort addresses the need for information on the economic consequences of investing in CBS products and services in two distinct ways.

First, the Office of Applied Economics (OAE) will conduct an *ex ante* (i.e., prospective) economic impact assessment of BFRL's CBS-related research, monitor outcomes, and conduct a follow-up economic impact assessment. The subject of this report is the *ex ante* economic impact assessment. OAE will also design and create a database for compiling information on CBS-related impacts. Once the database is in place, OAE will monitor outcomes and compile information on CBS-related impacts in preparation for the follow-up economic impact assessment.

Second, OAE will develop user-friendly, decision-support software to facilitate the economic evaluation of CBS products and services and the identification of cost-effective levels of investment in these products and services. To make cost-effective choices for investments in CBS products and services, decision makers must have data on benefits and costs associated with these products and services, information on who bears the costs and reaps the benefits, and tools (methods and software) for measuring those benefits and costs. Having a package of economic tools that helps users and stakeholders identify and measure the benefits and costs of choosing between CBS products and services and traditional products and services will accelerate the introduction and acceptance of CBS products and services in the U.S. and abroad. Thus, OAE will produce an integrated software package providing life-cycle cost (LCC) measurement capabilities for evaluating CBS products and services. To assure industry acceptance of the software package, it will be made consistent with ASTM's LCC standard practice, E 917. Once the software package has been finalized, OAE will seek out a private-sector collaborator to market, distribute, and maintain the decision support software package.

4. Market for CBS Products and Services

The construction industry is a key component of the US economy and is vital to its continued growth. Investment in plant and facilities, in the form of construction activity, provides the basis for the production of products and the delivery of services. Investment in infrastructure promotes the smooth flow of goods and services and the movement of individuals. Investment in housing accommodates new households and allows existing households to expand or improve their housing. Clearly, construction activities affect nearly every aspect of the US economy.[22]

This chapter provides a snapshot of the US construction industry. As such, it provides the context within which the scope and size of the market for CBS products and services is defined. The chapter contains three sections. Each section deals with a particular topic. The topics progress from general in nature to very specific. This progression is described below.

Section 4.1 presents information on the value of construction put in place to show the size of the construction industry and each of its four sectors. The four sectors, which taken together define the construction industry, are residential, commercial/institutional, industrial, and public works. Data from the past five years (i.e., 1993 through 1997) are used to highlight the magnitude of construction-related investments in each sector. Data from 1997 are then used to establish the relative shares of construction-related investments for each sector.

Section 4.2 uses information on the commercial/institutional sector ***both*** to focus on its importance within the overall construction industry ***and*** to define its key components. Information on investment activity, the number of commercial/institutional buildings, and the amount of commercial/institutional floorspace is used to identify both those characteristics that are changing and those that are remaining constant. Office buildings are a key component of the commercial/institutional sector. Information showing the relative share of construction-related investments in office buildings vis-à-vis the other components of the commercial/institutional sector is also presented.

Section 4.3 places special emphasis on identifying and detailing the key characteristics of office buildings. Office buildings are considered the most likely market for CBS products and services. Consequently, information detailing key characteristics (e.g., building floorspace and year of construction) is needed to define the scope and size of the market for CBS products and services in office buildings. Detailing the key characteristics of office buildings is crucial, because investments in CBS products and services affect not only new construction activities but additions and alterations and maintenance and repair activities as well. Ways in which these key characteristics affect the calculation of CBS-related benefits and costs are discussed in Chapter 6.

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[22] Readers interested in learning more about construction statistics, their sources and interpretation, are referred to the document by Rogers (Rogers, R. Mark. 1994. *Handbook of Key Economic Indicators*. Burr Ridge, IL: Irwin Professional Publishing).

4.1 Value of Construction Put in Place

This section provides information on a key indicator of construction activity; the value of construction put in place. Data published by the US Bureau of the Census are used to establish the composition of construction expenditures by type of construction/function (e.g., non-residential/office building). These expenditures are then assigned to the four key construction industry sectors. The reference document used throughout this section is the Current Construction Reports series C30 publication Value of Construction Put in Place.[23] A brief description of the "C30 report" follows. Special attention is given to the organization of the data in the C30 report and how these data map into the four key construction industry sectors. The section concludes with tabular and graphical summaries of the value of construction put in place.

Construction expenditures data are published monthly in the Current Construction Reports series C30 publication Value of Construction Put in Place. Construction expenditures refer to actual construction rather than planned or just initiated activity. It is noteworthy that the C30 report covers both private residential and non-residential construction activities and public sector construction activities.

The value of construction put in place is a measure of the value of construction installed or erected at a site during a given period. For an individual project, this includes: (1) cost of materials installed or erected; (2) cost of labor and a proportionate share of construction equipment rental; (3) contractor's profit; (4) cost of architectural and engineering work; (5) miscellaneous overhead and office costs chargeable to the project on the owner's books; and (6) interest and taxes paid during construction. Expenses do not include the cost of land nor do they include maintenance and repairs to existing structures or service facilities.

The C30 data are compiled via survey and through indirect estimation. In the context of the C30 survey, construction includes the following: (1) new buildings and structures; (2) additions, alterations, conversions, expansions, reconstruction, renovations, rehabilitations, and major replacements (e.g., the complete replacement of a roof or a heating system); (3) mechanical and electrical installations (e.g., plumbing, heating, electrical work, and other similar building services); (4) site preparation and outside construction of fixed structures or facilities (e.g., sidewalks, highways and streets, water supply lines, sewers, and similar facilities which are built into or fixed to the land); (5) installation of boilers, overhead hoists and cranes, and blast furnaces; (6) fixed, largely site-fabricated equipment not housed in a building (e.g., petroleum refineries and chemical plants); and (7) cost and installation of construction materials placed inside a building and used to support production machinery (e.g., concrete platforms, overhead steel girders, and pipes).

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[23] US Department of Commerce. 1998. *Current Construction Reports: Value of Construction Put in Place*. ***C30***. Washington, DC: US Bureau of the Census.

The data presented in the C30 report are summarized in Tables 4-1 and 4-2. To facilitate comparisons between this report and the C30 report, Tables 4-1 and 4-2 use the same row and column headings as are used in the C30 report.

Tables 4-1 and 4-2 record annual values for the years 1993 through 1997. Table 4-1 records annual values in millions of constant 1992 dollars. Table 4-2 records annual values in millions of current dollars.[24] Reference to Table 4-1 reveals that total construction expenditures in real terms have increased modestly over the five-year period (i.e., from $461.1 billion to $520.1 billion). When the effects of inflation are included, the rate of increase appears more pronounced. Table 4-2 shows total construction expenditures in current dollars.

Tables 4-1 and 4-2 are organized to allow for in-depth analyses of the components/subcomponents of total construction expenditures. To facilitate such analyses, the data presented in Tables 4-1 and 4-2 are initially divided into two parts: (1) private construction; and (2) public construction.

Private construction contains two major components--residential buildings and non-residential buildings--plus a number or subcomponents. Both the two major components and the various subcomponents are shown as headings in the first column of Tables 4-1 and 4-2.

The residential buildings component includes new private housing and improvements. New private housing includes new houses, apartments, condominiums, and town houses. New private housing units are classified as "1 unit" or "2 or more units." The value of improvements put in place are a direct measure of the value of residential additions and alterations activities.

The non-residential buildings component includes industrial, office buildings, hotels and motels, and "other commercial" (e.g., shopping centers, banks, service stations, warehouses, and other categories). Also falling under the non-residential buildings component are religious, educational, hospital and institutional, and "miscellaneous" non-residential buildings.

[24] 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.

Table 4-1. Value of Construction Put in Place in Millions of Constant 1992 Dollars

Type of Construction	VALUE OF CONSTRUCTION PUT IN PLACE (SERIES C30) Constant (1992) Dollars				
	1993	1994	1995	1996	1997
Total construction	***461,078***	***480,620***	***478,069***	***506,655***	***520,117***
Private construction	**347,851**	**367,247**	**360,040**	**385,967**	**395,321**
Residential buildings	200,502	218,005	201,677	220,017	221,546
New housing units	137,243	153,250	142,413	153,966	156,038
1 unit	126,960	140,416	126,773	136,516	137,156
2 or more units	10,283	12,833	15,640	17,450	18,882
Improvements	63,259	64,755	59,264	66,052	65,508
Nonresidential buildings	106,729	111,416	120,627	131,188	139,067
Industrial	25,554	26,803	29,043	28,503	26,440
Office	20,197	20,553	22,891	24,329	27,631
Hotels, motels	4,405	4,308	6,351	9,521	10,741
Other commercial	31,292	34,756	38,098	42,042	42,748
Religious	3,748	3,584	3,864	3,955	4,951
Educational	4,484	4,471	4,908	5,880	7,101
Hospital and institutional	12,050	11,377	10,051	10,280	11,576
Miscellaneous	5,000	5,565	5,421	6,677	7,880
Farm nonresidential	3,271	2,990	2,692	3,319	3,329
Public utilities	34,120	32,074	32,401	29,286	29,448
Telecommunications	9,468	9,785	10,073	10,245	9,918
Other public utilities	24,652	22,289	22,328	19,041	19,529
Railroads	3,056	3,186	3,201	3,894	4,321
Electric light and power	15,096	13,877	12,656	9,914	10,545
Gas	5,536	4,308	5,637	4,330	3,820
Petroleum pipelines	965	918	834	903	843
All other private	3,229	2,763	2,643	2,156	1,931
Public construction	**113,227**	**113,373**	**118,029**	**120,688**	**124,796**
Buildings	46,813	45,728	49,683	51,119	53,515
Housing and redevelopment	3,833	3,495	3,928	3,958	4,055
Industrial	1,658	1,358	1,348	1,214	842
Educational	18,465	18,838	20,800	21,035	22,786
Hospital	3,579	3,663	3,871	4,050	4,247
Other	19,279	18,373	19,737	20,863	21,585
Highways and streets	34,164	36,219	35,303	36,483	38,605
Military facilities	2,405	2,196	2,728	2,317	2,223
Conservation and development	5,771	5,996	5,779	5,335	4,841
Sewer systems	8,622	8,199	8,557	9,260	8,951
Water supply facilities	4,868	4,237	4,695	5,187	5,393
Miscellaneous public	10,583	10,799	11,284	10,987	11,267

Table 4-2. Value of Construction Put in Place in Millions of Current Dollars

Type of Construction	VALUE OF CONSTRUCTION PUT IN PLACE (SERIES C30) Current Dollars in Millions				
	1993	1994	1995	1996	1997
Total construction	***478,648***	***519,539***	***538,134***	***583,638***	***618,217***
Private construction	**362,688**	**399,346**	**407,477**	**446,306**	**471,159**
Residential buildings	210,455	238,874	230,688	256,460	265,610
New housing units	144,071	167,919	162,898	179,448	187,075
1 unit	133,282	153,838	145,009	159,124	164,444
2 or more units	10,788	14,081	17,889	20,324	22,631
Improvements	66,384	70,955	67,790	77,012	78,535
Nonresidential buildings	110,635	120,285	135,022	150,350	165,146
Industrial	26,482	28,947	32,505	32,657	31,394
Office	20,920	22,178	25,613	27,886	32,816
Hotels, motels	4,565	4,648	7,112	10,912	12,752
Other commercial	32,453	37,551	42,654	48,188	50,763
Religious	3,887	3,869	4,326	4,534	5,885
Educational	4,649	4,822	5,493	6,742	8,437
Hospital and institutional	12,492	12,268	11,248	11,780	13,741
Miscellaneous	5,188	6,002	6,071	7,650	9,358
Farm nonresidential	3,392	3,226	3,014	3,804	3,956
Public utilities	34,925	34,071	35,859	33,261	34,188
Telecommunications	9,619	10,121	11,093	11,772	11,626
Other public utilities	25,306	23,950	24,766	21,489	22,562
Railroads	3,108	3,340	3,509	4,398	5,059
Electric light and power	15,567	14,918	14,049	11,211	12,144
Gas	5,645	4,694	6,279	4,865	4,390
Petroleum pipelines	986	998	929	1,015	969
All other private	3,281	2,890	2,893	2,431	2,258
Public construction	**115,960**	**120,193**	**130,657**	**137,333**	**147,058**
Buildings	48,559	49,446	55,700	58,659	63,603
Housing and redevelopment	4,011	3,835	4,491	4,614	4,861
Industrial	1,718	1,465	1,508	1,389	998
Educational	19,129	20,361	23,278	24,112	27,065
Hospital	3,710	3,951	4,332	4,638	5,042
Other	19,991	19,834	22,089	23,907	25,637
Highways and streets	34,299	37,419	38,498	41,243	45,197
Military facilities	2,453	2,318	3,011	2,634	2,620
Conservation and development	5,937	6,363	6,368	6,011	5,658
Sewer systems	8,863	8,700	9,435	10,433	10,463
Water supply facilities	5,085	4,647	5,283	5,964	6,339
Miscellaneous public	10,765	11,301	12,362	12,388	13,177

Rounding out the private construction component are farm non-residential, public utilities, and "all other private." These are generally of a non-residential nature but are not part of non-residential buildings. Farm non-residential construction includes structures such as barns, storage houses, and fences. Land improvements such as leveling, terracing, ponds, and roads are also a part of this subcomponent. Privately owned public utilities construction is categorized by industry rather than function of the building or structure. This subcomponent includes expenditures made by utilities for telecommunications, railroads, petroleum pipelines, electric light and power, and natural gas. "All other private" includes privately owned streets and bridges, sewer and water facilities, airfields, and similar construction.

For public construction, there are two major components--building and non-building. Both the two major components and the various subcomponents are shown as headings in the first column of Tables 4-1 and 4-2. The building component contains subcomponents similar to those for private construction, with educational buildings being the largest subcomponent. Expenditures for the non-building component overwhelmingly consist of outlays for highways and streets, with sewer systems being a distant second subcomponent.

To get the sector totals, each subcomponent was assigned to a sector and summed. The sector assignments are identical to those used in Chapman and Rennison.[25] The sector totals and the overall total are recorded in Tables 4-3 and 4-4. Reference to the tables reveals that sector totals vary considerably, with residential being the largest and industrial the smallest.

Table 4-3. Value of Construction Put in Place: Sector Totals and Sum Total in Millions of Constant 1992 Dollars[26]

Sector	Value of Construction Put in Place ($ Millions)				
	1993	1994	1995	1996	1997
Residential	204,335	221,500	205,605	223,975	225,601
Commercial/Institutional	125,770	128,478	138,684	151,951	164,575
Industrial	27,212	28,161	30,391	29,717	27,282
Public Works	103,763	102,483	103,390	101,011	102,658
Total - All Sectors	461,080	480,622	478,070	506,654	520,116

[25] Chapman, Robert E., and Roderick Rennison. 1998. *An Approach for Measuring Reductions in Operations, Maintenance, and Energy Costs: Baseline Measures of Construction Industry Practices for the National Construction Goals*. NISTIR 6185. Gaithersburg, MD: National Institute of Standards and Technology.

[26] Note that due to rounding the values entered in the "Total – All Sectors" row in Table 4-3, differ slightly from the values entered in the "Total Construction" row in Table 4-1.

Table 4-4. Value of Construction Put in Place: Sector Totals and Sum Total in Millions of Current Dollars[27]

Sector	Value of Construction Put in Place ($ Millions)				
	1993	1994	1995	1996	1997
Residential	214,466	242,709	235,179	261,074	270,471
Commercial/Institutional	130,376	138,710	155,230	174,153	195,452
Industrial	28,200	30,412	34,013	34,046	32,392
Public Works	105,608	107,709	113,709	114,365	119,900
Total - All Sectors	478,650	519,540	538,131	583,638	618,215

Reference to Table 4-3 reveals that the commercial/institutional sector is the only sector to have grown consistently in real terms over the entire five-year period. In real terms, expenditures in the commercial/institutional sector grew from $125.8 billion in 1993 to $164.6 billion in 1997, an increase of almost 31 percent. Real expenditures for two of the four sectors, industrial and public works, were essentially constant over the same five-year period. Real expenditures for the residential sector exhibited a cyclical pattern.

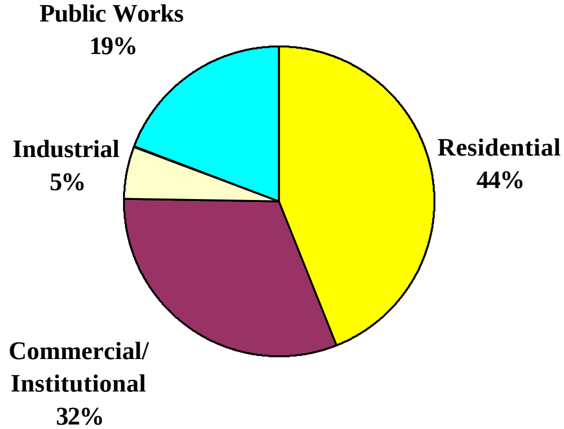
The data contained in Tables 4-3 and 4-4 provide the basis for calculating each sector's relative share of total construction expenditures. Each sector's relative share of total construction expenditures is shown graphically in pie chart form in Figure 4-1. It was constructed using 1997 data from Table 4-4 (i.e., current dollar expenditures). Reference to Figure 4-1 reveals that in 1997 the commercial/institutional sector accounted for 32 percent of total construction expenditures (i.e., 32 percent of $618.2 billion). The commercial/institutional sector's relative share of total construction expenditures is exceeded only by the residential sector, which constitutes 44 percent of the total. In addition, the commercial/institutional sector's relative share exceeds the combined total for the industrial and public works sectors.

4.2 Overview of the Commercial/Institutional Sector

The commercial/institutional sector, defined in economic terms, consists of establishments that provide services. Defined in this way, the commercial/institutional sector is extremely varied. It includes office buildings, service businesses (e.g., retail and wholesale stores, hotels and motels, restaurants, and hospitals), as well as a wide range of facilities that would not be considered "commercial" in a traditional sense (e.g., public schools, correctional institutions, and religious and fraternal organizations).

[27] Note that due to rounding the value entered in the "Total-All Sectors" row in Table 4-4 differ slightly from the values entered in the "Total Construction" row of Table 4-2.

Figure 4-1. 1997 Breakdown of $618B Construction Market



Expenditures by establishments in the commercial/institutional sector for the built environment include construction expenditures (e.g., new construction and additions and alterations) as well as expenditures for facility operations, for maintenance and repair activities, and for energy. The market for CBS products and services both affects and is affected by each type of expenditure. Consequently, it is instructive to first define what is included in each type of expenditure and then examine the characteristics of commercial/institutional buildings that affect these expenditures. This approach is aimed at producing a better understanding of the market for CBS products and services within the commercial/institutional sector.

Construction expenditures include both new construction activities and additions and alterations.

New construction activities include the complete original building of structures and essential service facilities and the initial installation of integral equipment (e.g., elevators and plumbing, heating, and air-conditioning supplies and equipment).

Additions and alterations include construction work that adds to the value or useful life of an existing building or structure, or which adapts a building or structure to a new or different use. Included are major replacements of building systems (e.g., installation of a new roof or heating system).

Facility operations include all non-process or end-product related activities required to operate a building or structure (e.g., water consumption, trash removal/environmental costs, cleaning services/janitorial, and security services/life safety costs), with the exception of maintenance and repair activities and energy. In some cases, fixed operations components may also be included (e.g., real estate and other taxes, insurance, and leasing expenses).

Maintenance and repair activities include incidental construction work that keeps a building or structure in ordinary working condition.

Energy is defined as including all non-process or end-product related energy consumption required to operate a building or structure. Energy consumption can be categorized by energy source (e.g., electricity, gas, and oil) and by end-use (e.g., space heating, cooling, and lighting).

Construction expenditures in 1997 for the commercial/institutional sector were $195.5 billion in current dollars (see Table 4-4). Total expenditures include expenditures from subcomponents listed under both the "private construction" and "public construction" headings in Tables 4-1 and 4-2. The subcomponents included under the private construction heading are: office, hotels and motels, other commercial, religious, educational, hospital and institutional, miscellaneous, and farm nonresidential. The subcomponents included under the public sector heading are: educational, hospital and other. Because the commercial/institutional sector is so varied, it is useful to group these subcomponents into a small number of key components. For convenience, these subcomponents are grouped into four key components, three of which are fairly homogeneous. The four key components are: office, educational, hospital, and other. The relative share of the overall commercial/institutional sector's construction expenditures for each of the four key components is shown graphically in pie chart form in Figure 4-2. It was constructed using 1997 data from Table 4-2 (i.e., current dollar expenditures). Reference to Figure 4-2 reveals that in 1997 the office buildings component accounted for 17 percent of the commercial/institutional sector's construction expenditures.

A recent report by Chapman and Rennison presented and analyzed information on operations, maintenance, and energy costs.[28] The commercial/institutional sector figured prominently in these analyses. Readers interested in an in-depth discussion and analysis of operations, maintenance, and energy costs in the commercial/institutional sector are referred to the report by Chapman and Rennison.[29] Wherever possible, Chapman and Rennison normalized data on a per unit area basis. If the data were sufficiently detailed, as was the case with energy data, they were classified into "bins" within which certain characteristics were homogeneous (e.g., building type, size, and age) and then normalized on a per unit area basis. Although there are a number of data sets which allow such in-depth analyses, the data associated with the Department of Energy's (DOE's)

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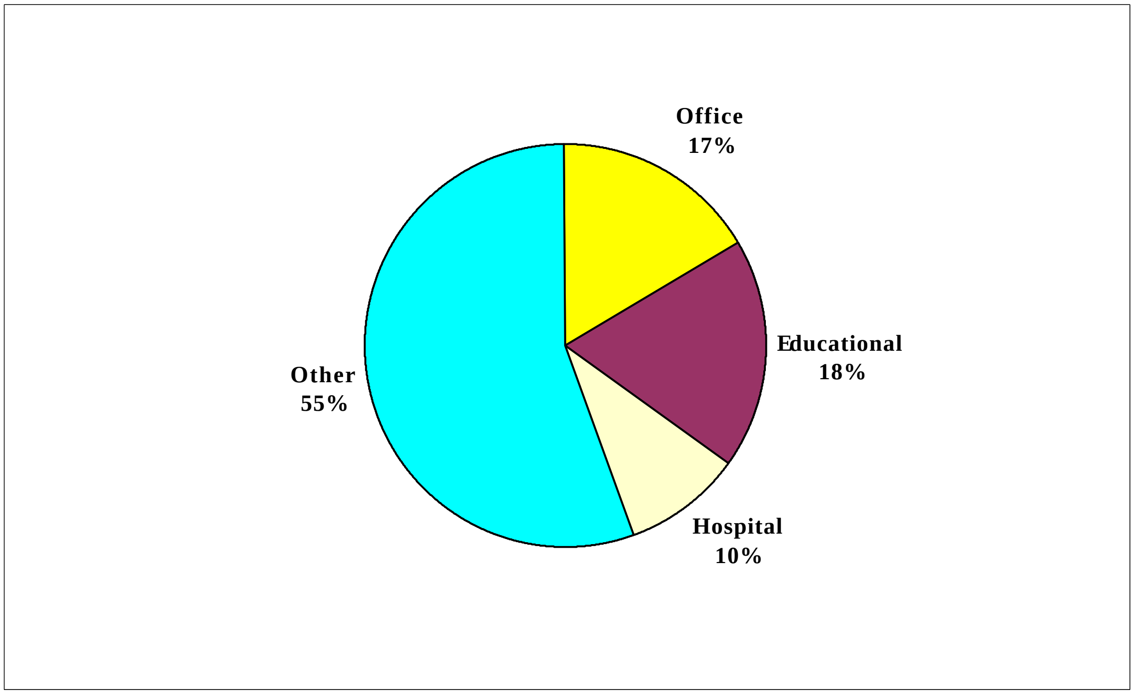
[28] Chapman and Rennison, *An Approach for Measuring Reductions in Operations, Maintenance, and Energy Costs*.
[29] *Ibid*., pp. 115-182.

Commercial Building Energy Consumption Survey (CBECS) is the source of preference for summarizing the characteristics of the commercial/institutional sector's stock of buildings.

Figure 4-2. 1997 Breakdown of $195B Commercial/Institutional Sector



The CBECS collects information on physical characteristics of commercial buildings, building use and occupancy patterns, equipment use, conservation features and practices, and types and uses of energy in buildings. The survey also collects information on the amount of energy consumed and the costs for energy in commercial buildings. The survey is conducted in two stages, the Building Characteristics Survey and the Energy Suppliers Survey. The focus of this section and the next is on the Building Characteristics Survey. Readers interested in the CBECS and its associated micro-data files are referred to Section 6.1.2.

The most recent DOE Commercial Buildings Characteristics report[30] provides detailed information on the size, age, and other characteristics of commercial/institutional buildings. In 1995, there were 4.58 million commercial buildings and 5.46 billion square meters (58.78 billion square feet) of commercial floorspace in the United States. The mean size of all commercial buildings was 1,193 square meters (12,840 square feet). The DOE report grouped buildings into eight size categories and into eight age categories. The vast majority of commercial buildings were found in the smallest size categories, with more than half in the smallest category and three quarters in the two smallest

[30] US Department of Energy. 1997. *Commercial Buildings Characteristics 1995*. DOE/EIA-E024695. Washington, DC: Energy Information Administration.

categories. Most commercial buildings, once constructed, are expected to last for decades or longer. New buildings are constructed each year and older buildings are demolished, but the commercial buildings stock at any point in time is dominated by older buildings. More than 70 percent of all commercial buildings and total floorspace were constructed prior to 1980, and more than 50 percent of buildings and floorspace were constructed prior to 1970.

The DOE report also examined whether any changes in major characteristics had occurred between 1989 and 1995. The report concluded that the profiles of major characteristics of commercial buildings showed no statistically significant changes from 1989 to 1992 to 1995, the years in which the last three surveys were conducted.[31] Significant changes between surveys would occur if characteristics in the newest buildings (i.e., those constructed since the previous survey) were quite different, or if changes were made to buildings in the existing stock. However, each three-year increment of new buildings and floorspace was generally small compared to all buildings and floorspace in a given category and the changes that did occur were not great enough to be statistically significant.

The profiles of major characteristics which showed no significant changes included the total number of buildings, the total amount of floorspace, the distribution of floorspace by principal building activity (e.g., office buildings), the distribution of buildings by size of building, and the distribution of floorspace by census region. The findings presented in the DOE report and the characteristics just referenced are of particular importance in defining the market for CBS products and services for two reasons.

First, the market for CBS products and services, or any new technology intended for use in the built environment, is dominated by the characteristics of the current building stock. Thus, the diffusion of new technologies in general, and CBS technologies in particular, must include explicit reference to the current building stock and not just to new construction. This statement is consistent with the assumption that CBS products and services will be employed both as retrofits to existing buildings and as initial installations in new buildings.

Second, DOE's findings imply that both total floorspace for the entire commercial/ institutional sector and total floorspace by principal building activity have remained constant for an extended period of time. Consequently, the total floorspace associated with each of the major components shown in Figure 4-2 has remained constant over the same period of time. If this trend continues, as seems likely, then total floorspace for each key component will continue to remain constant. It is important to note that during the period covered by the last survey the commercial/institutional sector experienced steady growth in construction expenditures relative to the rest of the construction industry. Even during this period of growth, total floorspace in the commercial/ institutional sector remained constant.

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[31] *Ibid*., p. vii. and p.10.

The choice to adopt a new technology is driven by a number of factors. These factors are discussed in some detail in Section 6.4.5. However, one factor that is of particular importance to decision makers considering investments in new technologies is the ability of those technologies to reduce costs. Clearly, cost reductions have an immediate impact on the bottom line and thus are reflected on the "corporate" balance sheet. In the case of office buildings, expenditures for facility operations, for maintenance and repair activities, and for energy are dwarfed by expenditures for employees' wages and salaries.[32] Thus, any investments which have the potential both to reduce expenditures for facility operations, for maintenance and repair activities, and for energy and to increase productivity will have a doubly beneficial impact on the bottom line. As is shown in Chapter 5, CBS products and services offer such an opportunity in the office buildings component of the commercial/institutional sector. Although such a doubly beneficial impact will probably result for the other key components of the commercial/ institutional sector, office buildings are considered more likely candidates for early adoption of CBS technologies. Consequently, this impact assessment adopts a conservative approach in defining the scope of the market for CBS products and services to be the office buildings component of the commercial/institutional sector. The next section defines the size of the market for CBS products and services by detailing information on key office building characteristics.

4.3 Characteristics of Office Buildings

The previous section concluded with a market scope statement. This section demonstrates how that market scope statement is translated into a specific statement of market size. To better understand both the scope and size of the CBS market, it is useful to examine in some detail the characteristics of office buildings.

In 1995, there were 705,000 office buildings in the United States. Collectively, these 705,000 office buildings had 973 million square meters (10,478 million square feet) of floorspace. Office buildings, which include some of the largest commercial buildings in the United States, had a mean size of 1,384 square meters (14,900 square feet).[33] A common image of an office building is the multi-story building that dominates the skyline of the central business district. However, the key category of office buildings is actually dominated by smaller buildings. These smaller office buildings bring the mean size of all office buildings close to the mean size of all commercial/institutional buildings (1,193 square meters (12,840 square feet)).

Figures 4-3 through 4-8 provide detailed snapshots of the nation's stock of office buildings. In each figure, information is classified along one of two major dimensions, either by building size, measured in terms of total floorspace, or by building age,

[32] Wright, Richard N., Arthur H. Rosenfeld, and Andrew J. Fowell. 1995. *National Planning for Construction and Building R&D.* NISTIR 5759. Gaithersburg, MD: National Institute of Standards and Technology.
[33] *Commercial Buildings Characteristics 1995,* p. 5.

measured in terms of year of construction. Each set of figures (e.g., Figures 4-3, 4-4, and 4-5) uses the same bar chart format to facilitate comparisons of characteristics.

Figures 4-3, 4-4, and 4-5 record the distribution of the number of office buildings and total office floorspace by building size. All three figures use the same eight size categories specified in the DOE report. The DOE size categories are specified in customary units; they range from 1,001 square feet to 5,000 square feet (93.0 square meters to 464.5 square meters) for the smallest size category to over 500,000 square feet (over 46,451.5 square meters) for the largest size category. The eight size categories, as defined in this section, are used throughout this report. To facilitate reference to the DOE report, customary units are shown on the left-hand axis and SI units on the right-hand axis of each figure.

Figure 4-3 records the distribution of the number of office buildings by building size. Figure 4-3 shows clearly why smaller buildings dominate the key category of office buildings. More than half of the stock of office buildings (406,000 of 705,000) is contained in the smallest size category, and more than three quarters (538,000 of 705,000) in the two smallest size categories. By contrast, only 16,000 buildings are contained in the three largest size categories, and only 1,000 in the largest category.

Figure 4-4 shows a very different snapshot of the stock of office buildings than was seen in Figure 4-3. Figure 4-4 records the distribution of total floorspace by building size. When the total floorspace associated with each size category is tabulated, the floorspace in the largest category, which contains 1,000 buildings, exceeds the floorspace in the smallest category, which contains 406,000 buildings. Furthermore, the two smallest size categories, which contain more than three quarters of the office building stock, have the two smallest amounts of floorspace. Total floorspace in these categories is approximately one sixth of the total floorspace of all office buildings.

Figure 4-5 introduces an additional characteristic, the number of floors in the building. This characteristic serves to sharpen the distinctions between the buildings in each size category. Figure 4-5 uses the same classification scheme as employed in the DOE report. DOE grouped office buildings into one of five categories, based on the number of floors. These categories are one floor, two floors, three floors, four to nine floors, and ten or more floors. Each floor category is coded by shading; a legend is provided on the figure to match the floor category to a specific bar in each of the eight size categories. Figure 4-5 shows clearly how the distribution of total floorspace shifts as building size increases. For example, buildings with one and two floors dominate total floorspace in the two smaller size categories. As building size increases, the total floorspace in buildings with four or more floors rises quickly.

Figure 4-3. Total Number of Office Buildings by Size Category: 1995

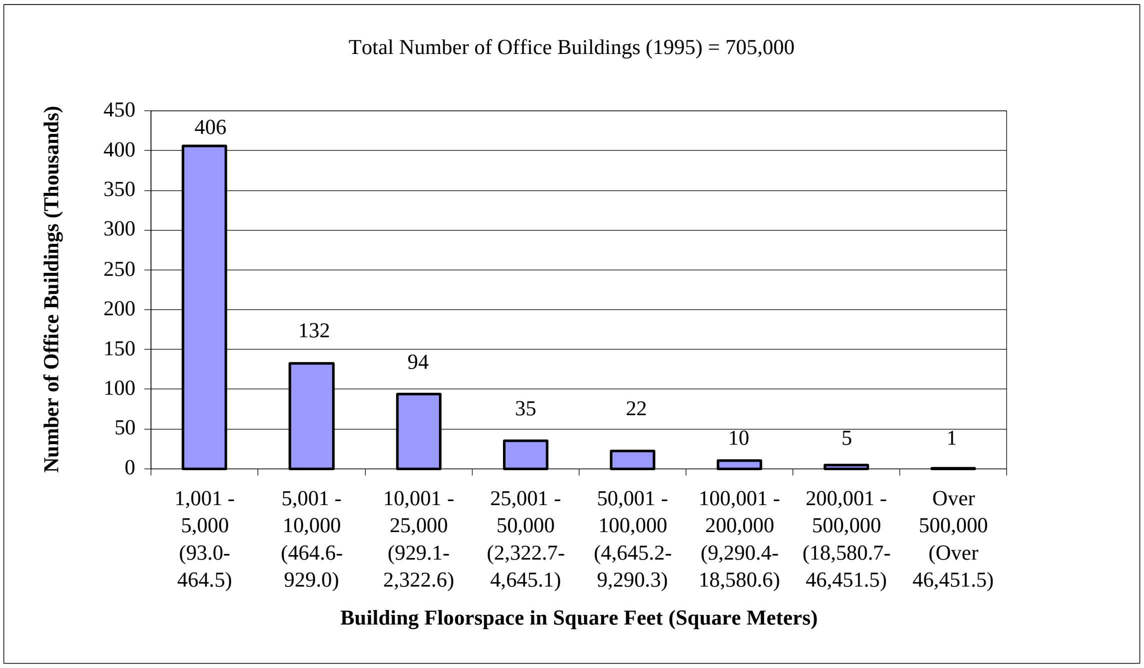


Figure 4-4. Total Office Floorspace by Building Size Category: 1995

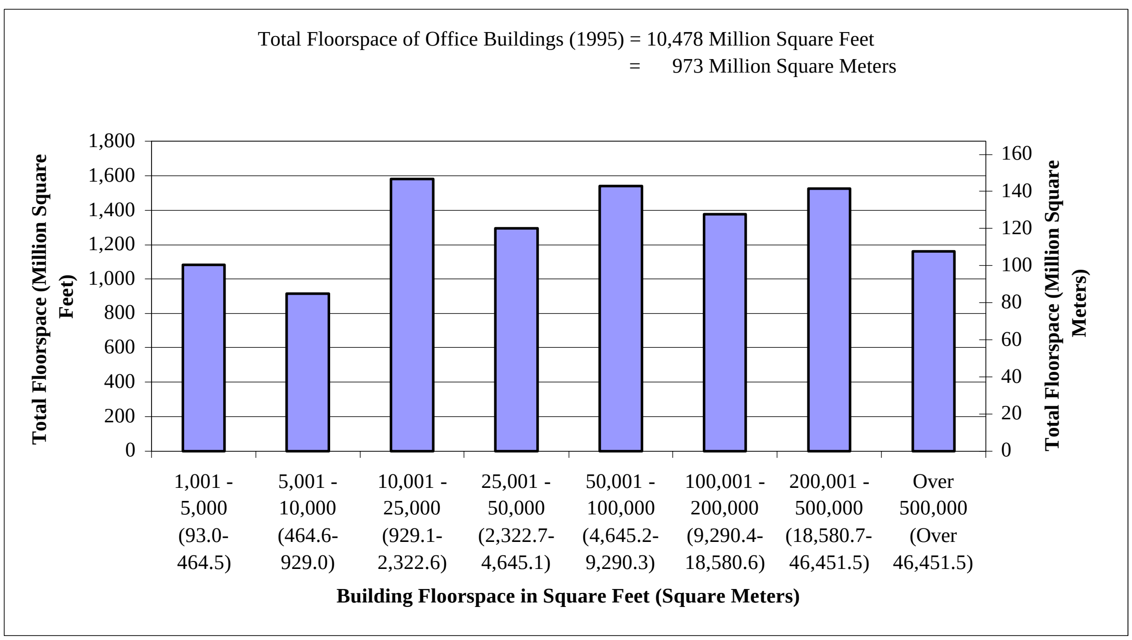
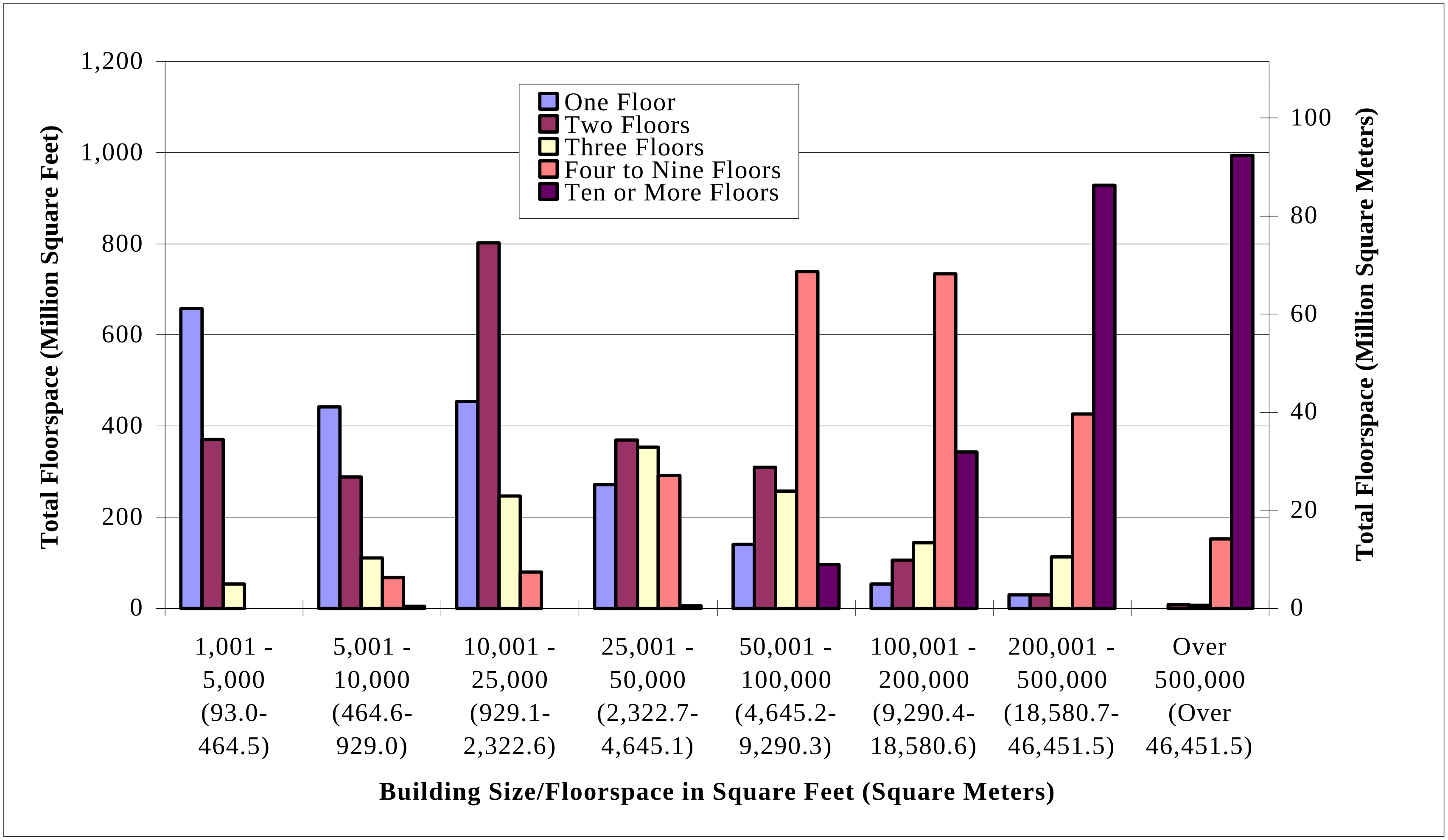


Figure 4-5. Total Office Floorspace by Building Size Category and Number of Floors: 1995



Figures 4-6, 4-7, and 4-8 record the distribution of the number of office buildings and total office floorspace by year of construction. All three figures use seven year of construction (i.e., age) categories. It is important to note that these seven year of construction categories differ from the eight year of construction categories specified in the DOE report. This is because the last two DOE year of construction categories have been combined. The last two DOE year of construction categories were 1990 to 1992 and 1993 to 1995. These categories were combined to form the 1990 to 1995 year of construction category. The year of construction categories used are 1919 or before, 1920 to 1945, 1946 to 1959, 1960 to 1969, 1970 to 1979, 1980 to 1989, and 1990 to 1995. The seven year of construction categories, as defined in this section, are used throughout this report.

Figure 4-6 records the distribution of the number of office buildings by year of construction. Figure 4-6 shows that more than half of the stock of office buildings (371,000 of 705,000) has been constructed since 1970. Approximately one fifth of the stock was constructed prior to 1946.

Figure 4-7 records the distribution of floorspace by year of construction. Note that more than 60 percent of the total floorspace has been constructed since 1970. In addition, approximately one third of all office floorspace was constructed between 1980 and 1989.

Figure 4-8 introduces information on the number of floors. Begin by comparing Figure 4-8 with Figure 4-5. Recall that Figure 4-5 showed a definite shift in the distribution of total floorspace among the floor categories as building size increased. When year of construction is the characteristic under investigation, a different pattern emerges. Basically, since 1946, the distribution of floorspace among the floor categories within a given year of construction category is U-shaped. For each year of construction category since 1946, total floorspace for one and two floor buildings and for four or more floor buildings tends to exceed the floorspace for buildings with three floors. Although this outcome may seem puzzling at first, it is easily rationalized. In any extended period, say 1980 to 1989, the distribution of building sizes tends to take on the characteristics (e.g., shape) of the distribution of building sizes for the overall population. Thus the characteristics of the building size distribution for the 1980 to 1989 year of construction category would be similar to Figure 4-5, the distribution for the overall population. Consequently, summing across building size for each floor category would produce a U-shaped distribution with a relatively lower value of total floorspace for buildings with three floors than for the other four floor categories.

Figure 4-6. Total Number of Office Buildings by Year of Construction: 1995

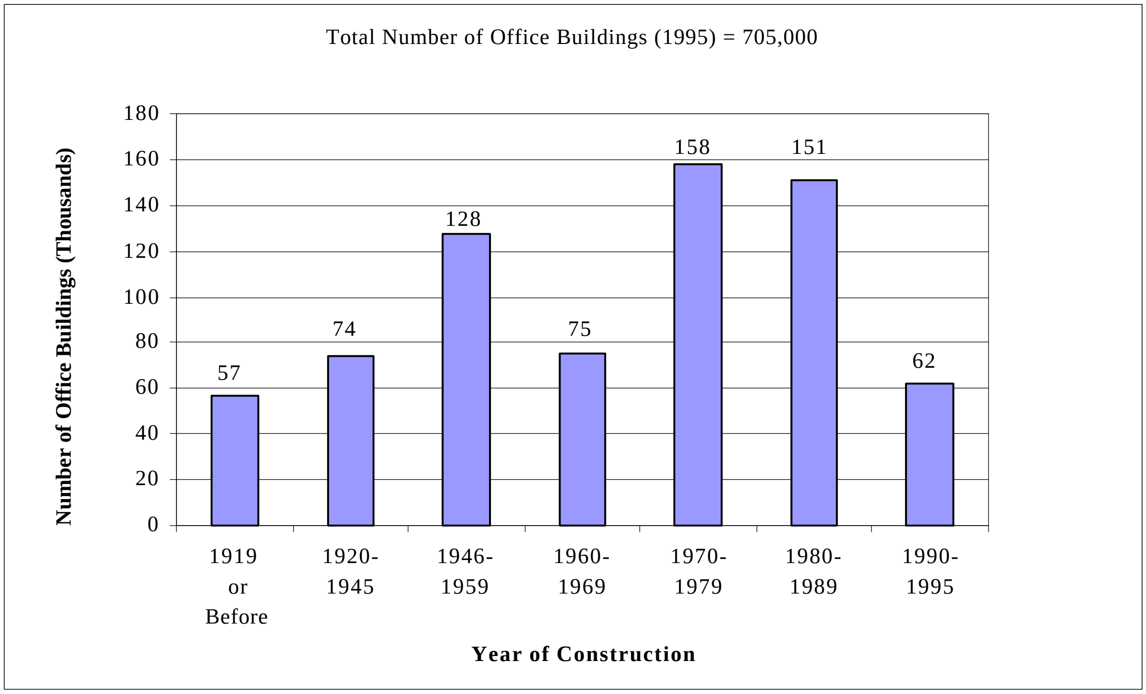


Figure 4-7. Total Office Floorspace by Year of Construction: 1995

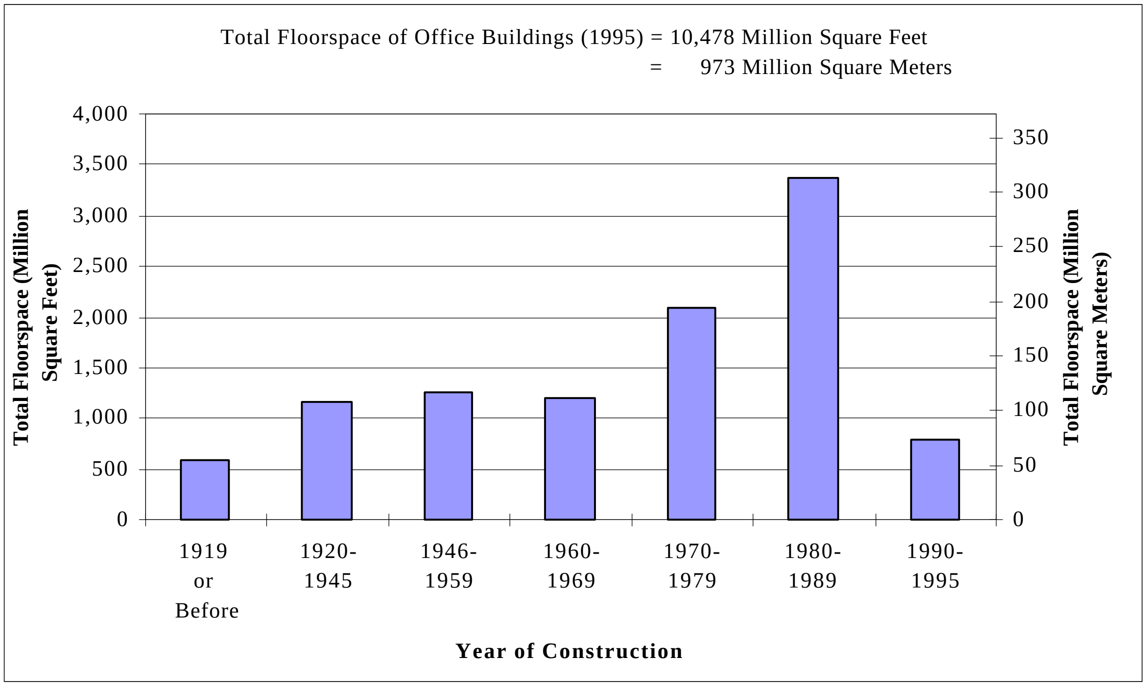
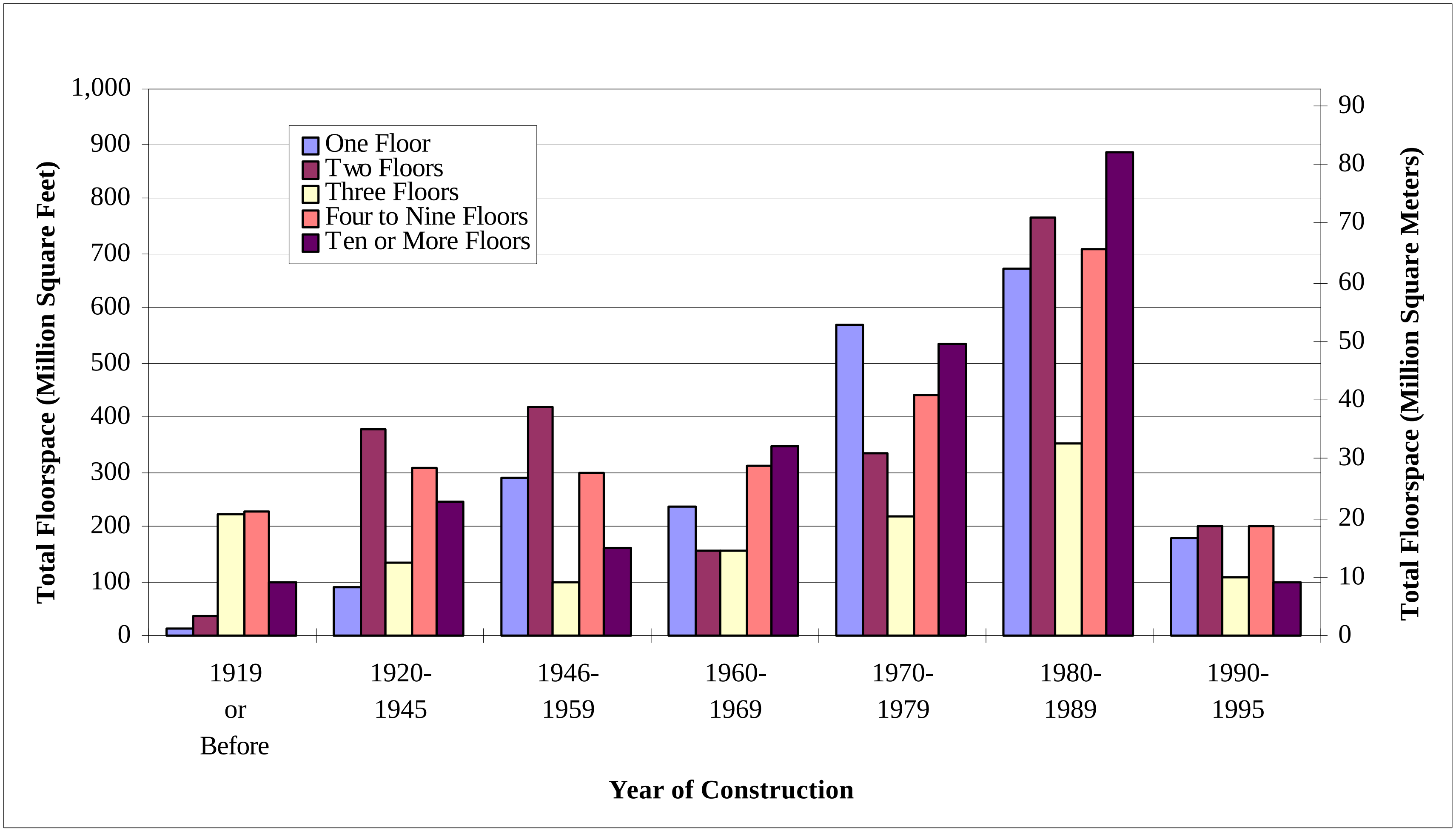


Figure 4-8. Total Office Floorspace by Year of Construction and Number of Floors: 1995



The material presented in this section demonstrated several ways in which the nation's 973 million square meters (10,478 million square feet) of office floorspace can be characterized. This section's approach to characterizing the market for CBS products and services and detailing the market in terms of total floorspace sets the stage for the impact assessment. By focusing on total office floorspace as the potential target market, the calculation of CBS-related costs and benefits is driven by floorspace-related considerations. This is fortuitous because the construction industry is geared towards processing information presented in terms of per unit costs (e.g., costs per square meter or per square foot). As a consequence, most published information on construction industry expenditures for facility operations, for maintenance and repair activities, and for energy is presented on a per unit basis. By casting the economic impact assessment in terms of total floorspace, this study will be able to denominate all key inputs in dollars per unit of area. This approach will promote a better understanding of the findings of this study and its implications for the construction industry.

5. A Strategy for Identifying, Collecting, and Measuring CBS-Related Benefits and Costs

The strategy outlined in this chapter was developed through an iterative process. First, information was solicited from all of the members of the BFRL CBS team. A brainstorming session was used to develop candidate lists of key stakeholder classes (e.g., building owners) and general types of CBS-related benefits and costs. Second, the lists were refined and organized into a suite of "classification" hierarchies. Third, the classification hierarchies were distributed to each of the BFRL CBS project leaders (see Section 3.2 for a description of each CBS project) and, upon their review of the classification hierarchies, critiqued in a series of meetings with the project leaders. The meetings with the BFRL CBS project leaders also sought to identify subject matter experts for follow-on discussions. Finally, subject matter experts from industry and government were interviewed. These interviews were used to finalize the analysis strategy and the classification hierarchies presented in this chapter as well as to collect information on current industry practices and to identify additional data sources.

5.1 Identification of Key Stakeholders

Because individual stakeholders are affected in different ways by the introduction, adoption, and use of CBS products and services, it is useful to first identify classes of individual stakeholders and then classify them into stakeholder groups. By developing a classification hierarchy of stakeholders, we are better able to *understand and identify* both potential opportunities (i.e., real or perceived benefits and cost savings accruing to that stakeholder) and potential barriers (i.e., real or perceived additional costs and benefit reductions borne by that stakeholder) to the adoption of CBS products and services.

Since individual stakeholder classes evaluate the benefits and costs of CBS products and services purely from their "stakeholder" viewpoint, it is important to reflect not only that viewpoint, but the viewpoints of aggregations of stakeholder classes (i.e., a single stakeholder group or a collection of stakeholder groups) and all stakeholder groups as well. The viewpoint of the individual stakeholder is important because they make the decision of whether or not to invest in CBS products and services. Examples of individual stakeholder classes are building owners, engineering consultants, and trade associations. A single stakeholder group is a special aggregation of individual stakeholders classified according to a common theme. An example of a stakeholder group is construction and associated support services. This stakeholder group contains four classes of individual stakeholders: general contractors, specialty trade contractors, wholesale/retail trade/supply, and trade associations. A collection of stakeholder groups is important because an individual stakeholder class may be a key player in several stakeholder groups. The overall picture (i.e., all stakeholder groups) is important because it reflects the benefits and costs of CBS-related products and services to society. BFRL's assessment of CBS-related impacts is undertaken from society's frame of reference. Thus, it includes all benefits and costs to whomsoever they accrue.

Tables 5-1 and 5-2 identify the classes of individual stakeholders and the corresponding stakeholder group(s) used in the assessment of CBS-related benefits and costs. Both tables provide the same information, but are organized in different ways.

Table 5-1 is a hierarchy of stakeholders; it lists stakeholder groups with their corresponding classes of individual stakeholders. It shows how the stakeholder groups are formed. In Table 5-1, the eight stakeholder groups are listed in a ***bold-italics*** typeface.

Table 5-2 is arranged as a checklist; it assigns each of the 36 classes of individual stakeholders to its corresponding stakeholder group(s). Table 5-2 lists the classes of individual stakeholders in alphabetical order to facilitate cross-referencing of individual stakeholders and stakeholder groups. Note that an individual stakeholder class may be associated with more than one stakeholder group. For example, trade associations are associated with three stakeholder groups.

The analysis conducted in this report encompasses all stakeholder groups. However, if analyses from the perspective of a single stakeholder or stakeholder group were desired, Tables 5-1 and 5-2 could be used to structure these analyses (see Section 5.4). In such cases, either Table 5-1 or Table 5-2 may be used to select which class (classes) of individual stakeholders is (are) appropriate.

5.2 CBS-Related Benefits and Cost Savings

Stakeholders invest in CBS products and services because they anticipate receiving, in present value terms, benefits or cost savings in excess of the costs or benefit reductions associated with these investments. Table 5-3 provides a framework for one side of the stakeholders investment decision problem. Namely, how to measure CBS-related benefits and cost savings.

Table 5-3 is organized as a two-tiered hierarchy. Table 5-3 represents the culmination of the Office of Applied Economics CBS project team's efforts to produce a consensus on a comprehensive list of CBS-related benefits and cost savings.

The first tier of the hierarchy lists generic types of CBS-related benefits and cost savings. Although the types of benefits and cost savings appearing in the first tier are generic, the list is considered to be exhaustive. In addition, the generic types of benefits and cost savings listed in the first tier are considered to be self-evident. The 23 first tier elements are listed in a ***bold-italics*** typeface. Examples of first tier benefits and costs savings are fewer false alarms, increased occupant productivity, lower energy costs, and lower operations and maintenance costs.

Table 5-1. Hierarchy of CBS Stakeholders: CBS Stakeholder Groups and Classes of Individual CBS Stakeholders

Building Owners and Managers
- Building Owners
- Building Managers

Codes, Standards, and Support Services
- Code Organizations
- Standards Organizations
- Research Organizations
- Building Owners
- Building Products Manufacturers
- Trade Associations
- Professional Societies
- Product Evaluation Services
- Product Certification Services
- Code Officials
- Building Permitting and Inspection

Manufacturing Interest Group
- Building Products Manufacturers
- Product Innovators
- Product Designers
- Research Organizations
- Testing Laboratories
- Testing Services
- Trade Associations
- Professional Societies
- Product Marketing, Sales, and Distribution
- Customer Service Operations

Construction and Associated Support Services
- General Contractors
- Specialty Trade Contractors
- Wholesale/Retail Trade/Supply
- Trade Associations

Professional and Financial Services
- Designers
- Architects
- Engineering Consultants
- Investment Banking Services
- Insurance Companies
- Warranty Companies
- Real Estate Companies

Emergency and Security Services
- Fire, Rescue, and Police Services
- Security Services

Utilities and Energy Providers
- Utilities
- Energy Distribution Network
- Energy Providers

Other
- Building Occupants
- Special Interest Groups
- Third Parties

Table 5-2. Assignment of Classes of Individual CBS Stakeholders to CBS Stakeholder Groups

Individual Stakeholder Class	Stakeholder Group							
	Building Owners & Managers	Codes, Standards, & Support Services	Manufacturing Interest Group	Construction & Associated Support Services	Professional & Financial Services	Emergency & Security Services	Utilities & Energy Providers	Other
Architects					✓			
Building Managers	✓							
Building Occupants								✓
Building Owners	✓	✓						
Building Permitting and Inspection		✓						
Building Products Manufacturers		✓	✓					
Code Officials		✓						
Code Organizations		✓						
Customer Service Operations			✓					
Designers					✓			
Energy Distribution Network							✓	
Energy Providers							✓	
Engineering Consultants					✓			
Fire, Rescue, and Police Services						✓		
General Contractors				✓				
Insurance Companies					✓			
Investment Banking Services					✓			
Professional Societies		✓	✓					
Product Certification Services		✓						

Table 5-2. Assignment of Classes of Individual CBS Stakeholders to CBS Stakeholder Groups (Continued)

Individual Stakeholder Class	Stakeholder Group							
	Building Owners & Managers	Codes, Standards, & Support Services	Manufacturing Interest Group	Construction & Associated Support Services	Professional & Financial Services	Emergency & Security Services	Utilities & Energy Providers	Other
Product Designers			✓					
Product Evaluation Services		✓						
Product Innovators			✓					
Product Marketing, Sales, and Distribution			✓					
Real Estate Companies					✓			
Research Organizations		✓	✓					
Security Services						✓		
Special Interest Groups								✓
Specialty Trade Contractors				✓				
Standards Organizations		✓						
Testing Laboratories			✓					
Testing Services			✓					
Third Parties								✓
Trade Associations		✓	✓	✓				
Utilities							✓	
Warranty Companies					✓			
Wholesale/Retail Trade/Supply				✓				

Table 5-3. CBS-Related Benefits and Cost Savings

Better Load-Leveling Capabilities
- Better Overall Load Management
- Allows for Graceful Degradation of Services

Fewer False Alarms

Fire and Rescue Services Better Able to Deploy Resources
- Faster Response
- Improved Fire-Fighting Capabilities (e.g., room of origin, fuel load)
- Allows Elevators to be Integrated Into Fire Response System
- Improved Safety for Fire and Rescue Personnel

Helps Create an Emerging Service Industry
- Facilitates Use of Third Party Operations, Maintenance, and Repair Services

Improved Health, Safety, and Security
- Lower Risk of Building-Related Illnesses
- Lower Risk of Injuries and Fatalities During Emergencies
- Evacuate Affected Areas vs. Entire Building

Improvements in Energy Pricing
- Optimization of Time-of-Use Pricing
- Better Able to Handle Real-Time Pricing Changes

Increased Functionality and Performance
- Better Control of Temperature, Humidity, and Lighting Levels
- Increased Potential for both Systems Integration and Systems Optimization

Increased Occupant Productivity
- Improved Indoor Air Quality
- Fewer Lost Workdays
- Increased Occupant Comfort
- Less Down Time

Increased Sales for System Design/Integration/Optimization Services

Increased Sales of Building Products with New Features

Increased Sales of Complementary Product Lines and Services

Less Occupant Turn Over

Table 5-3. CBS-Related Benefits and Cost Savings (Continued)

Lower Energy Costs

- Energy Cost Savings Due to Better Controls
- Ability to Aggregate Buildings and Negotiate Lower Electricity Rates

Lower First Costs/Acquisition Costs

- More Opportunities for Input Substitution (e.g., products of different vendors)
- Potential for Cycle Time Reduction

Lower Health Costs

- Less Building-Related Sickness
- Lower Medical Costs
- Lower Workman's Compensation Insurance Premiums

Lower Operations and Maintenance Costs

- Better Diagnostics Saves Time in Trouble-Shooting Maintenance Problems
- Availability of Online Information on the Building's Characteristics Promotes Use of Fact-Based Operations and Maintenance Programs
- Facilitates Cross-Training of Support Staff for Multi-Building Operations
- Better Management of Unoccupied Spaces

Lower Repair and Replacement Costs

- Enables Electronically-Transmitted Fixes for Many Repair Problems
- Longer Equipment Life

Promotes Code Changes Due to New Ways of Controlling Building Functions

Reduced Property Losses

- Reductions in Expected Building Losses in the Event of a Fire
- Reductions in Expected Losses of Occupant Assets in the Event of a Fire

Reductions in Insurance Costs

- Lower Premiums Due to Expected Reductions in Property Losses
- Reductions in Health-Related Claims

Reductions in Warranty Costs

Reductions in Waste and Pollution

Smoother Start-Up Operations

- Increased Potential for Automated Commissioning

The second tier lists specific types of benefits and cost savings associated with its "parent" first tier element. The second tier elements are listed as a series of bullets under the parent first tier element. An example of a second tier element for lower energy costs is energy cost savings due to better controls. Not all generic types of benefits and cost savings have a second tier (e.g., fewer false alarms, less occupant turnover, and reductions in warranty costs).

It is important to recognize that the benefits and cost savings listed in Table 5-3 might accrue to any individual stakeholder (i.e., they are aggregated according to society's frame of reference). Thus, Table 5-3 is structured from "society's" frame of reference rather than from the perspective of a single stakeholder or stakeholder group. The main purpose of Table 5-3 is to illustrate how BFRL approaches the assessment of the "benefits" side of CBS-related impacts. Specifically, BFRL used this table to identify the data needed to measure these impacts. For the impact assessment presented in this report, Table 5-3 identifies the potential "benefits" data links. However, if the focus is on an individual stakeholder or stakeholder group, it will be necessary to develop a crosswalk between the generic types of benefits and cost savings listed in Table 5-3 and the stakeholder groups listed in Table 5-1. This crosswalk is the subject of Section 5.4.

The classification hierarchy presented as Table 5-3 has been limited to two tiers. Because Tables 5-3 and 5-4 (see Section 5.3) are used to measure the "benefits" and "costs" sides of CBS-related impacts, the end product of these classification hierarchies is a collection of economic data. In the case of CBS-related benefits and cost savings, the depth of the hierarchy (i.e., the number of tiers) is equal to two. In principle, the depth of these data-related classification hierarchies could be equal to one, to two, or to some number greater than two. The rule governing the depth of the hierarchy is how far down in the hierarchy one must go until all lowest level elements in the hierarchy are indicative of economic data. For CBS-related benefits and cost savings, two tiers were considered adequate.

5.3 CBS-Related Costs and Benefit Reductions

Costs are at the heart of any investments in new products.[34] For the CBS economic impact assessment, costs are incurred at several points in the "product" life cycle. Specifically, CBS-related costs include research costs, product development costs, production costs, dissemination costs, and installation costs. In addition, a particular vendor may experience benefit reductions due to reduced sales of some of its more "traditional" products. These costs and benefit reductions are summarized in Table 5-4; they are organized as a three-tiered hierarchy.

The first tier of the hierarchy lists generic types of CBS-related costs and benefit reductions. The list is considered to be exhaustive and self-evident. The eight first tier elements are listed in a ***bold-italics*** typeface. Examples of first tier costs and benefit

[34] The word product is used generically to represent technologies, hardware (e.g., building systems, subsystems, components, piece parts, and support equipment), software, and services.

reductions are higher evaluation costs, increased costs for new standards development, and increased investments by building products manufacturers.

The second tier lists specific types of costs and benefit reductions associated with its “parent” first tier element. The second tier elements are listed as a series of bullets under the parent first tier element. An example of a second tier element for increased investments by building products manufacturers is increased research and development costs. Not all generic types of costs and benefit reductions have a second tier (e.g., increased costs for new standards development, increased training costs, and reduced sales of selected product lines and services).

Table 5-4. CBS-Related Costs and Benefit Reductions

Higher Evaluation Costs

- Increased Cost for Building Code Allowances/Permits

Higher First Costs

- Longer Cycle Time Due to Building with New Equipment, Technologies, or Processes
- Additional Building Systems Infrastructure Needed to Monitor and Control Systems and Components

Increased Costs of Adapting New Building Products to Industry Use

Increased Costs for New Standards Development

Increased Investments by Building Products Manufacturers

- Increased Research and Development Costs
  - Increased Costs for Product Testing/Simulation
  - Increased Costs for Product Development
- New Plant and Equipment
- New Production Processes

Increased Marketing, Advertising, and Distribution Costs

Increased Training Costs

Reduced Sales of Selected Product Lines and Services

The third tier elements are concerned with increased research and development costs. These costs are of central importance to both BFRL and its industry collaborators. Consequently, it was desirable to increase the depth of the CBS-related costs and benefit reductions classification hierarchy to three. Information on increased research and development costs is presented and discussed in Section 6.3.2.2. Examples of increased research and development costs are increased costs for product testing/simulation and increased costs for product development.

5.4 Relationships Between Benefits, Costs, and Stakeholders

Recall that BFRL's assessment of CBS-related impacts is undertaken from society's frame of reference. Thus, it includes all benefits and costs to whomsoever they accrue. Although this is the traditional approach for public-sector economic impact studies, it is too broad for most stakeholder groups. This is because most stakeholder groups want to evaluate the pros and cons of "their" investments in CBS products and services. In addition, the traditional approach employed in public-sector studies complicates the data collection effort. Basically, the higher the level of abstraction, the more difficult it becomes to define data "categories" and collect the types of data that lead to meaningful results. Consequently, this study develops crosswalks between stakeholder groups and CBS-related benefits and cost savings and CBS-related costs and benefit reductions. The two crosswalks are presented as Table 5-5 and Table 5-6. Table 5-5 lists key types of benefits and cost savings by stakeholder group; Table 5-6 lists key types of costs and benefit reductions by stakeholder group.

The two crosswalks serve three purposes. First, they define in an unambiguous manner all of the potential data categories from which to collect economic data. In fact, each data category may be specified as a unique combination of stakeholder group and type of benefit or type of cost. Second, the crosswalks promote a priority-setting process for identifying what specific types of data to collect and where to collect them. For example, if we know that three stakeholder groups—building owners and managers, utilities and energy providers, and other (e.g., building occupants)—are beneficiaries of lower energy costs (see the cells beneath the "stakeholder group" column headings in Table 5-5 that are checked), then we can focus our "energy cost" data collection effort on these three stakeholder groups. Thus, the data collection strategy, stated in its simplest terms, is to limit the data collection effort to those cells of Table 5-5 and Table 5-6 with check marks (✓). This priority-setting approach to data collection is employed throughout the next three chapters. Finally, the crosswalks provide the means through which an individual stakeholder or stakeholder group may evaluate the pros and cons of investing in CBS products and services. Thus, the crosswalks not only greatly simplify the current economic impact assessment they also provide the framework for identifying key data elements and for specifying a data collection strategy for individual stakeholders.

The third purpose of the crosswalks is best understood by considering a specific stakeholder group, say building owners and managers. If building owners and managers are considering investing in a specific CBS product versus a traditional product, they need to know if the life-cycle cost over the proposed study period of the CBS product is less than that of the traditional product.

The first step in this “decision problem” is to identify the types of benefits and the types of costs. The “benefits” accruing to and the “costs” borne by building owners and managers are recorded in the first “stakeholder group” column of Tables 5-5 and 5-6, respectively. Reference to Table 5-5 shows that building owners and managers benefit from all but four of the twenty-three types of benefits and cost savings. Examples of specific types of benefits and cost savings are better load-leveling capabilities, fewer false alarms, lower energy costs, and smoother start-up operations. Reference to Table 5-6 shows that building owners and managers bear four types of increased costs. They are: higher evaluation costs, higher first costs, increased cost of adapting new building products to industry use, and increased training costs. The second step is to compile a list of the types of benefits and the types of costs for which data are available and are relevant (i.e., data that allow comparisons between the products being considered). The third step is to collect the economic data. The economic data collected in the third step are used to support a life-cycle cost analysis of the products being considered. Finally, evaluate the economic performance of each product being considered. This is done by calculating the life-cycle cost for each product and selecting the one that minimizes the life-cycle cost over the proposed study period.

The same procedure can be used for an individual stakeholder class. First, select the individual stakeholder class. Then, refer to Table 5-2 to identify the appropriate stakeholder group(s). Finally, follow the procedure just described to determine whether or not that stakeholder should invest in the CBS product under consideration.

Table 5-5. Types of CBS-Related Benefits and Cost Savings Classified by Stakeholder Group

Type of Benefit or Cost Saving	Stakeholder Group							
	Building Owners & Managers	Codes, Standards, & Support Services	Manufacturing Interest Group	Construction & Associated Support Services	Professional & Financial Services	Emergency & Security Services	Utilities & Energy Providers	Other
Better Load-Leveling Capabilities	✓						✓	✓
Fewer False Alarms	✓					✓		✓
Fire and Rescue Services Better Able to Deploy Resources	✓					✓		✓
Helps Create an Emerging Service Industry		✓	✓		✓			
Improved Health, Safety, and Security	✓					✓		✓
Improvements in Energy Pricing	✓						✓	✓
Increased Functionality and Performance	✓	✓	✓		✓			✓
Increased Occupant Productivity	✓							✓
Increased Sales for System Design/Integration/Optimization Services			✓	✓	✓			
Increased Sales of Building Products with New Features		✓	✓	✓	✓			
Increased Sales of Complementary Product Lines and Services			✓	✓	✓			

Table 5-5. Types of CBS-Related Benefits and Cost Savings Classified by Stakeholder Group (Continued)

Type of Benefit or Cost Saving	Stakeholder Group							
	Building Owners & Managers	Codes, Standards, & Support Services	Manufacturing Interest Group	Construction & Associated Support Services	Professional & Financial Services	Emergency & Security Services	Utilities & Energy Providers	Other
Less Occupant Turn Over	✓							✓
Lower Energy Costs	✓						✓	✓
Lower First Costs/Acquisition Costs	✓			✓				
Lower Health Costs	✓				✓			✓
Lower Operations and Maintenance Costs	✓							
Lower Repair and Replacement Costs	✓							
Promotes Code Changes Due to New Ways of Controlling Building Functions	✓	✓	✓		✓			✓
Reduced Property Losses	✓				✓	✓		✓
Reductions in Insurance Costs	✓					✓		✓
Reductions In Warranty Costs	✓		✓	✓		✓		
Reductions in Waste and Pollution	✓		✓	✓			✓	✓
Smoother Start-Up Operations	✓	✓	✓	✓	✓		✓	✓

Table 5-6. Types of CBS-Related Costs and Benefit Reductions Classified by Stakeholder Group

Type of Cost or Benefit Reduction	Stakeholder Group							
	Building Owners & Managers	Codes, Standards, & Support Services	Manufacturing Interest Group	Construction & Associated Support Services	Professional & Financial Services	Emergency & Security Services	Utilities & Energy Providers	Other
Higher Evaluation Costs	✓	✓	✓	✓	✓	✓	✓	✓
Higher First Costs	✓			✓				
Increased Cost of Adapting New Building Products to Industry Use	✓	✓	✓	✓	✓	✓	✓	✓
Increased Costs for New Standards Development		✓	✓		✓	✓		✓
Increased Investments by Building Products Manufacturers			✓					
Increased Marketing, Advertising, and Distribution Costs			✓	✓	✓			
Increased Training Costs	✓	✓	✓	✓	✓	✓	✓	✓
Reduced Sales of Selected Product Lines and Services			✓	✓	✓			✓

6. Data and Assumptions for the CBS Economic Impact Assessment

This chapter describes the data and assumptions used to evaluate the economic impacts associated with the adoption and use of CBS products and services in office buildings. The goal of this chapter is fourfold. First, it establishes the sources and validity of the data used in the CBS economic impact assessment. Second, it defines the base case and the CBS alternative. Third, it produces estimated values for key sets of benefits and costs. Fourth, it documents the process by which key assumptions were established, including how the values of key parameters were set.

6.1 Data Sources

Establishing the sources and validity of the data used in the CBS economic impact assessment is essential if readers are to be able to follow the analysis, gain insights useful for their own applications, and reproduce our results. This section describes the three groups of data upon which the economic impact assessment is based. The material presented in this section is intended to establish an audit trail which readers can follow to gain access to the same information used in the CBS economic impact assessment.

6.1.1 Baseline Measures of Construction Industry Practices

The Construction and Building Subcommittee of the National Science and Technology Council has established seven National Construction Goals in collaboration with a broad cross section of the construction industry.[35] Data describing current practices of the US construction industry are needed to establish baselines against which the industry can measure its progress towards achieving the seven National Construction Goals. The Goals are: (1) reductions in the delivery time of constructed facilities; (2) reductions in operations, maintenance, and energy costs; (3) increases in occupant productivity and comfort; (4) reductions in occupant-related illnesses and injuries; (5) reductions in waste and pollution; (6) increases in the durability and flexibility of constructed facilities; and (7) reductions in construction worker illnesses and injuries.

Baseline measures and measures of progress will be produced for each National Construction Goal in each of the four key construction industry sectors. The four sectors are: (1) residential; (2) commercial/institutional; (3) industrial; and (4) public works. Industry performance in 1994 is used as the reference point from which the values of the baseline measures are calculated.

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[35] Wright, Richard N., Arthur H. Rosenfeld, and Andrew J. Fowell. 1995. *Construction and Building: Federal Research and Development in Support of the US Construction Industry*. Washington, DC: National Science and Technology Council.

A recent report by Chapman and Rennison[36] provides a detailed set of baseline measures for National Construction Goal 2, reductions in operations, maintenance, and energy costs. Goal 2 was identified as one of the highest priority National Construction Goals by the construction industry.

Chapter 6 of the Chapman and Rennison report[37] describes the commercial/institutional sector and traces the development of the baseline measures for the commercial/ institutional sector. The baseline measures for the commercial/institutional sector are based on data published by DOE, the International Facilities Management Association, the Building Owners and Managers Association, Whitestone Research, the Association of Higher Education Facilities Officers, and the Institute of Real Estate Management.

The Goal 2 baseline measures for the commercial/institutional sector were the starting point for collecting the data and information needed to conduct the CBS economic impact assessment. Specifically, the values of the baseline measures for operations, maintenance, and energy costs are reference data against which the values contained in this report can be compared. In addition, the report by Chapman and Rennison provided extensive cross-referencing of data to sources. This enabled the current effort to quickly and efficiently retrieve data and information focused exclusively on the office building component of the commercial/institutional sector. The remainder of this section is devoted to the description of these data sources and the key data sets associated with these data sources.

6.1.2 Energy Consumption Survey of Commercial Buildings

The purpose of this subsection is to establish the sources for two key data items: (1) the national average energy cost per square meter (per square foot); and (2) the rates of utilization of energy conserving features and practices. The first data item is needed to estimate per unit energy cost savings. The second data item provides a range of utilization rates on energy conserving features and practices, many of which have characteristics similar to those of CBS products and services.

The source of information on these data items is the DOE Commercial Buildings Energy Consumption Survey (CBECS). CBECS is a national sample survey that collects energy-related building characteristics and consumption and expenditure data for US commercial buildings. CBECS was first conducted in 1979 and then triennially since 1983.

In the 1995 CBECS, there were 6,590 sampled buildings of which 5,766 were successfully interviewed. Energy-related characteristics of the buildings are obtained in an on-site personal interview with the building managers, owners, or tenants during the

[36] Chapman, Robert E., and Roderick Rennison. 1998. *An Approach for Measuring Reductions in Operations, Maintenance, and Energy Costs: Baseline Measures of Construction Industry Practices for the National Construction Goals*. NISTIR 6185. Gaithersburg, MD: National Institute of Standards and Technology.
[37] *Ibid*., pp. 115-182.

Commercial Buildings Characteristics Survey. Energy consumption and expenditures information are obtained from the energy suppliers to the responding buildings during the Energy Suppliers Survey. The CBECS defines commercial buildings as enclosed roofed and walled structures used predominantly for commercial purposes with floorspace greater than 1,000 square feet (92.9 square meters). This definition includes buildings such as schools, health care buildings, and religious institutions, as well as office buildings and retail stores (i.e., the full range of the commercial/institution sector as defined in Chapman and Rennison).

The survey includes characteristics of each building sampled. One of these characteristics, principal building activity, is used to separate office buildings from other types of commercial buildings. Readers interested in a detailed description of the 1995 CBECS are referred to the recent report by the Energy Information Administration.[38]

The information presented in this subsection is derived from data contained in the CBECS Public Use Files. The Public Use Files are microdata files that contain 5,766 records, representing commercial buildings from the 50 States and the District of Columbia. Each record corresponds to a single sampled building and contains information for that building about the building size, year constructed, types of energy used, energy-using equipment, energy consumption and expenditures, conservation features and energy management practices, and energy used for nine end uses. The nine end uses are space heating, cooling, ventilation, lighting, water heating, cooking, refrigeration, office equipment, and other.

The CBECS sample was designed so that survey responses could be used to estimate characteristics of the entire commercial buildings stock nationwide. In order to arrive at national estimates from the CBECS sample, DOE calculated base-sampling weights for each building. Therefore, a building with a base weight of 1,000 represents itself and 999 similar, but unsampled buildings in the total building stock. The base weight is further adjusted to account for nonresponse bias. In order to obtain a weighted estimate, each sample building's value must be multiplied by the building's weight.

Figures 6-1 through 6-8 summarize the information on office buildings extracted from the CBECS microdata files. All of the figures record building size on the horizontal axis. The same eight size categories introduced in Chapter 4 are used in each figure. Tic marks on the horizontal axis are used to help separate the size categories. Two different measures are recorded on the vertical axis. For Figure 6-1 the vertical axis records the annual fuel expenditure per unit of floor area. For Figures 6-2 through 6-8 the vertical axis records the percent of total floorspace covered by the factors (i.e., end-use equipment and energy conservation features and practices) under analysis. It is important to recognize that portions of a building's floorspace may be covered by more than one factor. Consequently, the sum total across all factors may exceed 100 percent of total floorspace.

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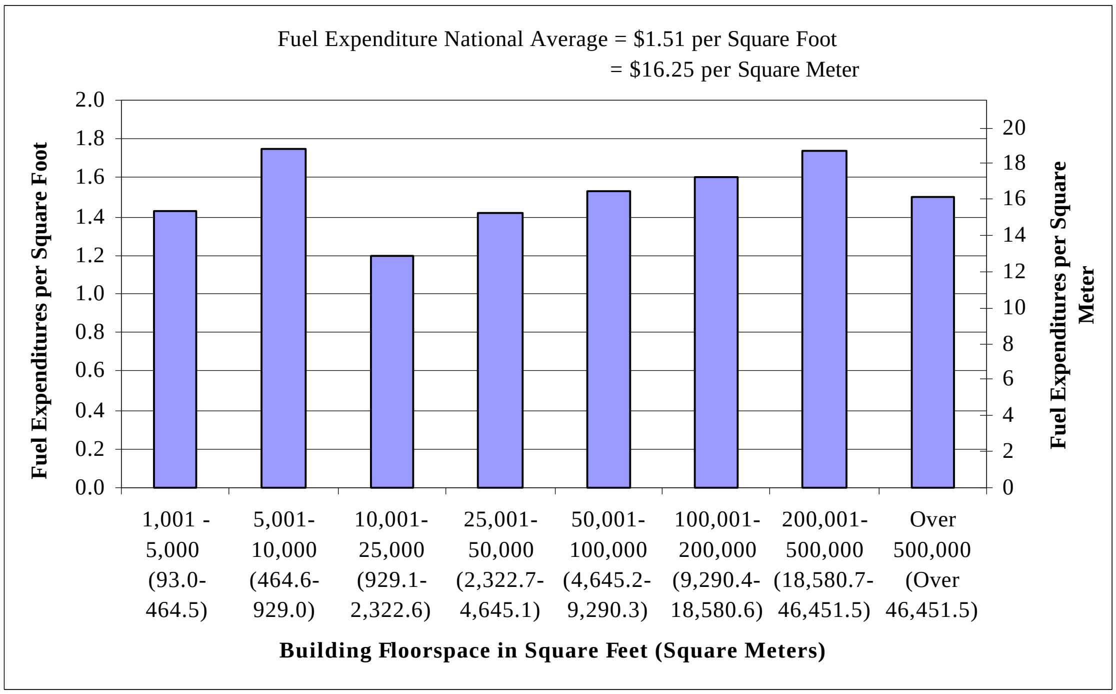
[38] US Department of Energy. 1998. *A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures*. DOE/EIA-0625(95). Washington, DC: Energy Information Administration.

Figure 6-1 shows how annual energy expenditures per unit of floor area vary by building size. The figure also records the national average energy expenditure per square meter (per square foot). Reference to the figure shows that the national average energy expenditure is \$16.25 per square meter (\$1.51 per square foot). Examination of the figure shows considerable variability about the national average across the eight building size categories. However, the figure does not show any trend towards higher or lower energy expenditures per unit of floor area as building size increases. The national average energy expenditure per square meter is used as the reference point against which cost savings per square meter are estimated (see Section 6.3.1.1).

Figure 6-1. Sum of Major Fuel Expenditures by Office Building Size Category: 1995



Figures 6-2 through 6-8 are concerned with end-use equipment and energy conservation features and practices. Energy is used within buildings by end-use equipment. End-use equipment refers to the specific type of equipment that is used to perform a given end use. Types of end-use equipment include heat pumps, furnaces, packaged air-conditioning units, central chillers, fluorescent light fixtures, and compact fluorescent bulbs. Figures 6-2 through 6-4 record information on end-use equipment. Office buildings use a variety of features and practices to conserve the use of energy by end-use equipment. Energy conservation features include those related to the building shell, HVAC systems, and lighting systems. Figures 6-5 through 6-7 record information on energy conservation features. Energy management practices are conservation programs and energy technologies designed to reduce the energy used by specific end-use equipment. Figure 6-8 records information on energy management practices.

For Figures 6-2 through 6-8 the factors under analysis are listed in a box beneath the legend for the horizontal axis. The number of factors analyzed in each figure range from a high of seven (see Figure 6-2) to a low of four (see Figure 6-6). Each factor is cross-referenced to a bar in the figure. This is done by shading each bar, and for selected bars bolding their border. Each factor is indicated by a small shaded box and a factor name pairing. To identify a specific factor, start at the top and read from left to right across the shaded box/factor name pairings until the factor of interest is found. Note that each factor is recorded for each size category in Figures 6-2 through 6-8. Due to different building characteristics, some factors will have a zero value for some size categories. In such cases, a gap will appear between one or more bars. The positions of each bar, however, will be the same as indicated by the order of the shaded box/factor name pairings.

Information on space heating equipment for office buildings is presented in Figure 6-2. Five types of heating equipment were used extensively in office buildings: packaged heating units, boilers, individual space heaters, district heat, and furnaces. Although all five types were used extensively, their use in office buildings of different sizes varied considerably. For example, boilers, individual space heaters, and district heat were used more in larger buildings, while packaged heating units and furnaces were used more in smaller buildings.

Information on cooling equipment for office buildings is presented in Figure 6-3. Reference to the figure reveals that packaged air-conditioning units were by far the most widely used type of cooling equipment. Two types of cooling equipment showed significant differences in use by size of building. Residential-type central air-conditioning units showed relatively greater use in the smallest office buildings. Central chillers were used primarily in the largest buildings. That equipment type cooled more than 60 percent of the combined floorspace of the three largest size categories, but less than 5 percent of the combined floorspace of the three smallest size categories.

Information on five types of lighting equipment is summarized in Figure 6-4. The five types of lighting equipment are: incandescent, standard fluorescent, compact fluorescent, high-intensity discharge, and halogen. Standard fluorescent lighting fixtures were found in nearly all office buildings (more than 90 percent of all floorspace). Incandescent lighting was also widely used (around 60 percent of all floorspace). The three newer kinds of lighting technology, high-intensity discharge, compact fluorescent, and halogen, were used primarily in larger office buildings.

Figure 6-5 summarizes information on building shell conservation features. Figure 6-5 shows that most office buildings had some type of building shell conservation feature. The feature most often found was roof or ceiling insulation; utilization of roof or ceiling insulation ranged from 80 percent to 90 percent of total floorspace within each size category.

Figure 6-2. Office Building Heating Equipment by Building Size Category

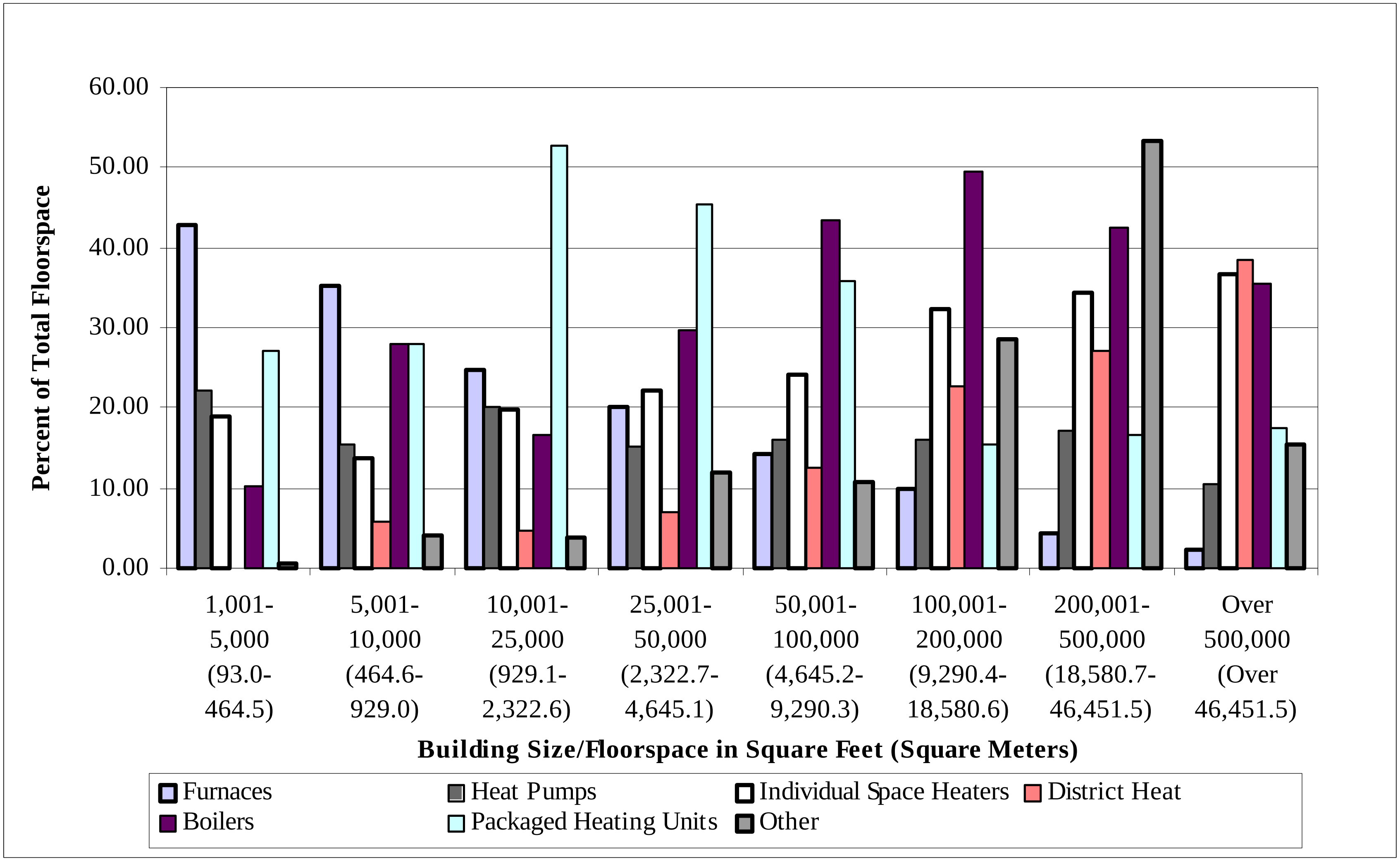


Figure 6-3. Office Building Cooling Equipment by Building Size Category

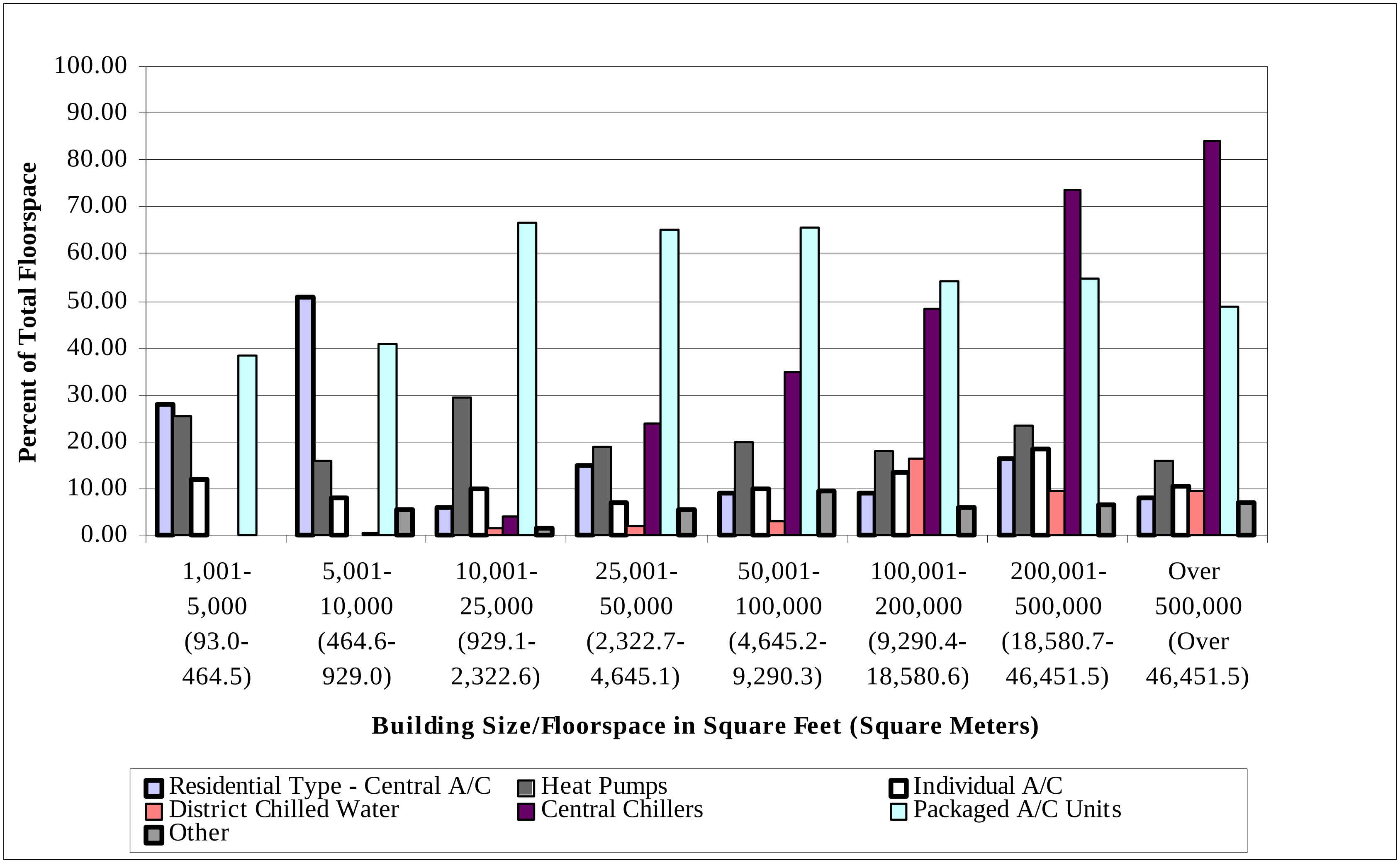


Figure 6-4. Office Building Lighting Equipment by Building Size Category

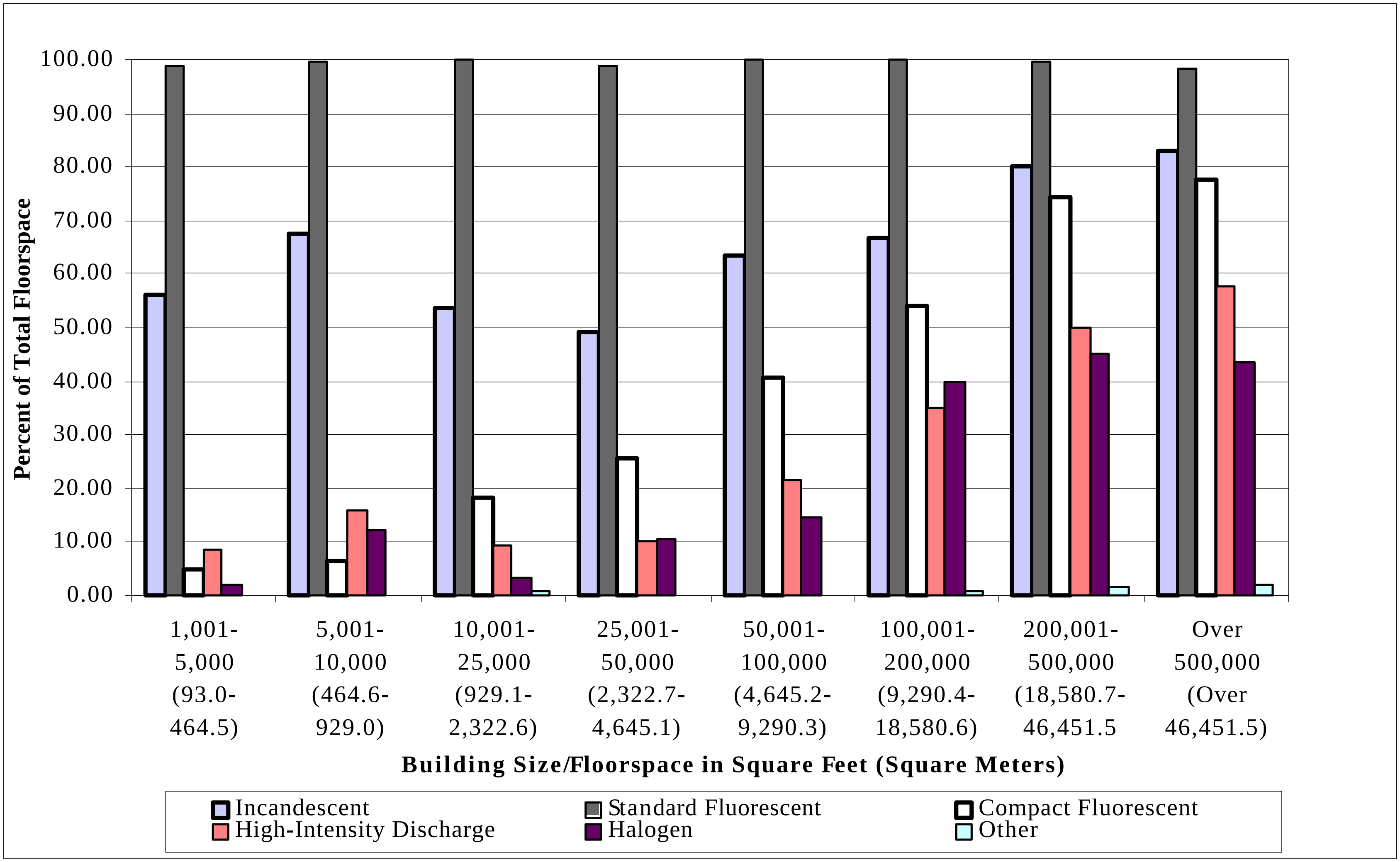


Figure 6-5. Office Building Shell Conservation Features by Building Size Category

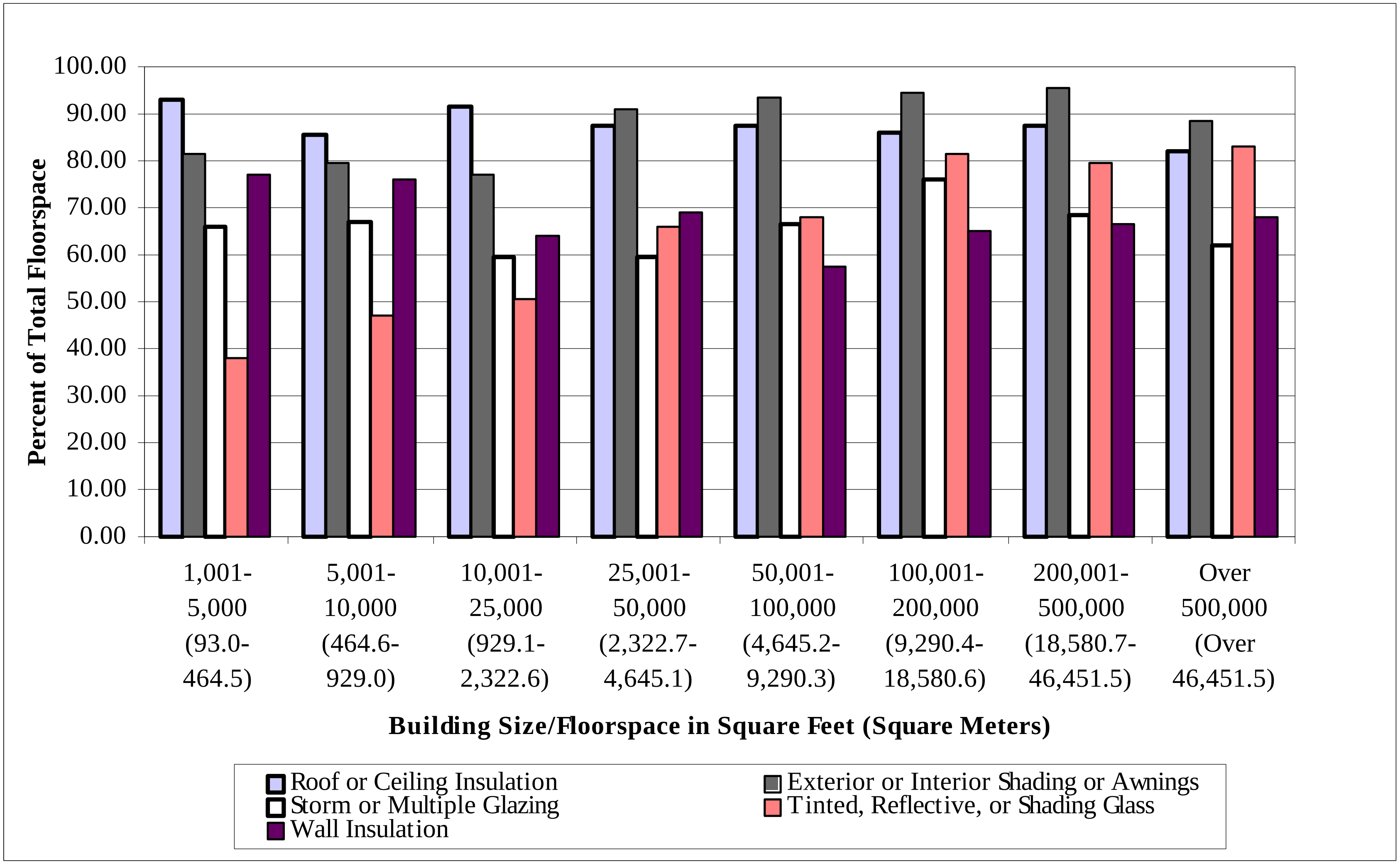


Figure 6-6. Office Building HVAC Conservation Features by Building Size Category

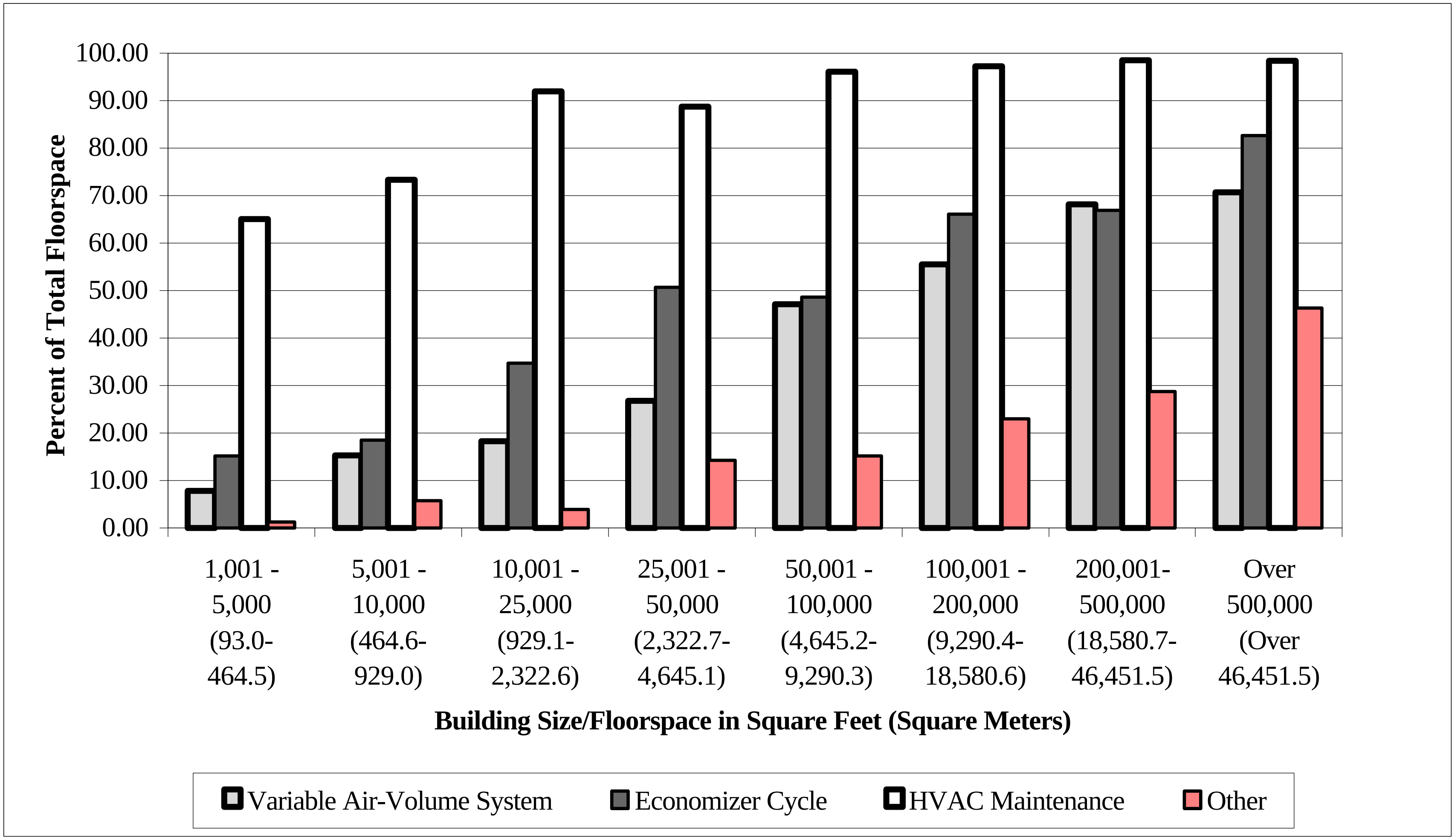


Figure 6-7. Office Building Lighting Conservation Features by Building Size Category

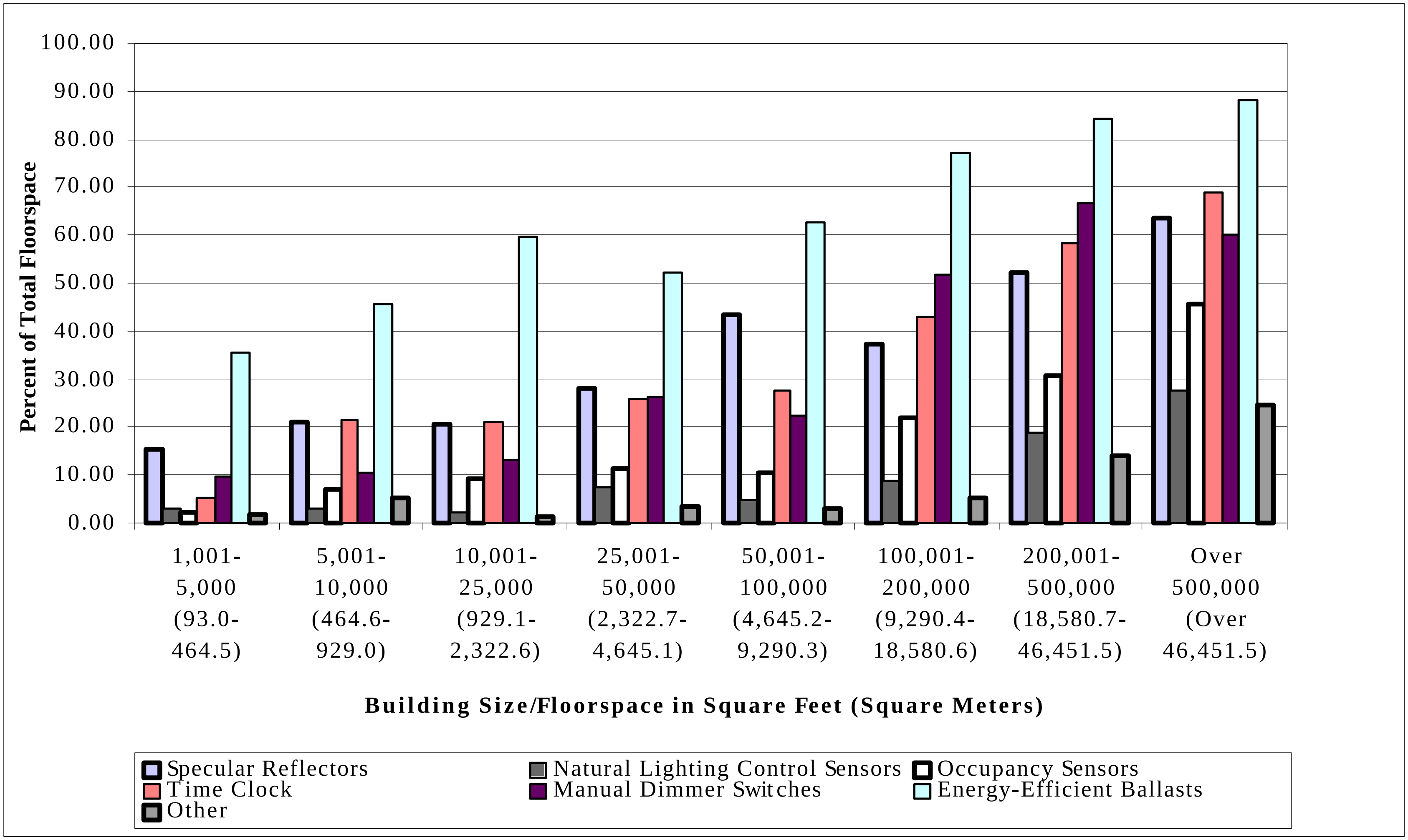


Figure 6-8. Use of Energy Management Practices in Office Buildings: Part A

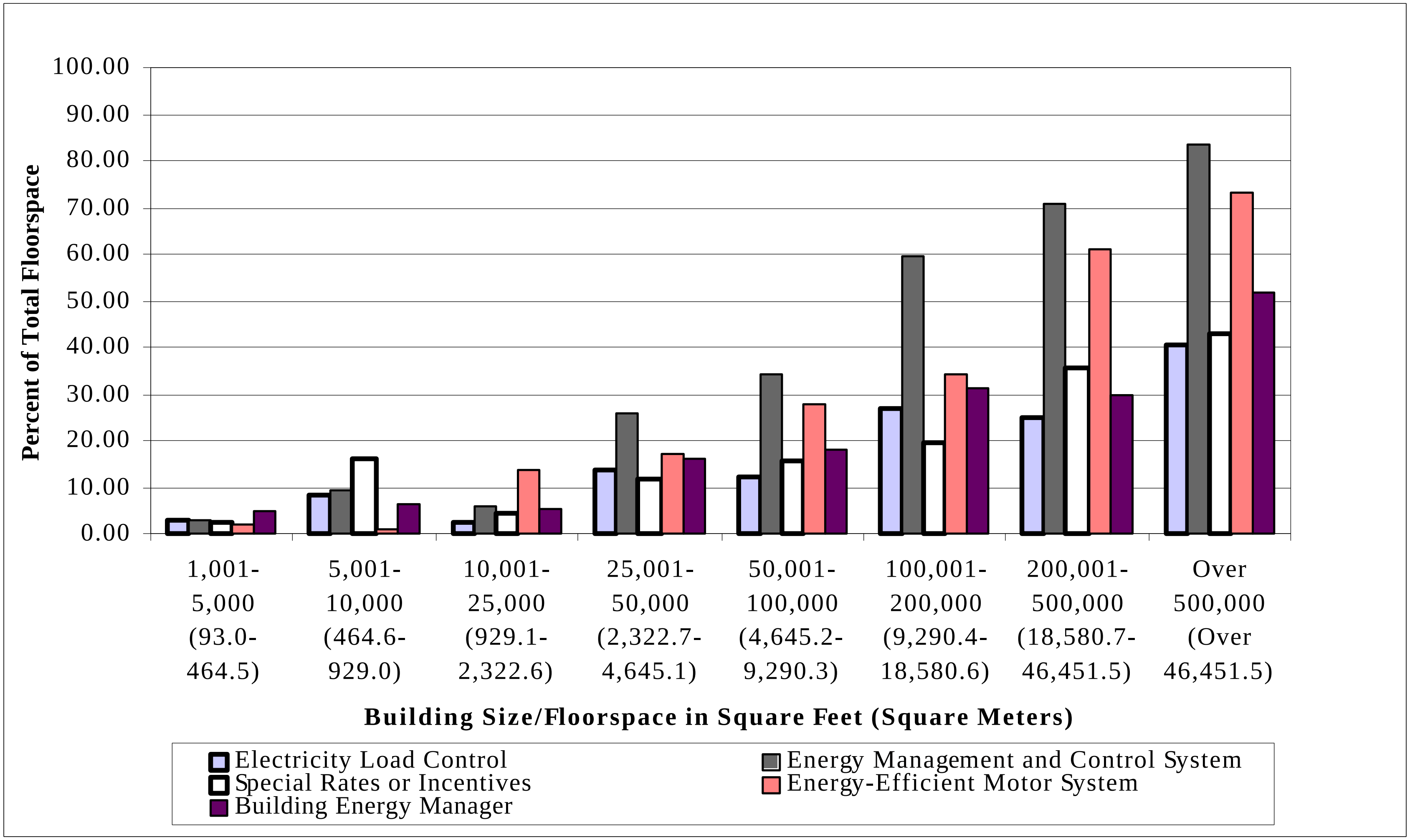


Figure 6-8. Use of Energy Management Practices in Office Buildings: Part B

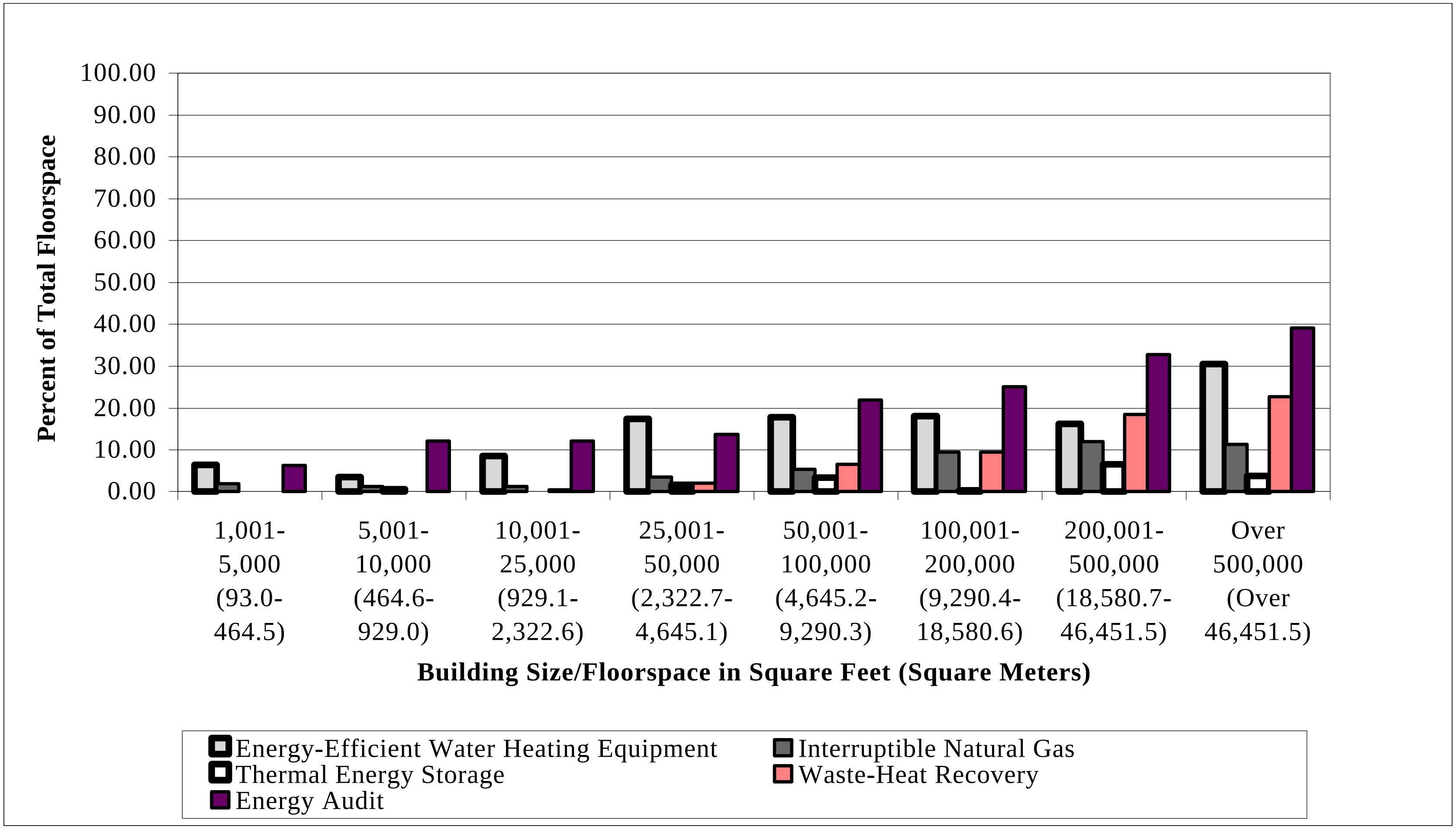


Figure 6-6 summarizes information on HVAC conservation features. Comparison between Figure 6-5 and Figure 6-6 shows that HVAC conservation features were, in general, less common than building shell features. HVAC maintenance, the most widely practiced of the HVAC conservation features, was performed in about 80 percent of the floorspace. For the four largest size categories, HVAC maintenance was performed in 95 percent or more of the floorspace.

Reference to Figure 6-7 reveals that a significant percentage of office building floorspace employed some type of lighting conservation feature. The most widely used lighting conservation feature was energy-efficient ballasts. About two-thirds of office building floorspace was covered by energy-efficient ballasts. Comparisons between Figures 6-5, 6-6, and 6-7 show that both HVAC and lighting system conservation were more often found in larger office buildings.

The CBECS collected information on buildings that participated in, or used, a variety of conservation programs and energy technologies, collectively referred to by DOE as energy management practices. This information is summarized in Figure 6-8, Parts A and B. As a whole, the level of participation/use was low for office buildings. The most widely used energy management practice was energy management and control systems. Use of energy management and control systems rises steadily as building size increases (from less than 5 percent in the smallest size category to more than 80 percent in the largest size category). The ten energy management practices shown in Figure 6-8, Parts A and B, serve as a reference point against which the introduction of CBSs can be measured. Specifically, the percentage of floorspace covered by these ten energy management practices provides a range of values against which the potential for use of CBSs can be measured. This subject is covered in considerable detail in Section 6.4.4, where they are used to estimate the level at which the market for CBS products and services reaches saturation.

6.1.3 Other Data Sources

In addition to the information extracted from CBECS, information on maintenance costs, repair costs, amount of floorspace per office worker, and office worker cost per unit of floorspace was needed. The focus of this subsection is on identifying the data sources and presenting the values of key data items. How this information is used to develop estimates of savings per unit of floorspace is described in Section 6.3.1.

Information on the maintenance cost and repair costs per square foot for a typical office building are available from a variety of published sources. Four sources were particularly useful in producing estimated values for the maintenance cost per square foot and the repair cost per square foot. These sources are: (1) International Facilities Management Association (IFMA); (2) Institute of Real Estate Management (IREM); (3) Building Owners and Managers Association International (BOMA); and (4) Whitestone Research.

IFMA is an association serving the facility management profession. IFMA has carried out a number of benchmarking studies covering both the commercial/institutional and

industrial sectors. IFMA's Research Report #13,[39] published in 1994 is the result of a 1993 survey of IFMA members. The report presents benchmarking data derived from 283 survey questionnaires.

IREM is an organization that educates and certifies real estate professionals and carries out a variety of annual surveys of apartment buildings, commercial office buildings, and most recently, open and enclosed shopping centers. The *1997 Income/Expense Analysis: Office Buildings*[40] provides detailed information on operations, maintenance, and energy costs. The 1997 edition presents 1996 data collected from over 2,900 private-sector office buildings across the US and Canada.

BOMA is a trade association providing technical support to its membership in the building management sector. The *1996 BOMA Experience Exchange Report: Operating a Cost Effective Office Building*[41] provides published tables of operating income and expense data for over 4,000 office buildings located throughout North America for fiscal year 1995. The sample includes 3,657 US private-sector properties, 213 US government buildings, 175 private properties in Canada, and 430 government buildings in Canada. The BOMA Report provides detailed descriptions of operations, maintenance, and energy costs for commercial office buildings in both the US and Canada for both the government and private sector, as well as national cross tabulations, and city specific analyses.

The *Whitestone Building Maintenance and Repair Cost Reference 1997*[42] is the third of a series of annual reports produced by Whitestone Research which presents estimates of 50-year maintenance cost profiles for 24 different building models. Building types include fast food restaurants, motels, auto service garages, and supermarkets, as well as office buildings. The profile for each model includes a building description, a list of major building components, and forecasts of maintenance and repair costs at various levels of aggregation over the service life of the building. These can be adjusted for selected metropolitan areas, and modified to include different building components.

In this report, data from the *Whitestone Building Maintenance and Repair Cost Reference 1997* have been used to produce estimated values for the annual per unit maintenance cost and the annual per unit repair cost for a typical office building. These values are $16.04 per square meter ($1.49 per square foot) per year for maintenance, and $6.57 per square meter ($0.61 per square foot) per year for repairs. Note that the value for repair costs used in this report are for mechanical and electrical systems and components only. These values are used as the basis for computing savings due to reduced maintenance and repair costs resulting from the installation of CBS products and services in office buildings.

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[39] International Facilities Management Association. 1994. *Benchmarks II*. Research Report #13. Houston, TX: International Facilities Management Association.
[40] Institute of Real Estate Management. 1997. *1997 Income/Expense Analysis: Office Buildings*. Chicago, IL: Institute of Real Estate Management.
[41] Building Owners and Managers Association International. 1996. *1996 BOMA Experience Exchange Report: Operating a Cost Effective Office Building*. Washington, DC: Building Owners and Managers Association International.
[42] Lufkin, Peter S., and Anthony J. Pepitone. 1997. *Whitestone Building Maintenance and Repair Cost Reference 1997*. Seattle, WA: Whitestone Research.

Information on the amount of floorspace per office worker is available from both IFMA and BOMA reports. Although this information is a useful reference point, data collected as part of CBECS are considered more authoritative. Consequently, the estimated value for the number of square meters per office worker used in this report is based on data from CBECS. The estimated value used in the CBS economic impact assessment is 35.95 square meters (387 square feet) per office worker.

To calculate the annual office worker cost per square meter, it is first necessary to estimate the average annual salary of an office worker. This information is available, both on the national and regional levels, in the County Business Patterns.[43] The "national" average annual salary of an office worker was estimated as the total payroll divided by the total number of employees in five Standard Industrial Classification (SIC) Codes. These five SIC Codes are: 73, business services; 81, legal services; 871, engineering and architectural services; 872, accounting, auditing, and bookkeeping services; and 874, management and public relations services. Based on the County Business Patterns data, the average annual salary of an office worker was estimated to be $30,377 in 1997 dollars. Combining this figure with the average amount of floorspace per office worker produces an estimated annual office worker cost per square meter of $844.90 ($78.49 per square foot). The $844.90 per square meter figure is used as the basis for computing savings expected due to improvements in occupant productivity resulting from the installation of CBS products and services in office buildings.

6.2 Defining the Base Case and the CBS Alternative

The purpose of this section is to define the base case and the CBS alternative to the base case. This "definition step" is done to draw two key distinctions between the base case and the CBS alternative (i.e., the two configurations). These distinctions are important because they facilitate the estimation of the benefits and costs covered in Section 6.3.

It is anticipated that CBS products and services will be installed in both new and existing office buildings. In the case of new office buildings, CBS products and services will be installed during construction. In the case of existing office buildings, CBS products and services will be retrofitted into the building while the building is undergoing renovation. Verification that the CBS products and services once installed are performing "as stipulated" is done as part of a formal building commissioning/recommissioning. If the CBS alternative is not chosen, the same process applies for an installation of the base case. Thus, for new buildings, either the base case or the CBS alternative is installed during construction. Similarly, for existing buildings, either the base case or the CBS alternative is installed while the building is undergoing renovation.

Both the base case and the CBS alternative (i.e., both configurations) have features against which costs, savings, and performance are measured. These features include equipment and software required for heating, cooling, lighting, and life safety. It is

[43] US Department of Commerce. 1995. *County Business Patterns 1993*. CBP-93-1. Washington, DC: Bureau of the Census.

important to recognize that both configurations must meet all building-related performance requirements. This "performance requirement" constraint is needed to ensure that both configurations are comfort-compatible, reliable, serviceable, user-friendly, safe, and at a minimum, neutral with regard to occupant productivity and design aesthetics.[44] The performance requirement applies both to either configuration installed during the construction of a new office building and to either configuration installed during the renovation of an existing office building.

Throughout the remainder of this report, the term base case is used to represent the configuration that maintains the *status quo* (i.e., the use of traditional heating, cooling, lighting, and life safety technologies). The CBS alternative is that collection of products and services (i.e., configuration) that provides equivalent or enhanced performance for all features of the base case while satisfying the definition of a CBS given in Section 3.1.

Based on the definitions of the base case and the CBS alternative, there are two key differences between the two configurations. First, the degree to which the building service features are integrated, automated, and controlled is significantly higher in the CBS alternative. The second difference is that the CBS alternative has the potential to achieve enhanced performance for selected building service features. These differences, although interrelated, are crucial in structuring differences in costs (e.g., due to the installation of additional equipment and software to generate improved systems integration, automation, and control) and savings (e.g., energy cost savings due to improved performance of HVAC and lighting systems) between the two configurations. Quantitative measures of these differences are developed in Section 6.3.

6.3 Estimating Significant Benefits and Costs

This section develops estimates of the key benefits and costs that are the focus of the CBS economic impact assessment. These benefits and costs are well-defined subsets of the comprehensive lists of benefits and costs presented in Chapter 5.

It is important to recognize that every effort has been made to capture and record any cost-related information affecting the users of CBS products and services. Similarly, considerable effort went into documenting or estimating BFRL's CBS-related investments. Relatively less effort went into estimating the full range of CBS-related benefits and cost savings. We focused on what we judged the most substantial and measurable benefits, which we termed the "significant few" benefits. Thus, the return on BFRL's CBS-related investments is expected to be very conservative (i.e., the values presented in this report are lower bounds on the potential range of returns on BFRL's CBS-related investments).

[44] For more information on how to specify performance requirements, see Chapter 2 of Fuller and Petersen (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).

6.3.1 Benefits and Cost Savings

The enhanced performance of HVAC and lighting systems under the CBS alternative *vis-à-vis* the base case produces four types of benefits and cost savings. These benefits and cost savings are: (1) lower energy costs; (2) lower operations and maintenance costs; (3) lower repair and replacement costs; and (4) increased occupant productivity. The first three types listed are readily classified as cost savings. While increased occupant productivity may be thought of as a benefit, this report classifies it as a type of cost savings since it reduces the occupant company's cost of business for a given level of output.

Although the CBS alternative will result in enhanced fire safety performance, no estimates of these, potentially significant, benefits and cost savings are included in the current CBS economic impact assessment. Although subject matter experts have reached consensus on the generic types of benefits and cost savings due to enhanced fire safety performance (see Chapter 5), no such consensus emerged on how to quantify these benefits and cost savings. Similarly, estimates of the cost savings due to the ability to respond to real-time electricity price changes and to aggregate building stock for multi-facility operations are not included. Plans for incorporating such estimates in a future economic impact assessment are described in Section 9.2. It is important to recognize that although the benefits of these features are not included in this assessment, the costs of installing, operating, and maintaining such features are included. This decision was made to maintain the conservative approach of the CBS economic impact assessment.

6.3.1.1 Lower Energy Costs

In Section 6.1.2 information from the 1995 CBECS was presented on the national average energy expenditure per square meter (per square foot). This subsection begins by first updating the 1995 figure of $16.25 to 1997 dollars. This step is necessary because 1997 is the base year for the CBS economic impact assessment (see Section 6.4.1). Converting the 1995 cost per square meter figure to 1997 dollars, produces a value of $17.11 per square meter ($1.59 per square foot).

The next step is to estimate how much the use of CBS products and services will reduce the energy cost per square meter. The estimate used in this report is based on information provided by industry experts and facility operators and managers who were interviewed in the fall of 1998. The consensus among the experts was a range of energy cost savings of between 5 and 15 percent. Consequently, the baseline value used in this report is 10 percent. Estimated baseline annual energy cost savings are thus $1.71 per square meter ($0.16 per square foot). The range of values for energy cost savings (i.e., 5 to 15 percent) is used to set the range of values for annual energy cost savings used in the sensitivity analysis (see Chapter 8).

Because energy prices change over time, it is necessary to develop an energy price index to apply to the per unit energy cost savings. The index is used to produce both annual per unit cost savings and national level energy cost savings on a year-by-year basis. The index used in this report makes use of indices contained in the annual supplement to

NIST Handbook 135[45] and data retrieved from the 1995 CBECS. The indices contained in the annual supplement to NIST Handbook 135 are based on official DOE projections. The data retrieved from the 1995 CBECS were used to compute weights for each of the three major types of energy used in office buildings (i.e., electricity, natural gas, and distillate oil). These weights are 0.915 for electricity, 0.075 for natural gas, and 0.010 for distillate oil. These weights are applied to the three sets of energy price indices recorded in Table Ca-5[46] of the annual supplement to NIST Handbook 135. The three computed values for each year between 1997 and 2015 (i.e., the product of each energy price index for each year and its weight) are then summed to get a weighted time series for energy for office buildings. Table 6-1 shows the results of the process just described. The first three columns of the table are the annual values of the price index for each energy type taken from Table Ca-5 of the annual supplement to NIST Handbook 135. The last column is the weighted time series for energy for office buildings.

6.3.1.2 Lower Operations and Maintenance Costs

The use of CBS products and services will lower the costs of operating and maintaining office buildings. How much these costs are reduced depends on a number of factors, such as, the ability to reduce overtime expenses, to reconfigure operations and maintenance staff functions, and to use third-party operations and maintenance contractors. The focus of this subsection is on annual maintenance costs; it uses the value of $16.04 per square meter ($1.49 per square foot) published by Whitestone Research (see Section 6.1.3) as its reference point. Note that all dollar amounts are expressed in 1997 dollars.

To develop a range of estimates for annual per unit maintenance costs savings, industry experts and facility managers and operators were interviewed during the fall of 1998. The general consensus was that a significant proportion of overtime expenses could be eliminated (estimates ranged up to 80 percent). In addition, many occupant complaints related to heating and cooling problems could be handled remotely. Maintenance staff could then follow-up during normal work hours to ensure that the problem had been solved. The advantage of this approach is that it enabled both smaller crew sizes and the ability to handle more client-initiated requests with a given size of maintenance staff. Based on these inputs, cost savings were estimated to range from 5 percent to 20 percent. This range of values is used to specify the range of values for maintenance cost savings used in the sensitivity analysis (see Chapter 8). The baseline value for annual per unit maintenance cost savings used in the economic impact assessment is 10 percent, or $1.60 per square meter ($0.15 per square foot).

[45] Fuller, Sieglinde K. 1997. *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis*. NISTIR 85-3273-12. Gaithersburg, MD: National Institute of Standards and Technology.
[46] *Ibid*., pp. 36-37.

Table 6-1. Projected Fuel Price Indices (excluding general inflation) by Fuel Type and Weighted Time Series for Energy

Year	Projected Electricity Price Index	Projected Natural Gas Price Index	Projected Distillate Oil Price Index	Weighted Time Series for Energy
1997	1.00	1.00	1.00	1.000
1998	1.00	1.00	0.99	1.000
1999	1.00	1.00	1.00	1.000
2000	0.99	1.01	1.01	0.992
2001	0.98	1.00	1.02	0.982
2002	0.98	1.01	1.03	0.983
2003	0.97	1.01	1.04	0.974
2004	0.96	1.00	1.05	0.964
2005	0.95	1.00	1.06	0.955
2006	0.95	0.99	1.07	0.954
2007	0.94	0.99	1.07	0.945
2008	0.94	0.98	1.07	0.944
2009	0.94	0.97	1.08	0.944
2010	0.93	0.97	1.09	0.935
2011	0.92	0.96	1.08	0.925
2012	0.91	0.96	1.07	0.915
2013	0.89	0.96	1.07	0.897
2014	0.89	0.96	1.07	0.897
2015	0.90	0.96	1.07	0.906

6.3.1.3 Lower Repair and Replacement Costs

The use of CBS products and services will allow systems and equipment to operate under near optimal conditions for extended periods of time. In addition, through the use of FDD technologies, equipment and component malfunctions can be diagnosed and remedied before a catastrophic failure occurs. As a result, equipment life will be extended, fewer replacements will be required, and replacement costs will decline. Furthermore, having better diagnostic tools will enable support staff to more quickly and effectively repair equipment and components. These improvements will result in lower repair costs over the useful life of a major system (e.g., HVAC).

To estimate how much annual per unit repair and replacement costs will be reduced, we begin with the long-term average per unit repair and replacement cost for mechanical and

electrical systems published by Whitestone Research (see Section 6.1.3). The resultant figure is $6.57 per square meter ($0.61 per square foot). Note that all dollar amounts are expressed in 1997 dollars.

It is important to recognize that this study uses mechanical and electrical systems as its reference point rather than the entire range of building systems. This approach was taken to ensure that the values were reflective of systems, equipment, and components likely to be affected by the use of CBS products and services. For example, interior finishes, exterior closures, roofing, and interior construction did not appear to be affected in any significant way by the use of CBS products and services. Consequently, their long-term repair and replacement costs are excluded from the reference data point (i.e., $6.57 per square meter) used in this study. Based on these inputs, cost savings were estimated to be 10 percent. Thus, the baseline value for annual per unit repair and replacement cost savings used in the economic impact assessment is $0.66 per square meter ($0.06 per square foot).

6.3.1.4 Increased Occupant Productivity

The use of CBS products and services will increase occupant comfort by providing HVAC and lighting systems with enhanced operating performance *vis-à-vis* the base case configuration. Industry and government studies have shown that the annual salary costs of the occupants of a commercial or institutional building are of the same order of magnitude as the capital cost of the building.[47] Studies[48,49,50] have shown that the quality of indoor environments also has a large impact on occupant health and productivity. Improvement of the productivity of occupants is an important performance characteristic for most constructed facilities. National Construction Goal 3 targets a 30 percent increase in occupant productivity and comfort.[51]

Improvements in comfort and control can have major impacts on worker productivity. A recent article by Lomonaco and Miller[52] surveyed a number of studies on the effects of improvements in comfort and control. They concluded that the physical environment could have a measurable impact on worker productivity of about 3 to 15 percent.[53]

It is important to recognize that some improvements in occupant productivity are likely under the base case configuration. Thus, the task at hand is concerned with estimating how much productivity improvement over and above the base case configuration will be

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[47] Wright, Rosenfeld, and Fowell. *Construction and Building*, p. 8.
[48] Fisk, William J., and Arthur H. Rosenfeld. 1977. "Estimates of Improved Productivity and Health from Better Indoor Environments," *Indoor Air* (Vol.7): pp. 158-172.
[49] Lorsch, Harold G., and Ossama A. Abdou. 1994. "The Impact of Building Indoor Environment on Occupant Productivity," *ASHRAE Transactions*: pp. 895-901.
[50] Kroner, Walter M., and Jean A. Stark-Martin. 1994. "Environmentally Responsive Workstations and Office-Worker Productivity," *ASHRAE Transactions*: pp. 750-755.
[51] Wright, Rosenfeld, and Fowell. *Construction and Building*, pp. 7-9.
[52] Lomonaco, Carol, and Dennis Miller. 1997. "Comfort and Control in the Workplace," *ASHRAE Journal* (September): pp. 50-56.
[53] *Ibid*., p. 55.

generated through installation of the CBS alternative. Because professional opinion on the range of values for productivity improvement is so broad, we have chosen to use a very conservative estimate, which has a high probability of being achieved. In addition, the range used in this study includes the possibility that no improvements in occupant productivity result from the installation of CBS products and services (i.e., the lowest value used is 0 percent). Similarly, the maximum improvement in occupant productivity used in this study is 1 percent. This 0 to 1 percent range of values is used for improvements in occupant productivity in the sensitivity analysis (see Chapter 8). The baseline value for improvement in occupant productivity is 0.5 percent. Thus, the baseline value for annual per unit cost savings due to improvements in occupant productivity is $4.20 per square meter ($0.39 per square foot).

6.3.2 Costs and Benefit Reductions

Two types of costs—higher costs to building owners and managers and increased research and development costs—are central to this economic impact assessment. Understanding the types of costs that affect building owners and managers is necessary in order to estimate annual values of net savings on a national level. These estimates affect not only the present value of net savings nationwide, but the estimated return on BFRL's CBS-related investments as well. The second type of costs, increased research and development costs, focuses only on BFRL's CBS-related investments. No estimates of the investments required to develop, test, and market CBS products and services by the vendor tier (see Figure 3-1) are included in this subsection. Plans for incorporating these costs in a future economic impact assessment are described in Section 9.2.

6.3.2.1 Higher Costs to Building Owners and Managers

If building owners and managers install the CBS alternative rather than the base case, they can expect to bear four types of additional costs (see Table 5-6). These costs are: (1) higher evaluation costs; (2) higher first costs; (3) increased costs of adapting new building products and services to industry use; and (4) increased training costs.

With the exception of higher first costs, the three remaining costs may be classified as new-technology introduction costs. Ehlen and Marshall[54] define new-technology introduction costs as those costs covering the activities that bring the material/product from the research laboratory to full field implementation. New-technology introduction costs include the extra time and labor to design, test, monitor, and use the new technology. Ehlen's and Marshall's research on new-technology introduction costs is particularly relevant for this economic impact assessment because they demonstrate that new-technology introduction costs disappear once the designer is satisfied with the technology's performance and service life, the technology enters full implementation, and its application has become routine.[55]

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[54] Ehlen, Mark A., and Harold E. Marshall. 1996. *The Economics of New-Technology Materials: A Case Study of FRP Bridge Decking*. NISTIR 5864. Gaithersburg, MD: National Institute of Standards and Technology.
[55] *Ibid.*, p. 15.

Higher first costs from installing a CBS are expected due to the increased use of sensors. While the increased use of sensors will result in higher first costs, the use of open systems is not expected to increase first costs. Discussions with industry experts leads to the conclusion that any "premium" attached to the costs of open systems would be quickly eliminated through a competitive procurement process. In addition, the increased first cost associated with the increased use of sensors is likely to decline over time due both to improved sensor technology and increased competition.

Finally, the establishment of the VCBT will enable manufacturers to bring actual control products that they have under development, obtain assistance in testing and evaluating their performance, and perform interoperability tests with other manufacturers. Thus, both higher costs in the form of new-technology introduction costs and first costs in general are expected to decline over time. However, in keeping with the conservative approach employed in this economic impact assessment, these costs are held constant throughout the study period. Specifically, an additional cost of $10.76 per square meter ($1.00 per square foot) is assigned when an office building first installs the CBS alternative. Discussions with industry experts were used to specify a conservative value for this additional cost. As more information becomes available, the estimated value of $10.76 per square meter will be revised (see Section 9.2).

6.3.2.2 Increased Research and Development Costs

BFRL launched a multidisciplinary CBS research effort in Fiscal Year (FY) 1998. This effort and the six projects that support the overall CBS effort are described in Chapter 3. Because CBS products and services are targeted for demonstration in 2002 and commercial availability in 2003, BFRL's highest level of investment is for FY1998 through FY2002. Beginning in FY2003, BFRL's CBS-related investments will decline rapidly.

It is also important to recognize that BFRL's research on BACnet was crucial to the establishment of its overall CBS effort. Consequently, BFRL's BACnet-related investments between FY1991 and FY1997 are included as part of its CBS-related investments. FY1991 was chosen as the starting point, since by that time BFRL's research on BACnet had reached a high-level of maturity.

BFRL's CBS-related investments are summarized in Table 6-2. The first two columns of the table record *actual investments* by Fiscal Year in thousands of dollars for Fiscal Years FY1991 through FY1997. The second two columns of the table record *actual investments* by Fiscal Year in thousands of dollars for Fiscal Years FY1998 and FY1999 and *estimated investments* for FY2000 through FY2004. Note that all values recorded in Table 6-2 are on a Fiscal Year basis. Because the vast majority of BFRL's investment costs are staff-related costs, it is straightforward to convert Fiscal Year dollars to calendar year dollars. This conversion is necessary, because the values presented in Chapters 7 and 8 are on a calendar year basis. For example, the estimated FY2000 investment is

$2,000,000. Of the $2,000,000 total, 25 percent, or $500,000, is allocated to calendar year 1999, and 75 percent, or $1,500,000, is allocated to calendar year 2000.

Table 6-2. BFRL Investment Costs by Fiscal Year

Fiscal Year 1991 - 1997	BFRL Actual Investment Costs (In Thousands of Dollars)	Fiscal Year 1998 - 2004	BFRL Investment Costs (In Thousands of Dollars)
1991	300	1998	1,390[a]
1992	291	1999	1,610[a]
1993	200	2000	2,000[e]
1994	190	2001	2,500[e]
1995	190	2002	2,500[e]
1996	300	2003	1,000[e]
1997	300	2004	500[e]

a = actual investment costs
e = estimated investment costs

6.4 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. 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; (3) the discount rate; (4) the process by which CBS products and services diffuse into the marketplace; and (5) the process by which BFRL's contribution is measured. The assumed values of these five key sets of parameters figure prominently in evaluating the economic impacts of CBS products and services. 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 and savings 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.

The base year establishes the anchor point for all cost and savings calculations. The starting and ending points in the study period define both the scope of the study period—those years over which costs and savings are tabulated—and the length of the study period—a key parameter in the AIRR calculation. Because cash flows, both costs and savings, are distributed throughout the study period, the choice of the discount rate is of central importance to the analysis. The diffusion process is the critical link between per unit savings (see Section 6.3.1) and cost savings nationwide (see Section 7.2). The model

of the diffusion process presented in Section 6.4.4 provides the basis for calculating year-by-year savings following the introduction of CBS products and services. Because BFRL's CBS-related research is expected to speed up the introduction of CBS products and services into the commercial marketplace, a process for evaluating the "value" of BFRL's contribution is needed. This process is described in Section 6.4.6.

In addition to the five key sets of parameters used to make explicit the assumptions of the economic impact assessment, there are issues linking the baseline analysis to the sensitivity analysis. These "analysis issues" are concerned with the discount rate, the diffusion process, measuring BFRL's contribution, and dealing with uncertainty. The first three analysis issues, in conjunction with per unit savings, provide the necessary linkage between the baseline analysis and the sensitivity analysis. They are crucial in measuring how variations about the baseline input values affect the economic outcome measures. The last analysis issue, dealing with uncertainty, is the core concept in structuring the sensitivity analysis. This analysis issue is discussed in Section 6.4.5.

6.4.1 Base Year for Computing Benefits and Costs

The base year for computing all CBS-related costs and savings is 1997. There are two reasons, one primary and one secondary, why 1997 was selected as the base year.

(1) 1997 marks the year in which BFRL formed an integrated CBS project team. BFRL is working towards a fully operational CBS being tested and deployed in a full-scale demonstration project by 2002. Thus, by using 1997 as the base year, this economic impact study maintains its *ex ante* (i.e., prospective) nature while still being rooted in the present.

(2) 1997 is the latest year for which authoritative and comprehensive construction industry cost data are available. Thus, cost conversions for previous years may be accomplished through the use of a well-defined cost index to equate them to constant 1997 dollars. Similarly, estimated energy costs and associated energy cost savings for subsequent years may be equated to constant 1997 dollars based on official projections (i.e., energy cost indices) published by DOE.

6.4.2 Length of the Study Period

The study period begins in 1991 and ends in 2015. Thus, the length of the study period is 25 years. Any costs and/or savings that occur after 2015 are not included. Two factors were instrumental in determining the beginning and end of the study period.

(1) The study period begins in 1991, which is when BFRL's research on BACnet had reached a high-level of maturity. BFRL's research on BACnet is crucial to the overall CBS effort, as BACnet provides the communication protocol for all major CBS products and services. However, major investments in the overall CBS effort did not begin until 1997, when BFRL formed an integrated CBS project team.

BFRL's CBS-related investments will continue at a fairly high level until 2002, at which point they will rapidly decline.

(2) The end of the study period is 2015. By 2002, BFRL will be completing a full-scale demonstration project. By 2003, the first commercial applications of CBS products and services are anticipated (i.e., other than demonstration projects). Thus, 2003 marks the point at which CBS products and services penetrate the commercial marketplace. By 2015, the use of CBS products and services is expected to be widespread.

6.4.3 Discount Rate

The baseline analysis for the CBS economic impact assessment uses a real rate of 7 percent to convert dollar amounts to present values. This rate is specified in Section 8.b of *OMB Circular A-94*[56] as the rate for all benefit-cost analyses of public investments and regulatory programs that provide benefits or incur costs to the general public. For purposes of this analysis, all CBS-related research costs are classified as a public investment. The benefits that accrue to the public are in the form of cost savings, including improvements in occupant productivity.

OMB recommends that separate analyses be used to evaluate the sensitivity of key economic measures to variations in the discount rate.[57] The sensitivity analysis presented in Chapter 8 evaluates the implications of raising the discount rate to 10 percent or lowering the discount rate to 4 percent. All values of the discount rate used in this report are real rates, since constant dollar estimates of benefits and costs are used.

Readers familiar with energy conservation practices will recognize that the discount rate used in the baseline analysis and the discount rates used in the sensitivity analysis are higher than the DOE discount rate for 1997, which was 3.8 percent real (i.e., net of general price inflation).[58] Because energy cost savings occur in the future (i.e., once CBS products and services become available commercially) a lower value for the discount rate will increase the present value of these savings. Conversely, a higher value for the discount rate will decrease the present value of these savings. Higher rates are used in this study to ensure that the return on BFRL's CBS-related investments calculated both in the baseline analysis and in the sensitivity analysis are very conservative.

6.4.4 Diffusion Process

Facts and data are essential components in any rigorous analysis. Factual information on the number of office buildings was tabulated from published sources (see Section 4.3). These data provide the basis for estimating the likely per unit savings (i.e., annual cost savings per square meter) associated with the use of the CBS products and services in

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[56] Executive Office of the President. 1992. *OMB Circular A-94*. Washington, DC: Office of Management and Budget.
[57] *Ibid*., p. 7.
[58] Fuller, *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis*, p. 1.

office buildings (see Section 6.3.1). However, to develop realistic estimates of cost savings nationwide, it is also necessary to generate estimated values for the following three factors: (1) the overall rate of adoption of CBS products and services in office buildings; (3) the annual amount of office floorspace receiving new CBS installations; and (3) the total amount of office floorspace covered by CBS products and services. To generate estimates of cost savings nationwide, information on per unit savings must be coupled with a model of the diffusion process. Much of the discussion in this section and in Section 7.2 of the next chapter is aimed at establishing an audit trail for how the values of these three factors were established and employed in the economic impact assessment. The focus of this section is on how the diffusion process is modeled (i.e., the form of the model and its key parameter values). Section 7.2 focuses on how the diffusion model is employed in the economic impact assessment.

An economy is not affected in any material way by a new technology until the use or ownership of that technology is widespread. This spread of a new technology is a topic usually referred to as technological diffusion. It is modeled via a diffusion process. The underlying basis for the study of technological diffusion is to rationalize why, if a new technology is superior, it is not taken up immediately by all potential users.

The empirical analysis of diffusion processes is a vast and complex subject. Although a full treatment of the topic is beyond the scope of this report, four factors affecting the diffusion process are worth noting. Readers interested in thorough treatments of this important subject, including case studies, are referred to the books by Stoneman[59] and Mansfield.[60]

First, new technology and its adoption involve uncertainty. Thus, the attitude of decision makers to uncertainty needs to be considered. The degree of uncertainty may be related to the level of use of the new technology and to how learning proceeds.

Second, how learning proceeds affects the diffusion process in a number of ways. It can involve learning about the existence of a new technology or learning about its true characteristics. For example, firms might learn about how to use the new technology to produce new or current products at lower cost. For a given initial state of knowledge, the faster that learning occurs, the higher the rate of diffusion.

Third, during a diffusion process, how learning proceeds may not be the only factor changing. The good itself may be improving. This improvement may have a double-edged effect on diffusion: a direct effect, stimulating greater use; and an indirect effect, whereby expectations of future advances may lead to the postponement of adoption.

Fourth, to a large degree the adoption decision for the firm will be related to expected profitability, which in turn will be dependent upon a number of factors. Thus differences

[59] Stoneman, Paul. 1983. *The Economic Analysis of Technological Change.* New York: Oxford University Press.
[60] Mansfield, Edwin. 1995. *Innovation, Technology and the Economy: Selected Essays of Edwin Mansfield.* 2 vols. Economists of the Twentieth Century Series. Aldershot, UK:Elgar.

between firms will be important, as may be the behavior of the industry supplying any new goods. The market structure of the user and supplying industries (i.e., situations involving imperfect competition) are also important.

The most widely accepted model of technology diffusion was developed by Edwin Mansfield. Consequently, the Mansfield model is employed in the CBS economic impact assessment. The Mansfield model estimates the proportion of potential users who have adopted the new technology by time *t*. The mathematical representation of the model is

$$P(t) = \left[1 + e^{(a - b\ t)}\right]^{-1}$$

where

P(t) = the proportion of potential users who have adopted the new technology by time *t*,

e = Euler's number, the base of the natural system of logarithms,

" = the location parameter, and

$ = the shape parameter ($ > *0*).

A plot of *P(t)* produces an S-shaped logistics curve, which is asymptotic to 0 as the value of *t* gets small and to 1 as the value of *t* gets large. Because the diffusion of a new technology may not achieve 100 percent penetration of the marketplace, *P(t)* must be modified to reflect the level at which the potential market is saturated. The version of the Mansfield model employed in this report uses a subscript *0* to designate the market saturation level. The mathematical representation of the model is

$$P_h(t) = h\ \left[1 + e^{(a - b\ t)}\right]^{-1}$$

where

P0(t) = the proportion of potential users who have adopted the new technology by time *t*,

0 = the market saturation level,

e = Euler's number, the base of the natural system of logarithms,

" = the location parameter, and

$ = the shape parameter ($ > *0*).

An extensive review of the economics literature on the diffusion process produced candidate values for " and $. Readers interested in case studies based on the Mansfield model that are useful in specifying values for " and $ are referred to Mansfield's

collection of articles.[61] An additional factor used to specify the values of *"* and *$* is the length of time it takes for $P_0(t)$ to reach 50 percent of its "designated" potential market (i.e., η/2). Due to the relationship between the Mansfield model and the logistics distribution, the value at which $P_0(t)$ reaches 50 percent of its designated potential market has a closed-form relationship based solely on the values of *"* and *$*. If we assume *t = 1* is the time at which the technology is first introduced, then *" /$* is the number of years it takes that technology to reach 50 percent of its designated potential market. In order to get a meaningful value of *t*, it is necessary to constrain *"* to be positive (i.e., *" > 0*).

The values of the ratio *" /$* range from 8 years to 12 years in a wide range of articles published in the economics literature (see Mansfield,[62] Mansfield *et al*,[63] and Simon[64]). Consequently, this report uses a value of *10* for the ratio *" /$* as its baseline value. The corresponding baseline values for *"* and *$* are *6.0* and *0.6*, respectively.

In order to produce an estimate for *0*, data on the use of energy management practices were analyzed. These data were summarized in Figure 6-8 and are recorded in a slightly different form in Table 6-3. The estimated value for *0* was set equal to the median value of the 10 energy management practices recorded in Table 6-3. Thus, the baseline value for *0* is *0.1754*. This means that CBS products and services will eventually be installed in 17.54 percent of the nation's 973 million square meters (10,478 million square feet) of office floorspace. This estimate is considered to be conservative. For example, nearly 40 percent of office floorspace is covered by energy management and control systems. Thus, the estimated savings nationwide and the value of BFRL's contribution may be considered to be lower bound estimates.

The specification of the baseline values of the diffusion model is not complete until a *time of first use* is made explicit. As noted earlier, the time of first use corresponds to the value at which *t = 1*. The time of first use is based on the assumption that the demonstration project will be completed in 2002. Once the demonstration project has been completed, CBS products and services will become available commercially. Thus, the baseline value for the *time of first use* is *2003*.

The values of *"* and *$* specify the rate of adoption of CBS products and services in office buildings, whereas the value of *0* specifies the size of the potential market for these products and services. Consequently, once the time of first use is made explicit, it becomes possible to estimate the total amount of office floorspace covered by CBS products and services. For any given year, this amount is equal to the product of $P_0(t)$ for that year and the total amount of office floorspace (i.e., 973 million square meters). It is also necessary to estimate the annual amount of floorspace receiving new CBS installations. This amount is based on the annual change in value of $P_0(t)$; it is

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[61] Mansfield, *Innovation, Technology and the Economy*, Vol. II, pp. 3-83.
[62] *Ibid*., pp. 63-72.
[63] Mansfield, Edwin, John Rapport, Anthony Romeo, Edmond Villani, Samuel Wagner, and Frank Husic. 1977. *The Production and Application of New Industrial Technology*. New York: W. W. Norton & Company, Inc.
[64] Simon, P. 1975. *Models of Process Diffusion and Entry in the U.S. Chemical Industry*. Ph.D. dissertation, University of Pennsylvania.

designated as $)P_0(t)$. The value of $)P_0(t)$ is defined as: $)P_0(t) = P_0(t) - P_0(t\text{-}1)$. Thus, for any given year, the amount of new CBS installations is equal to the product of $)P_0(t)$ for that year and the total amount of office floorspace. Table 6-4 records the values of $P_0(t)$ and $)P_0(t)$ for values of *t* from 0 to 18 (i.e., from 2002 to 2020). Note that the years shown on the table extend past the end of the study period.

Table 6-3. Percent of Total Office Floorspace Covered by Selected Energy Management Practices

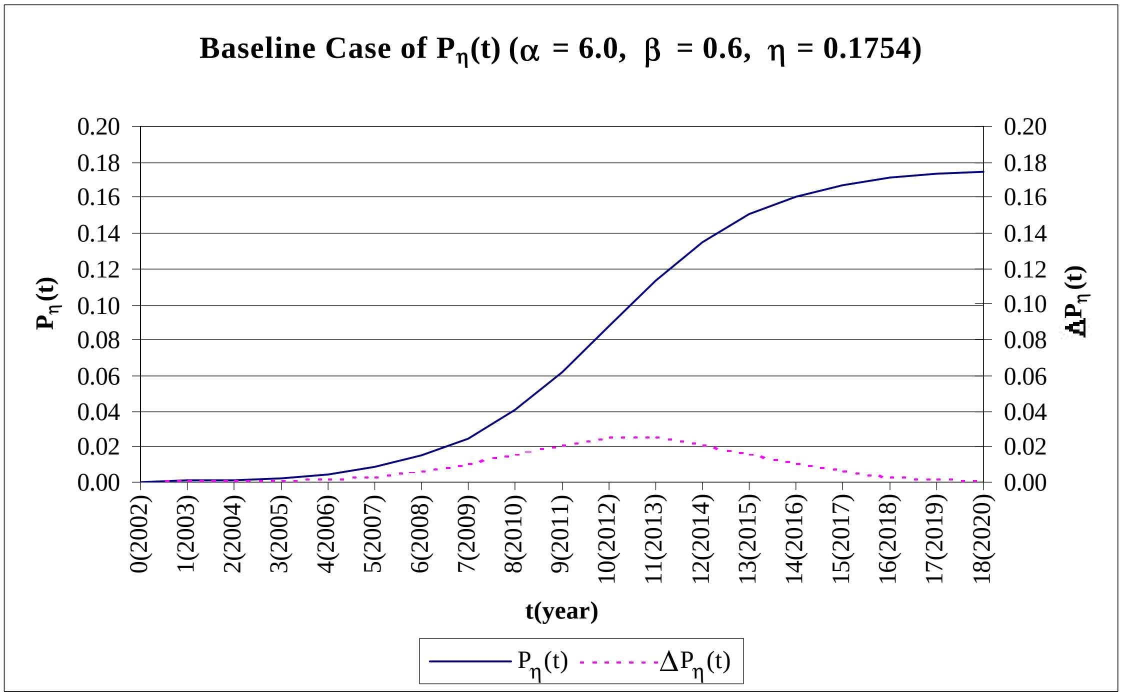
Energy Management Practice	Percent of Total Floorspace per Office Building Size Category			
	1,001 to 25,000 Square Feet	25,001 to 100,000 Square Feet	Over 100,000 Square Feet	All Office Buildings
Thermal Energy Storage	0.14	2.59	3.58	2.14
Interruptible Natural Gas	1.37	4.52	10.88	5.91
Waste-Heat Recovery	0.21	4.46	16.66	7.74
Energy-Efficient Water Heating Equipment	6.61	17.52	21.00	15.14
Electricity Load Control	4.10	12.92	30.10	16.57
Special Rates or Incentives	6.79	13.69	32.20	18.51
Building Energy Manager	5.41	17.04	36.64	20.67
Energy Audit	10.29	18.12	32.02	20.84
Energy-Efficient Motor System	7.04	22.68	55.50	30.07
Energy Management and Control System	5.88	30.20	70.72	37.60

Table 6-4. Baseline Case of $P_\eta(t)$ and $\Delta P_\eta(t)$ ($\alpha = 6.0$, $\beta = 0.6$, $\eta = 0.1754$)

Year	t	P(t)	ΔP(t)
2002	0	0.0000	0.0000
2003	1	0.0008	0.0008
2004	2	0.0014	0.0006
2005	3	0.0026	0.0012
2006	4	0.0047	0.0021
2007	5	0.0083	0.0037
2008	6	0.0146	0.0063
2009	7	0.0249	0.0103
2010	8	0.0406	0.0157
2011	9	0.0622	0.0216
2012	10	0.0877	0.0255
2013	11	0.1132	0.0255
2014	12	0.1348	0.0216
2015	13	0.1505	0.0157
2016	14	0.1608	0.0103
2017	15	0.1671	0.0063
2018	16	0.1707	0.0037
2019	17	0.1728	0.0021
2020	18	0.1740	0.0012

The diffusion model, as specified above and used in the baseline analysis, is plotted in a graphical form in Figure 6-9. The trace of $P_0(t)$ is shown as a solid line in Figure 6-9. The trace of)$P_0(t)$ is shown as a dashed line in Figure 6-9. The trace of)$P_0(t)$ is included to show how new CBS installations track against total installations. The figure includes both a left and right vertical axis. The left vertical axis of Figure 6-9 records the values of $P_0(t)$. The right vertical axis of Figure 6-9 records the values of)$P_0(t)$. The values on both vertical axes range from 0 to *0*. The horizontal axis of Figure 6-9 records the values of *t* and the years for which values of $P_0(t)$ and)$P_0(t)$ are calculated. Recall that in the baseline analysis $t = 1$ corresponds to the year 2003. Note that the years shown on the horizontal axis extend past the end of the study period. This is done to show that $P_0(t)$ does not approach the market saturation level, *0*, until well after the study period is over. Thus, substantial cost savings due to the use of CBS products and services will continue to accrue well after the end of the study period. Once again, this leads to the conclusion that the estimated savings nationwide are a lower-bound estimate.

Figure 6-9. Baseline Case of $P_\eta(t)$ and $\Delta P_\eta(t)$ by t(year)



Much of the sensitivity analysis is concerned with the diffusion model (see Chapter 8). As such, ranges of values were specified for *"*, *$*, *0*, and the *time of first use*. The ranges for *"* and *$* were selected based on values of *"* and *$* published in the economics literature ***and*** their implications for the values of the ratio *"/$* also published in the economics literature. The range of values for *"* used in the sensitivity analysis are a low of 5 and a high of 7 (i.e., 5 ≤ *"* ≤ 7). The range of values for *$* used in the sensitivity analysis are a low of 0.5 and a high of 0.7 (i.e., 0.5 ≤ *$* ≤ 0.7). These ranges of values for *"* and *$* result in a range of the ratio *"/$* which is consistent with the values published in the economics literature (i.e., 7.14 ≤ *"/$* ≤ 14.0).

The range of values for *0* is based on the range of values for the 10 energy management practices recorded in Table 6-3. Specifically, the estimated values of 10^{th} and 90^{th} percentiles for the data recorded in Table 6-3 are used. These values range from a low of 5.53 percent to a high of 30.82 percent (i.e., 0.0553 ≤ *0* ≤ 0.3082).

The range of values for the *time of first use* are based on expected times (i.e., years) at which CBS products and services will be available commercially. These times range from a low of 2002 to a high of 2005. That is, the earliest date at which CBS products and services are commercially available is in the year 2002 and the latest date is 2005. The alternative times of first use are specified by a discrete distribution, also known as the multinomial distribution. The discrete probabilities for each year are: 2002, 0.125; 2003, 0.5; 2004, 0.25; and 2005, 0.125.

6.4.5 Dealing with Uncertainty

Uncertainty enters into a benefit-cost analysis in three main ways. First, the value of cash flows (i.e., benefits, costs, and savings) may not be known with certainty. For example, a new technology may not be well understood by many potential users, implying that their benefits of adopting the technology may be subject to considerable variability. Consequently, decision makers are presented with a range of potential benefit values (e.g., high, moderate, and low). As the technology becomes better known, this range of values may be reduced (i.e., uncertainty, in the form of benefit variability, is being reduced with time as new information becomes available). In addition, variations in the discount rate affect the present value of any cash flows which do not occur in the base year.

Second, the timing of cash flows may not be known with certainty. In the case of a new technology, the process by which the technology diffuses to firms and households may take many time paths.[65] For example, one time path might imply slow adoption at first followed by a period of rapid adoption. Such might be the case if, shortly after introduction, the technology were adopted as a standard. Alternatively, the new technology might enjoy a brief period of rapid adoption followed by a relatively long period of slow adoption. Such might be the case if, after introducing the new technology, there were a series of product improvements that caused many potential users to adopt a "wait and see" attitude.

Third, the value, timing, and magnitude of cash flows may not be known with certainty. This "composite" source of uncertainty is more complex than the two cases just discussed. It includes three issues related to the time path overlaid by variability in benefits, costs, and savings. The three time path issues are related to the *time of first use* (i.e., when the technology is introduced to the market place), the *rate of adoption* over the time path, and the *level of adoption* that prevails when the market reaches saturation. Although the introduction of a new technology can be expected to result in variability of benefits, costs, and savings for users which adopt it (i.e., there is some uncertainty about the values of these cash flows and, via the discount rate, their present values), the case at hand is more complex. Variations in the time of first use and the rate of adoption are the principal sources of variability in the timing of cash flows. Variations in the level of adoption enter as factors affecting both the values and the magnitudes of cash flows. This is because the level of adoption comes into play as a multiplicative factor applied to any given time path. While different times of first use and rates of adoption affect the timings of cash flows, different adoption levels affect the values (i.e., due to its being overlaid by the variability in benefits, costs, and savings) and magnitudes (i.e., due to its

[65] The time paths by which a new technology may diffuse have several characteristics that are important. First, there is a *time of first use* (i.e., when the technology is introduced to the market place). If the time of first use is considered fixed, then it is the same for all that technology's time paths. Second, for each time path, there is a *rate of adoption*; the rate of adoption affects the slope of the time path. It is important to recognize that the slope of the time path need not be the same at different points on the time path. Finally, there is a *level of adoption* that prevails when the market reaches saturation.

affect on the size of the potential market) of these cash flows. Consider the case of the direct benefits to users from adopting a new technology. Other things being equal, higher levels of adoption result in larger benefit streams and higher variability (i.e., a wider range of values) of those benefit streams across all time paths than do lower levels of adoption.

6.4.6 Measuring BFRL's Contribution

This section describes the process used to measure the "value" of BFRL's contribution leading to the development and use of CBS products and services in office buildings. It begins with a review of the nature of BFRL's contribution.

BFRL's contribution serves two vital roles. One is that of a facilitator, and the other is that of a developer of key CBS enabling technologies. Both roles are crucial if commercial products and services are to be developed in a timely manner.

BFRL's role as facilitator has three facets. First, BFRL has formed a consortium of manufacturers and service providers interested in producing, testing, demonstrating, and selling CBS products and services. Second, BFRL has established the VCBT to facilitate the development and evaluation of new products and systems by manufacturers and external service providers. Third, BFRL is working towards a fully operational CBS being tested and deployed in a full-scale demonstration project by 2002.

BFRL's role as developer of key CBS enabling technologies is extensive and pervasive; it spans all six projects in the integrated CBS project team (see Section 3.2). However, four areas of BFRL's research and development effort are particularly important, since they provide platforms on which vendors can develop commercial products and services. First, BFRL is developing and testing standard communication protocols for the open exchange of information. Second, BFRL is developing advanced measurement technologies. Third, BFRL is developing performance measures, standards, and evaluation tools for protocol compliance testing, real time monitoring, and the evaluation and documentation of CBS interactions. Fourth, BFRL is developing interoperability testing and certification programs to facilitate the development and introduction of CBS products and services into the marketplace.

This review of the nature of BFRL's contribution makes it clear that BFRL is a catalyst in the development of CBS products and services. Does this mean that CBS products and services would not be developed without BFRL's participation? The answer to that question is an unequivocal "No." Eventually, CBS products and services would become commercially available. Would they have the same capabilities? The answer to that question is a qualified "Probably not." The reasoning stems from the fact that the nature of BFRL's dual role is one that few organizations can fill. Consider the case of an enabling technology. Few if any vendors will invest in enabling technologies, since they can not adequately recapture their investment. In fact, other vendors might be able to employ the enabling technology to develop their own proprietary products. BFRL and NIST do not have this problem, since a key part of their mission is to promote competitiveness through the development of enabling technologies. A similar reasoning

holds for BFRL's role as a facilitator. Thus, BFRL's contribution both serves to speed up the introduction of CBS products and services and to result in products and services with better understood properties and, in all likelihood, better capabilities. The remainder of this section focuses on how to measure the value of BFRL's contribution in speeding up the introduction of CBS products and services.

Because BFRL's research effort is expected to result in a faster introduction of CBS products and services into the commercial marketplace, those savings which would have been foregone in the event of a delay are attributable to BFRL. Information from subject matter experts and similar economic impact assessments[66] was used to develop an estimate of how much the commercial introduction of CBS products and services would have been delayed, were it not for BFRL's dual role as a facilitator and developer of key CBS enabling technologies. Without BFRL's involvement, the likely delay for the commercial introduction of CBS products and services is estimated to be seven years (i.e., commercial introduction in 2010 rather than in 2003). Therefore, any savings prior to the "delayed" introduction of CBS products and services in 2010 would have been foregone. Such an accounting framework may be handled through use of a 0-1 weighting factor. For those years in which savings are attributable to BFRL, the weighting factor takes on a value of 1. For all years after the "delayed" introduction of CBS products and services in 2010, the weighting factor takes on a value of 0.

An important part of the sensitivity analysis is concerned with measuring changes in the value of BFRL's contribution. The value of BFRL's contribution is measured through the use of a 0-1 weighting factor tied to an estimated delay for the commercial introduction of CBS products and services. In the sensitivity analysis, a range of values for the estimated delay for the commercial introduction of CBS products and services is specified. The range of values draws on the same information used to develop the baseline value (i.e., the likely delay). The range of values used in the sensitivity analysis is a low of four years and a high of ten years. To better understand how the range of values is used in the sensitivity analysis, consider the case where the time of first use is 2003 (i.e., the baseline value). If the estimated delay is four years, then the weighting factor takes on a value of 1 for those years up to and including 2006 and a value of 0 from 2007 until the end of the study period. If the estimated delay is ten years, then the weighting factor takes on a value of 1 for those years up to and including 2012 and a value of 0 from 2013 until the end of the study period.

[66] Chapman and Weber, *A Case Study of the Fire Safety Evaluation System*, pp. 31-42.

7. Baseline Analysis of Economic Impacts

The baseline analysis presented in this chapter is the reference point for the CBS impact assessment. Recall that in the baseline analysis, all data entering into the calculations are set at their likely values (see Section 2.1.1). Throughout this report, likely value and baseline value are used interchangeably. Thus, the baseline values represent a fixed state of analysis. The term baseline analysis is used to denote a complete analysis in all respects but one; it does not address the effects of uncertainty. Sensitivity analysis measures the impact on project outcomes of changing the values of one or more key variables about which there is uncertainty. Sensitivity analysis is the subject of Chapter 8.

The results of the baseline analysis portion of the CBS economic impact assessment are presented for two basic cases. First are the cost savings nationwide achievable through the use of CBS products and services in office buildings. Second are the cost savings attributable to BFRL and the return on BFRL's CBS-related investment costs.

Key economic measures show the present value of savings (PVS), the present value of net savings (PVNS), the savings-to-investment ratio (SIR), and the adjusted internal rate of return (AIRR) that are attributable to BFRL's CBS-related research, development, and deployment efforts (see Chapter 3). These values are derived by measuring how cost savings nationwide would have been reduced if BFRL had not been involved in the development of CBS products and services (see Section 6.4.6).

The results of the baseline analysis demonstrate that the use of CBS products and services will generate substantial cost savings to owners, managers, and occupants of office buildings. The present value of savings nationwide expected from the use of CBS products and services is in excess of $1.1 billion. Furthermore, because of BFRL's timely involvement, CBS products and services are expected to be commercially available in 2003. If BFRL had not participated in the development of CBS products and services, the commercial introduction of CBS products and services is expected to be delayed until 2010. Consequently, potential cost savings accruing to owners, managers, and occupants of office buildings over the period 2003 through 2009 would have been foregone. These cost savings are in excess of $90 million. These cost savings measure the value of BFRL's contribution for its CBS-related investment costs of approximately $11.5 million. Stated in present value terms, every public dollar invested in BFRL's CBS-related research, development, and deployment efforts is expected to generate $7.90 in cost savings to the public (i.e., an SIR of 7.9). The estimated annual percentage yield (AIRR) from BFRL's CBS-related investments over the study period is 16.2 percent.

7.1 BFRL Summary Impact Statement

Exhibit 7-1 is a summary impact statement, covering the background, approach, and results of the baseline analysis. Exhibit 7-1 utilizes the framework introduced in Chapter 2 (see Exhibit 2-1).

Exhibit 7-1. Summary of Economic Impacts of BFRL Research on Cybernetic Building Systems for Office Buildings

1.a Significance of Research Effort:

Owners and managers of office buildings are pressing building control companies, equipment and systems manufacturers, and design engineers to improve building systems performance and reduce costs. One means of accomplishing this is through the development, adoption, and use of cybernetic building systems (CBSs) that integrate building systems. A CBS is defined as a multi-system configuration able to communicate information and control functions simultaneously and seamlessly at multiple levels. The multiple levels of communication and control are based on the Building Automation and Control Networks (BACnet) layered protocol architecture.

BFRL's focused research on BACnet, under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, led to BACnet's acceptance as a national standard in 1995. Complementary efforts in fire technology, mechanical and electrical systems, fault detection and diagnostic systems, virtual reality modeling, and economic analysis led BFRL to form an integrated CBS project team in 1997. In addition, BFRL is uniquely positioned to collaborate with industry on the development of CBS products and services and to provide a forum for conducting interoperability testing. BFRL is working towards a fully operational CBS being tested and deployed by 2002. To achieve this goal, BFRL is working with equipment and systems manufacturers, service providers, facilities owners and managers, designers, trade associations, professional societies, standards organizations, university researchers, and other government agencies. Without BFRL's participation, it is likely that the introduction of CBS products and services will be delayed for at least seven years.

1.b Key Points:

- Pressure to increase building systems performance and reduce costs has created a potential market for CBS products and services.
- BFRL is uniquely positioned to collaborate with industry on the development of CBS products and services and to provide a forum for conducting interoperability testing.
- Without BFRL's participation, it is likely that the introduction of CBS products and services will be delayed for at least seven years.

2. Analysis Strategy: How Key Measures are Estimated

The objective of the study is to (1) evaluate, for the period 1991 through 2015, the net cost savings due to the adoption and use of CBS products and services in office buildings, and (2) estimate BFRL's contribution to these net cost savings. *The approach is to estimate in 1997 present value (PV) dollars:*
Present Value Cost Savings Nationwide in office buildings that install CBS products and services. PV cost savings nationwide are estimated for each year from 1991 to 2015 and summed.
Present Value Savings (PVS) attributable to BFRL by including the savings only for those years that accrued due to BFRL's participation (i.e., 1991 to 2009).
Present Value Net Savings (PVNS) attributable to BFRL by subtracting from BFRL PVS the present value of BFRL's investment costs (PV Costs). A PVNS >0 indicates an economically worthwhile project.
Two additional measures are also estimated:
Savings-to-Investment Ratio (SIR) attributable to BFRL by taking the ratio of BFRL PVS to BFRL PV costs. A ratio >1 indicates an economically worthwhile project.
Adjusted Internal Rate of Return (AIRR), the annual rate of return over the study period on BFRL's investment. An AIRR > the discount rate indicates that the project is economically worthwhile.

Exhibit 7-1. Summary of Economic Impacts of BFRL Research on Cybernetic Building Systems for Office Buildings (continued)

2. Analysis Strategy: Data and Assumptions

- The period over which costs and savings are measured begins in 1991 and ends in 2015. Hence the length of the study period is 25 years.
- The base year is 1997, and all amounts are calculated in PV 1997 dollars.
- The discount rate is 7 percent (real), which is the discount rate currently in effect for government projects.
- Estimates of cost savings associated with the adoption and use of CBS products and services are based on construction industry data and information provided by industry experts.
- The market potential for CBS products and services is based on data derived from the Commercial Building Energy Consumption Survey.
- Without BFRL's participation, the introduction of CBS products and services will be delayed by seven years.

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

Savings and Costs

Present Value Cost Savings Nationwide:
Sum from 1991 to 2015 of present value of cost savings nationwide by year
= $1,175.6 million

Present Value Savings (PVS) Attributable to BFRL:
Sum from 1991 to 2009 of present value of cost savings nationwide by year
= $90.7 million

Present Value Investment Costs (PV Costs) to BFRL:
Sum from 1991 to 2015 of present value of investment cost to BFRL by year
= $11.475 million

Present Value Net Savings (PVNS) Attributable to BFRL:
Difference between present value savings (PVS) attributable to BFRL and present value of investment costs (PV Costs) to BFRL

= $90.7 - $11.475 = $79.3 million

Additional Measures

SIR of BFRL Contribution:
Savings-to-Investment Ratio on BFRL investment
= $90.7/$11.475 = 7.9

AIRR of BFRL Contribution:
Adjusted Internal Rate of Return on BFRL investment
$= (1+ 0.07) * 7.9^{1/25} – 1$ = 0.162

3.b Key Results:

1997 Dollars
($ amounts in millions)

Cost Savings Nationwide:

$1,175.6

Savings Attributable to BFRL:

PVS	**$90.7**
PV Costs	**$11.475**
PVNS	**$79.3**
SIR	**7.9**
AIRR	**16.2%**

7.2 Cost Savings Nationwide

This section combines three types of information presented in Sections 6.3 and 6.4 to generate a baseline estimate of cost savings nationwide. These three types of information are related to: (1) the diffusion model developed in Section 6.4.4; (2) the per unit cost savings for energy, maintenance, repairs and replacements, and occupant productivity; and (3) the additional costs to building owners and managers for installing CBS products and services. These three types of information are combined via four sets of calculations to estimate "annual" cost savings to the nation. Estimates are produced for each year from 1991 to 2015. Each year's cost savings is then discounted to a present value and summed to get the present value of cost savings nationwide. The present value of cost savings nationwide is a key indicator of the merits of installing CBS products and services in office buildings. The results of the baseline analysis show that cost savings nationwide exceed $1.1 billion ($1,176 million in present value 1997 dollars). Each set of calculations used to produce the estimate of cost savings nationwide is summarized through a table and described in the text that follows. Each table presented in this section records information based on both SI units and conventional units. To facilitate distinctions between the two sets of units, references in the text to SI units are shown in a regular font and references in the text to conventional units are shown within parentheses in *Italics*.

Table 7-1 summarizes information derived from the diffusion model. Column 1 of the table lists each year of the study period from 1991 through 2015. Columns 2 and 5 of Table 7-1 record information on the calculated values of $P_0(t)$ and $)P_0(t)$ for each year. Recall that $t = 1$ corresponds to the year in which CBS products and services are expected to become commercially available (i.e., $t = 1$ corresponds to the year 2003). Thus, $P_0(t) = 0$ and $)P_0(t) = 0$ for all values of t less than 1. Next, the diffusion model is combined with information on office building floorspace to generate two sets of annual estimates (i.e., estimates for each year from 1991 to 2015). These estimates are (1) an estimate of the cumulative total CBS installations in millions of square meters (*millions of square feet*) and (2) an estimate of the new CBS installations in millions of square meters (*millions of square feet*). To get the cumulative total CBS installations in millions of square meters (*millions of square feet*), the value of $P_0(t)$ in Column 1 is multiplied by the total amount of office floorspace. The total amount of office floorspace is equal to 973 million square meters (*10,478 million square feet*). The product of the two terms equals the cumulative total CBS installations in millions of square meters (*millions of square feet*); its value is recorded in Column 3 (*Column 4*) of Table 7-1. Notice that following the commercial introduction of CBS products and services in 2003, the cumulative totals rise steadily until the end of the study period. To get the new CBS installations in millions of square meters (*millions of square feet*), the value of $)P_0(t)$ in Column 5 is multiplied by the total amount of office floorspace. The product of the two terms equals the new CBS installations in millions of square meters (*millions of square feet*); its value is recorded in Column 6 (*Column 7*) of Table 7-1. Notice that these values rise over the period 2003 to 2012, then level off, and then decline. This is because $P_0(t)$ reaches 50 percent of its designated potential market after 10 years (i.e., $\eta/2$). This point also corresponds to a point of inflection beyond which $P_0(t)$ increases at a decreasing rate.

Table 7-1. Baseline CBS Installations by Year: 1991-2015

Year	Proportion of Office Floorspace Covered by CBS Products and Services $P_{\eta}(t)$	Cumulative Total CBS Installations in Millions of		Proportion of Office Floorspace Covered by New CBS Installations $\Delta P_{\eta}(t)$	New CBS Installations in Millions of	
		Square Meters	Square Feet		Square Meters	Square Feet
Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (5)	Col. (6)	Col. (7)
1991	0	0	0	0	0	0
1992	0	0	0	0	0	0
1993	0	0	0	0	0	0
1994	0	0	0	0	0	0
1995	0	0	0	0	0	0
1996	0	0	0	0	0	0
1997	0	0	0	0	0	0
1998	0	0	0	0	0	0
1999	0	0	0	0	0	0
2000	0	0	0	0	0	0
2001	0	0	0	0	0	0
2002	0	0	0	0	0	0
2003	0.0008	0.8	8.3	0.0008	0.8	8.3
2004	0.0014	1.4	15.0	0.0006	0.6	6.7
2005	0.0026	2.5	27.2	0.0012	1.1	12.2
2006	0.0047	4.5	48.9	0.0021	2.0	21.7
2007	0.0083	8.1	87.2	0.0037	3.6	38.3
2008	0.0146	14.2	152.9	0.0063	6.1	65.7
2009	0.0249	24.2	260.7	0.0103	10.0	107.8
2010	0.0406	39.5	425.4	0.0157	15.3	164.7
2011	0.0622	60.5	651.2	0.0216	21.0	225.8
2012	0.0877	85.4	918.9	0.0255	24.9	267.7
2013	0.1132	110.2	1,186.6	0.0255	24.9	267.7
2014	0.1348	131.2	1,412.4	0.0216	21.0	225.8
2015	0.1505	146.5	1,577.1	0.0157	15.3	164.7

Table 7-2 summarizes how baseline energy cost savings are calculated. Recall that since energy prices change over time it is necessary to develop a weighted time series for energy. This process was described in Section 6.3.1.1; it was done through reference to information contained in the annual supplement to NIST Handbook 135. Because 1997 is the base year for the CBS economic impact assessment, the annual supplement for 1997 was used to construct the weighted time series for energy (see Table 6-1 in Section 6.3.1.1). Thus, the weighted time series for energy begins in 1997. The years for which the weighted time series for energy is defined are listed in Column 1 of Table 7-2. The years run from 1997 until 2015, the end of the study period. Column 2 of Table 7-2 contains the unweighted energy cost savings in millions of 1997 dollars. These savings are calculated for each year from 1997 until 2015. Notice that no energy cost savings occur until 2003, the year in which CBS products and services first become commercially available. The unweighted energy cost savings for each year is equal to the product of energy cost savings per square meter (*per square foot*) of $1.71 (*$0.16*) and the cumulative total CBS installations in millions of square meters (*millions of square feet*) for that year (i.e., the year of the specific calculation). The latter value is contained in the row of Column 3 (*Column 4*) of Table 7-1 corresponding to the year of the specific calculation. Column 4 of Table 7-2 contains the weighted energy cost savings in millions of 1997 dollars. These savings are calculated for each year from 1997 until 2015. The weighted energy cost savings for each year is equal to the product of the unweighted energy cost savings, contained in Column 2, and the weighted time series for energy, contained in Column 3.

Table 7-3 summarizes how baseline cost savings by category and in total are calculated. The years for which cost savings are calculated are listed in Column 1 of Table 7-3. The years run from 1991 until 2015 (i.e., the entire study period). The table records information on four categories of cost savings: (1) weighted energy cost savings; (2) maintenance cost savings; (3) repair and replacement cost savings; and (4) productivity cost savings. Annual values for each category of cost savings are recorded in Column 2 for energy, Column 3 for maintenance, Column 4 for repair and replacement, and Column 5 for productivity. Note that no cost savings for any category occur until 2003, the year in which CBS products and services first become commercially available. The weighted energy cost savings for each year, recorded in Column 2, is transferred from the respective row of Column 4 of Table 7-2. The maintenance cost savings for each year, recorded in Column 3, is equal to the product of maintenance cost savings per square meter (*per square foot*) of $1.60 (*$0.15*) and the cumulative total CBS installations in millions of square meters (*millions of square feet*) for that year. The latter value is contained in the row of Column 3 (*Column 4*) of Table 7-1 corresponding to the year of the specific calculation. The repair and replacement cost savings for each year, recorded in Column 4, is equal to the product of repair and replacement cost savings per square meter (*per square foot*) of $0.66 (*$0.06*) and the cumulative total CBS installations in millions of square meters (*millions of square feet*) for that year. The productivity cost savings for each year, recorded in Column 5, is equal to the product of productivity cost savings per square meter (*per square foot*) of $4.20 (*$0.39*) and the cumulative total CBS installations in millions of square meters (*millions of square feet*) for that year.

Table 7-2. Baseline Energy Cost Savings by Year: 1997-2015

Year	Unweighted Energy Cost Savings (In Millions of 1997 Dollars)	Weighted Time Series for Energy	Weighted Energy Cost Savings (In Millions of 1997 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2) x (3)
1997	0	1.000	0
1998	0	1.000	0
1999	0	1.000	0
2000	0	0.992	0
2001	0	0.982	0
2002	0	0.983	0
2003	1.322	0.974	1.287
2004	2.400	0.964	2.314
2005	4.344	0.955	4.148
2006	7.821	0.954	7.463
2007	13.946	0.945	13.179
2008	24.457	0.944	23.095
2009	41.712	0.944	39.361
2010	68.066	0.935	63.615
2011	104.196	0.925	96.340
2012	147.027	0.915	134.581
2013	189.858	0.897	170.312
2014	225.988	0.897	202.723
2015	252.343	0.906	228.673

Table 7-3. Baseline Cost Savings by Category and in Total in Millions of 1997 Dollars by Year: 1991-2015

Year	Annual Cost Savings By Category				Total Cost Savings by Year
	Weighted Energy Cost Savings	Maintenance Cost Savings	Repair and Replacement Cost Savings	Productivity Cost Savings	
Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (5)	Col. (6) (2)+(3)+(4)+(5)
1991	0	0	0	0	0
1992	0	0	0	0	0
1993	0	0	0	0	0
1994	0	0	0	0	0
1995	0	0	0	0	0
1996	0	0	0	0	0
1997	0	0	0	0	0
1998	0	0	0	0	0
1999	0	0	0	0	0
2000	0	0	0	0	0
2001	0	0	0	0	0
2002	0	0	0	0	0
2003	1.287	1.240	.496	3.223	6.245
2004	2.314	2.250	.900	5.851	11.314
2005	4.148	4.073	1.629	10.589	20.440
2006	7.463	7.332	2.933	19.064	36.791
2007	13.179	13.074	5.230	33.993	65.476
2008	23.095	22.929	9.171	59.615	114.810
2009	39.361	39.105	15.642	101.673	195.781
2010	63.615	63.812	25.525	165.912	318.864
2011	96.340	97.684	39.074	253.979	487.076
2012	134.581	137.838	55.135	358.379	685.934
2013	170.312	177.992	71.197	462.779	882.281
2014	202.723	211.864	84.746	550.846	1,050.179
2015	228.673	236.571	94.628	615.085	1,174.958

The cost savings by category for each year recorded in Table 7-3 are based on the cumulative total CBS installations up to and including that year. The reason for using cumulative total CBS installations rather than new CBS installations is that CBS products and services, once installed, continue to generate cost savings. Recall that CBS-related costs savings are based on comparisons between the base case and the CBS alternative. Thus, office buildings that installed the CBS alternative in 2003 continue to accrue cost savings *vis-à-vis* the base case throughout the remainder of the study period.

In addition to cost savings by category, Table 7-3 also contains total cost savings by year. These cost savings are recorded in Column 6. Total cost savings for each year equal the sum of each category's cost savings for that year. Total cost savings, denominated in millions of 1997 dollars, increase steadily between 2003 and 2015.

Table 7-4 summarizes how the present values of cost savings nationwide by year and in total are calculated. The table also includes information on total cost savings, additional CBS-related installation costs, net cost savings, and the discount factor needed to translate yearly net cost savings into yearly present value cost savings nationwide. The years for which present values are calculated are listed in Column 1 of Table 7-4. The years run from 1991 until 2015 (i.e., the entire study period). Column 2 of Table 7-4 contains total cost savings by year in millions of 1997 dollars. The total cost savings for each year is transferred from the respective row of Column 6 of Table 7-3. The additional cost to install CBS products and services for each year is recorded in Column 3 of Table 7-4. This cost equals the product of the additional cost to building owners and managers of $10.76 per square meter (*$1.00 per square foot*) and the new CBS installations for that year. The value for new CBS installations is contained in Column 6 (*Column 7*) of Table 7-1 for each year of the specific calculation. Note that these costs first increase, then level off, and finally begin to decline. The difference between total cost savings and the additional costs to install CBS products and services equals net cost savings. Column 4 of Table 7-4 records net cost savings for each year in millions of 1997 dollars. Note that net cost savings are negative in 2003, after which they become positive and increase steadily. The calculated value of the single compound amount factor for each year is recorded in Column 5 of Table 7-4. All entries are calculated using a real discount rate of 7 percent (see Section 6.4.3). Because 1997 is the base year, the single compound amount factor takes on a value of 1.0 for that year. For years prior to 1997, the single compound amount factor is greater than 1.0. For years following 1997, the single compound amount factor is less than 1.0. The single compound amount factor for any given year, Y, equals $(1.07)^{1997-Y}$ where $1991 \leq Y \leq 2015$. The present value of cost savings nationwide by year is recorded in Column 6 of Table 7-4. It equals the product of the net cost savings, in Column 4, and the single compound amount factor, in Column 5, for that year. Note that the present value of cost savings nationwide is negative in 2003, after which it becomes positive and increases steadily.

Because the entries in Column 6 are in present value terms, they can be summed to get total cost savings nationwide over the entire study period. Total cost savings nationwide resulting from the four sets of baseline analysis calculations exceed $1.1 billion ($1,176 million in present value 1997 dollars); see the bottom of Column 6 in Table 7-4.

Table 7-4. Baseline Computation of Present Value Cost Savings Nationwide in Millions of 1997 Dollars: 1991-2015

Year	Total Cost Savings by Year	Additional Cost to Install CBS Products and Services	Net Cost Savings	Single Compound Amount Factor by Year	Present Value of Net Cost Savings Nationwide by Year
Col. (1)	**Col. (2)**	**Col. (3)**	**Col. (4) (2) - (3)**	**Col. (5)**	**Col. (6) (4) x (5)**
1991	0	0	0	1.501	0
1992	0	0	0	1.403	0
1993	0	0	0	1.311	0
1994	0	0	0	1.225	0
1995	0	0	0	1.145	0
1996	0	0	0	1.070	0
1997	0	0	0	1.000	0
1998	0	0	0	0.935	0
1999	0	0	0	0.873	0
2000	0	0	0	0.816	0
2001	0	0	0	0.763	0
2002	0	0	0	0.713	0
2003	6.245	8.263	-2.018	0.666	-1.345
2004	11.314	6.738	4.576	0.623	2.850
2005	20.440	12.151	8.289	0.582	4.824
2006	36.791	21.729	15.063	0.544	8.193
2007	65.476	38.280	27.196	0.508	13.825
2008	114.810	65.697	49.113	0.475	23.333
2009	195.781	107.842	87.940	0.444	39.046
2010	318.864	164.715	154.149	0.415	63.966
2011	487.076	225.813	261.264	0.388	101.323
2012	685.934	267.693	418.241	0.362	151.590
2013	882.281	267.693	614.587	0.339	208.182
2014	1,050.179	225.813	824.366	0.317	260.973
2015	1,174.958	164.715	1,010.243	0.296	298.894
				TOTAL	**1,175.655**

Reference to Table 7-4 demonstrates the magnitude of the savings to the nation from using CBS products and services in office buildings. These cost savings nationwide also provide a basis for measuring the value of BFRL's contribution.

7.3 Measuring the Value of BFRL's Contribution and the Return on BFRL's CBS-Related Investments

Measuring the value of BFRL's contribution to the development of CBS products and services and the return on its CBS-related investments is the focus of this section. Information on BFRL's CBS-related research, development, and deployment efforts—in terms of its dollar investments—over the 25-year period from 1991 to 2015 are first presented. These figures demonstrate not only a significant, up-front research commitment by BFRL, but also a continued effort as CBS products and services move into the commercial marketplace. Next, the likely delay in the commercial availability of CBS products and services is addressed. Finally, a full array of economic measures summarizes the importance of BFRL's contribution to the development of CBS products and services for use in office buildings.

Table 7-5 summarizes information on BFRL's CBS-related investments. Column 1 of the table records the year in which CBS-related investments were made. Column 2 records the value (in millions of current dollars) by year of investment for each year between 1991 and 1996. For example, in 1991 the investment was $298,000 (in 1991 dollars), in 1992 the investment was $268,000 (in 1992 dollars), and in 1993 the investment was $198,000 (in 1993 dollars). For 1997 through 2015, the entries in Column 2 are in millions of 1997 dollars. Investments over the 1991 to 1996 time period cover BACnet-related research. Investments beginning in 1997 include research, development, and deployment efforts aimed at producing CBS products and services. Because the values for 1991 through 1996 in Column 2 are in current dollars by year, it is necessary to convert them to constant 1997 dollars and then convert them to present value (i.e., time equivalent) dollars. This involves a two-step process. First, each year's current dollar investment is converted to a "real" investment in 1997 constant dollars through application of the Consumer Price Index (CPI). The conversion factors, for each year, are shown in Column 3 of Table 7-5. The constant 1997 dollar values (in millions of dollars) are the year-by-year products of the entries in Column 2 and Column 3. These values are shown in Column 4. The values in Column 4 are converted into present values terms through the use of a single compound amount factor, based on a real discount rate of 7 percent. The value of each year's single compound amount factor is given in Column 5. The present values in millions of 1997 dollars are recorded in Column 6; they are the year-by-year products of the entries in Column 4 and Column 5.

Because entries in Column 6 are in present value terms, they can be summed to get the present value of BFRL's CBS-related investments. The present value of BFRL's CBS-related investments, PV Costs, totals $11.475; this value is recorded at the bottom of Column 6.

Table 7-5. Summary of BFRL Research Investments: 1991-2015

Year	Annual[a] Dollar Amount (In Millions of Dollars)	Conversion Factor by Year (Current Dollars to 1997 Dollars)	Investment Cost by Year (In Millions of 1997 Dollars)	Single Compound Amount Factor by Year	Present Value of Investment Cost by Year (In Millions of 1997 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2) x (3)	Col. (5)	Col. (6) (4) x (5)
1991	.298	1.178	.351	1.501	.527
1992	.268	1.144	.307	1.403	.430
1993	.198	1.111	.219	1.311	.288
1994	.190	1.083	.206	1.225	.252
1995	.218	1.053	.229	1.145	.262
1996	.300	1.023	.307	1.070	.328
1997	.573	1.000	.573	1.000	.573
1998	1.445	1.000	1.445	0.935	1.350
1999	1.708	1.000	1.708	0.873	1.491
2000	2.125	1.000	2.125	0.816	1.735
2001	2.500	1.000	2.500	0.763	1.907
2002	2.125	1.000	2.125	0.713	1.515
2003	.875	1.000	.875	0.666	.583
2004	.375	1.000	.375	0.623	.234
2005	0	1.000	0	0.582	0
2006	0	1.000	0	0.544	0
2007	0	1.000	0	0.508	0
2008	0	1.000	0	0.475	0
2009	0	1.000	0	0.444	0
2010	0	1.000	0	0.415	0
2011	0	1.000	0	0.388	0
2012	0	1.000	0	0.362	0
2013	0	1.000	0	0.339	0
2014	0	1.000	0	0.317	0
2015	0	1.000	0	0.296	0
				TOTAL	**11.475**

[a] The dollar amounts for 1991 through 1996 are in millions of current dollars. The dollar amounts for 1997 through 2015 are in millions of 1997 dollars.

Table 7-6 provides the information needed to calculate the present value of savings attributable to BFRL. The years for which present values are calculated are listed in Column 1 of Table 7-6. The years run from 1991 until 2015 (i.e., the entire study period). The present value of cost savings nationwide by year is recorded in Column 2 of Table 7-6. The present value of cost savings nationwide for each year is transferred from the respective row of Column 6 of Table 7-4. BFRL's dual role as a facilitator and developer of key CBS enabling technologies is expected to speed up the introduction of CBS products and services into the commercial marketplace. Without BFRL's participation, the introduction of CBS products and services into the commercial marketplace would likely have been delayed. Information from subject matter experts and similar economic impact assessments suggest a range of values from four to 10 years for the likely delay. The selected baseline value for the delay is seven years (see Section 6.4.6). Because BFRL's research, development, and deployment efforts resulted in faster introduction of CBS products and services, those savings which would have been foregone in the event of a delay are attributable to BFRL. Therefore, any savings over the first seven years (starting with 2003), prior to the "delayed" introduction of CBS products and services in 2010, would have been foregone. Such an accounting framework may be handled through use of a 0-1 weighting factor. For those years in which savings are attributable to BFRL, the weighting factor takes on a value of 1. The year-by-year values of the BFRL baseline weighting factor are given in Column 3 of Table 7-6. The present value of savings attributable to BFRL is the product of each year's present value of cost savings nationwide in Column 2 and the value of the BFRL baseline weighting factor in Column 3. The present value of savings attributable to BFRL on a year-by-year basis is given in Column 4 of Table 7-6.

Because entries in Column 4 are in present value terms, they can be summed to get the present value of savings attributable to BFRL. The present value of savings attributable to BFRL, PVS, totals \$90.7 million; this value is recorded at the bottom of Column 6.

Given the values of PV Costs and PVS attributable to BFRL, it is now possible to derive three other economic impact measures. These measures are: (1) present value of net savings (PVNS) attributable to BFRL; (2) the savings-to-investment ratio (SIR) on BFRL's CBS-related investments; and (3) the adjusted internal rate of return (AIRR) on BFRL's CBS-related investments.

The PVNS attributable to BFRL, expressed in millions of present value 1997 dollars and based on the approach outlined in Section 2.1.1, is equal to:

$$\begin{aligned} \text{PVNS} &= \text{PVS} - \text{PV Costs} \\ &= \$90.727 - \$11.475 \\ &= \$79.3 \text{ million} \end{aligned}$$

Table 7-6. Estimated Cost Savings in Millions of 1997 Dollars Attributable to BFRL

Year	Present Value of Cost Savings Nationwide by Year	BFRL Baseline Weighting Factor (7-Year Delay)	Present Value of Cost Savings by Year Attributable to BFRL
Col. (1)	**Col. (2)**	**Col. (3)**	**Col. (4) (2) x (3)**
1991	0	1	0
1992	0	1	0
1993	0	1	0
1994	0	1	0
1995	0	1	0
1996	0	1	0
1997	0	1	0
1998	0	1	0
1999	0	1	0
2000	0	1	0
2001	0	1	0
2002	0	1	0
2003	-1.345	1	-1.345
2004	2.850	1	2.850
2005	4.824	1	4.824
2006	8.193	1	8.193
2007	13.825	1	13.825
2008	23.333	1	23.333
2009	39.046	1	39.046
2010	63.966	0	0
2011	101.323	0	0
2012	151.590	0	0
2013	208.182	0	0
2014	260.973	0	0
2015	298.894	0	0
		TOTAL	**90.727**

Utilizing the approach outlined in Section 2.1.2, the SIR on BFRL's CBS-related investments is equal to:

$$\begin{aligned} SIR &= PVS / (PV\ Costs) \\ &= \$90.727 / \$11.475 \\ &= 7.9 \end{aligned}$$

Utilizing the approach outlined in Section 2.1.3, the AIRR on BFRL's CBS-related investments is equal to:

$$\begin{aligned} AIRR &= (1 + 0.07) * 7.9^{1/25} - 1 \\ &= 0.162 \\ &= 16.2\% \end{aligned}$$

The values of the five economic impact measures derived in Chapter 7 are the baseline values that appear in Section 3.b of Exhibit 7-1. These values also figure in the sensitivity analysis, which is the subject of the next chapter.

8. Sensitivity Analysis of Economic Impacts

The CBS economic impact assessment described in this report was carried out in two stages. In the first stage, a baseline analysis was performed. The data and assumptions underlying the baseline analysis were described in Chapter 6; the results of the baseline analysis were presented in Chapter 7.

In the second stage, nine variables were varied both singly and in combination according to an experimental design. The sensitivity analysis uses the same data and assumptions as the baseline analysis for its starting point. Information on how the deviations about the baseline values for each of the nine input variables were specified and how the range of values for each variable was determined is described and documented in Chapter 6. The sensitivity analysis described in this chapter is based on Monte Carlo techniques. The objective of the sensitivity analysis is to evaluate how uncertainty in the values of each of the nine input variables, both singly and in combination, translates into changes in each of six key economic measures. The six economic measures evaluated in the sensitivity analysis are: (1) the present value of savings nationwide; (2) the present value of savings due to BFRL; (3) the present value of BFRL's CBS-related investment costs; (4) the present value of net savings due to BFRL; (5) the savings-to-investment ratio on BFRL's CBS-related investments; and (6) the adjusted internal rate of return on BFRL's CBS-related investments. Three of these measures are particularly helpful in understanding BFRL's contribution, since each measure provides a different perspective. The first, the present value of net savings due to BFRL is a magnitude measure; it show a dollar value to the public net of BFRL's CBS-related investments. The second, the savings-to-investment ratio on BFRL's CBS-related investments is a multiplier; it shows, in present value terms, how many dollars the public receives for each public dollar spent. The third, the adjusted internal rate of return on BFRL's CBS-related investments is a rate of return; it shows the return on the public monies going into the development of CBS products and services throughout the 25-year study period.

8.1 Methodology

Because the values of many variables that enter into the CBS economic impact assessment are not known with certainty, it is advisable to select a small set of variables whose impact is likely to be substantial and subject them to a sensitivity analysis. Variations in the values of these input 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.

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 the SIR is less than 1.0).

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., the SIR) 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. This is the approach used in the two previous economic impact assessments.[67]

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.

The approach selected for this study makes use of works by McKay, Conover, and Beckman[68] and by Harris;[69] it is based on the method of model sampling. Model sampling provides the basis for many probabilistic sensitivity analyses. Model sampling is a procedure for sampling from a stochastic process to determine, through multiple trials, the characteristics of a probability distribution.

The method of model sampling was implemented through application of the *@RISK* software product.[70] This software product is an add-in for spreadsheets. For the case at hand, selected columns of the spreadsheet were associated with one or more of the nine input variables. The *@RISK* software product allows the user to specify a unique probability distribution for each input 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 each input variable or combination of input variables under analysis. The number of simulations was chosen to ensure that values in the tails of the distribution for each input variable would be selected for inclusion in the analysis. When the *@RISK* software product is executed, it randomly

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[67] See Chapman and Fuller, *Two Case Studies in Building Technology*, and Chapman and Weber, *A Case Study of the Fire Safety Evaluation System*.

[68] McKay, M. C., W. H. Conover, and R.J. Beckman. 1979. "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code." *Technometrics* (Vol. 21): pp. 239-245.

[69] Harris, Carl M. 1984. *Issues in Sensitivity and Statistical Analysis of Large-Scale, Computer-Based Models*. NBS GCR 84-466. Gaithersburg, MD: National Bureau of Standards.

[70] 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.

samples from the parent probability distribution for each input variable of interest (i.e., the input variable(s) specified by the experimental design).

In reality, the exact nature of the parent probability distribution for each input 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. The true specification of the parent probability distribution can only be known after CBS products and services have been operating in the marketplace for an extended period of time. Therefore, in order to implement the procedure without undue attention to the characterization of the parent probability distribution, it was decided to focus on only three probability distributions. These probability distributions are: (1) the triangular; (2) the uniform; and (3) the discrete or multinomial. Readers interested in learning more about these probability distributions, including variate relationships, estimation procedures, and random number generation, are referred to Evans, Hastings, and Peacock.[71]

One reason for using these three probability distributions is that they are all defined over a finite interval. 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. Discussions with subject matter experts and reference to selected publications indicated six input variables for which clustering about a central value was to be expected. Once the triangular distribution was selected for these six input variables, all three values were derived through investigation and discussions with subject matter experts. 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. It was used for one input variable (see Section 8.2). The discrete distribution is used whenever the range of input values is discrete. It was used for two input variables (see Section 8.2).

8.2 Key Variables

Information on the nine input variables that are the focus of the sensitivity analysis is presented in this section. The nine variables are: (1) alpha, α, the location parameter in the diffusion model; (2) beta, β, the shape parameter in the diffusion model; (3) eta, η, the market saturation level in the diffusion model; (4) the time of first use; (5) the length of the delay; (6) per unit energy cost savings; (7) per unit maintenance cost savings; (8) per unit productivity cost savings; and (9) the discount rate.

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[71] Evans, Merran, Nicholas Hastings, and Brian Peacock. 1993. *Statistical Distributions*. New York, NY: John Wiley & Sons, Inc.

Table 8-1 summarizes information on each of the nine input variables. The table includes information on the type of probability distribution used to model variations about the baseline value for each input variable, the baseline value for each input variable, and the minimum and maximum values for each input variable.

Reference to the entries under the heading Probability Distribution shows that all but three of the nine input variables use the triangular distribution to model variations about the baseline value for that variable. One of these variables, α, employs the uniform distribution. The input variable α is modeled with a uniform distribution because a review of the economics literature on the diffusion process produced no *a priori* reason for expecting a clustering of values around a value of 6.0. The economics literature was, however, useful in specifying the range about the baseline value of α. The other two input variables, the time of first use and the length of delay, employ the discrete distribution. Both of these variables designate a year. For example, the time of first use (i.e., when CBS products and services first become available commercially) either occurs in 2003 (i.e., the year corresponding to the baseline value) or in some other year. It does not occur in year 2003.5. Thus, the discrete distribution is the most meaningful way to model when CBS products and services first become available commercially.

Table 8-1. Baseline and Extreme Values of the Nine Input Variables Used in the Sensitivity Analysis

Variable Name	Probability Distribution	Setting and Value		
		Baseline	Minimum	Maximum
(1) Alpha	Uniform	6	5	7
(2) Beta	Triangular	0.6	0.5	0.7
(3) Eta	Triangular	0.175	0.0553	0.3082
(4) Time of First Use	Discrete	2003	2002	2005
(5) Length of Delay	Discrete	7	4	10
(6) Energy Cost Savings	Triangular	$1.71 (*$0.16*)	$0.86 (*$0.08*)	$2.58 (*$0.24*)
(7) Maintenance Cost Savings	Triangular	$1.60 (*$0.15*)	$0.81 (*$0.075*)	$3.23 (*$0.30*)
(8) Productivity Cost Savings	Triangular	$4.20 (*$0.39*)	$0.00 (*$0.00*)	$8.39 (*$0.78*)
(9) Discount Rate	Triangular	0.07	0.04	0.10

The next three headings record, for each input variable, its setting (i.e., baseline, minimum, and maximum) and value. For each input variable, the baseline value is recorded first. For example, the baseline value for the discount rate is 7 percent (real); it is recorded in decimal form as 0.07. Two other values for the discount rate, 4 percent and 10 percent, are selected to bracket the baseline value. These values are recorded in decimal form as 0.04 and 0.10, respectively.

Note that three input variables have two sets of entries. These input variables are all associated with per unit cost savings. In Chapter 7, information was presented based both on SI units and on conventional units. This chapter also includes information based both on SI units and on conventional units. To facilitate distinctions between the two sets of units, references to SI units are shown in a regular font—e.g., energy cost savings per square meter are $1.71—and references to conventional units are shown within parentheses in *Italics*—e.g., (*energy cost savings per square foot are $0.16*).

8.3 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 nine input variables is varied singly. The first set of results is designed to show the effect of each input on each of the economic measures. This is done by varying each input variable singly while holding the other eight input variables at their baseline values. These results are summarized in Tables 8-2 through 8-10. The second set covers the case where all nine 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 8-11 and 8-12 and in Figures 8-1 through 8-6. To facilitate comparisons among each of the Monte Carlo simulations, Tables 8-2 through 8-11 use the same presentation format. Table 8-12 summarizes in tabular form the results plotted in Figures 8-1 through 8-6.

8.3.1 Changing One Input

Tables 8-2 through 8-11 report a series of statistical measures for each economic measure. To facilitate comparisons among the economic measures, a shorthand notation for each is used. The present value of savings nationwide over the entire study period is denoted by PVS_{ALL}. The present value of savings due to BFRL is denoted by PVS_{BFRL}. The present value of BFRL's CBS-related investment costs is denoted by PVC_{BFRL}. The present value of net savings due to BFRL is denoted by $PVNS_{BFRL}$. The savings-to-investment ratio on BFRL's CBS-related investments is designated by SIR_{BFRL}. The adjusted internal rate of return on BFRL's CBS-related investments is designated by $AIRR_{BFRL}$. 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 25th percentile, denoted by 25%; (3) the 50th percentile (i.e., the median), denoted by 50%; (4) the 75th percentile, denoted by 75%; (5) the maximum; (6) the mean; and (7) the standard deviation. The minimum and the maximum define the range of values for the results from each of the Monte Carlo simulations. The 50th percentile and the mean are measures of central tendency. The 25th and 75th percentiles define the interquartile range, a range that includes the middle 50 percent of the observations. The interquartile range is also a crude measure of central

tendency. The standard deviation measures the variability of the results from each of the Monte Carlo simulations. It is important to recognize that the values reported for PVS_{ALL}, PVS_{BFRL}, PVC_{BFRL}, and $PVNS_{BFRL}$ are all in millions of 1997 dollars.

The results presented in Tables 8-2, 8-3, and 8-4 are related to the values of the parameters in the diffusion model (see Section 6.4.4). Each parameter, α, β, and η is analyzed in turn. Table 8-2 shows how variations about the baseline value for α (i.e., α = 6.0) affect each economic measure. The parameter α was selected for evaluation because it is the location parameter for the diffusion model. The effect of α is as follows: lower values of α produce a thicker tail immediately following the introduction of CBS products and services into the marketplace (i.e., higher values of $P_{\eta}(t)$, whenever t is small), whereas higher values of α produce a thinner tail (i.e., lower values of $P_{\eta}(t)$, whenever t is small). Reference to Table 8-2 reveals that α exerts a strong effect on all six of the economic measures. For example, the minimum value of PVS_{ALL} is only one third of the highest value. Although the present value of savings nationwide is strongly affected by changes in the value of α, the measures of BFRL's influence are affected to a far greater degree. The reason is due to the way in which BFRL's influence is measured. Because those savings occurring in the first seven years are attributable to BFRL, higher values of α reduce these savings and lower values of α increase these savings over the value calculated in the baseline analysis. For example, the minimum value of SIR_{BFRL} is one-seventh the highest value, and $PVNS_{BFRL}$ varies by a factor of 10. Note that PVC_{BFRL} is unaffected by changes in the value of α. Thus, the standard deviation for PVC_{BFRL} is 0.0. Consequently, the standard deviation for PVS_{BFRL} and the standard deviation for $PVNS_{BFRL}$ are equal (i.e., $55.4 million in 1997 dollars).

Table 8-2. Summary Statistics Due to Changes in the Input Variable Alpha

Economic Measure	Statistical Measure						
	Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
PVS_{ALL}	624.164	894.965	1,168.150	1,486.652	1,904.940	1,197.917	362.409
PVS_{BFRL}	33.874	57.573	89.707	140.576	235.455	103.486	55.414
PVC_{BFRL}	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$PVNS_{BFRL}$	22.399	46.098	78.232	129.101	223.980	92.011	55.414
SIR_{BFRL}	2.952	5.017	7.818	12.250	20.519	9.018	4.829
$AIRR_{BFRL}$	0.117	0.141	0.162	0.183	0.207	0.162	0.025

Table 8-3 shows how variations about the baseline value for β (i.e., β = 0.6) affect each economic measure. The parameter β was selected for evaluation because it specifies the rate of change for the diffusion model. The effect of β is as follows: higher values of β produce a higher rate of adoption of CBS products and services in the marketplace immediately following the introduction of these products and services (i.e., higher values of $P_{\eta}(t)$, whenever t is small), whereas lower values of β produce a lower rate of adoption (i.e., lower values of $P_{\eta}(t)$, whenever t is small). Reference to Table 8-3 reveals that β exerts a moderate to strong effect on all six of the economic measures. For example, the

range of values for PVS_{ALL} is slightly in excess of $1.0 billion in 1997 dollars. Although the present value of savings nationwide is strongly affected by changes in the value of β, the measures of BFRL's influence are affected to lesser degree than for changes in α. The reason is due to the way in which BFRL's influence is measured. Because those savings occurring in the first seven years are attributable to BFRL, lower values of β reduce these savings and higher values of β increase these savings over the value calculated in the baseline analysis. However, these differences are less than those associated with α, because α affects the thickness of the lower tail of $P_\eta(t)$, whereas β only affects the rate of change of the slope of the tail in the period immediately following the introduction of CBS products and services. For example, the minimum value of SIR_{BFRL} is slightly less than half the highest value, and $PVNS_{BFRL}$ varies by a factor of slightly less than 2.5. Note that PVC_{BFRL} is unaffected by changes in the value of β. Thus, the standard deviation for PVC_{BFRL} is 0.0. Consequently, the standard deviation for PVS_{BFRL} and the standard deviation for $PVNS_{BFRL}$ are equal (i.e., $15.2 million in 1997 dollars).

Table 8-3. Summary Statistics Due to Changes in the Input Variable Beta

Economic Measure	Statistical Measure						
	Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
PVS_{ALL}	676.822	1,020.123	1,189.457	1,349.001	1,704.823	1,187.159	224.237
PVS_{BFRL}	61.709	80.999	91.635	102.775	133.418	92.574	15.244
PVC_{BFRL}	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$PVNS_{BFRL}$	50.234	69.524	80.160	91.300	121.943	81.099	15.244
SIR_{BFRL}	5.378	7.059	7.986	8.956	11.627	8.067	1.328
$AIRR_{BFRL}$	0.144	0.157	0.163	0.168	0.180	0.163	0.008

Table 8-4 shows how variations about the baseline value for η (i.e., η = 0.1754) affect each economic measure. The parameter η was selected for evaluation because it specifies the level at which the market for CBS products and services saturates. The effect of η is as follows: higher values of η produce a higher level of adoption of CBS products and services in the marketplace towards the latter part of the study period (i.e., higher values of $P_\eta(t)$, for all values of *t*, especially whenever *t* is large), whereas lower values of η produce a lower level of adoption (i.e., lower values of $P_\eta(t)$). Reference to Table 8-4 reveals that η exerts a moderate to strong effect on all six of the economic measures. For example, the range of values for PVS_{ALL} (i.e., Maximum – Minimum) exceeds $1.5 billion in 1997 dollars. Although the present value of savings nationwide is strongly affected by changes in the value of η, the measures of BFRL's influence are affected to a lesser degree than for changes in α. The reason, once again, is due to the way in which BFRL's influence is measured. Because those savings occurring in the first seven years are attributable to BFRL, lower values of η reduce these savings and higher values of η increase these savings over the value calculated in the baseline analysis. However, these differences are less than those associated with α, because α affects the thickness of the lower tail of $P_\eta(t)$, whereas η affects the level at which the market saturates. Thus, the influence of η on the years immediately following the introduction

of CBS products and services is quite modest. Consequently, the range of values for the measures of BFRL's influence due to variations about the baseline value for η tend to be wider than for β, but narrower than for α.

Table 8-4. Summary Statistics Due to Changes in the Input Variable Eta

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
PVS_{ALL}	377.648	953.668	1,187.391	1,468.240	2,025.147	1,199.016	359.822
PVS_{BFRL}	29.144	73.596	91.633	113.306	156.284	92.530	27.768
PVC_{BFRL}	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$PVNS_{BFRL}$	17.669	62.121	80.158	101.831	144.809	81.055	27.768
SIR_{BFRL}	2.540	6.414	7.985	9.874	13.619	8.064	2.420
$AIRR_{BFRL}$	0.111	0.153	0.163	0.173	0.188	0.161	0.015

Table 8-5 shows how variations about the baseline value for the time of first use (i.e., t = 1 in the year 2003) affect each economic measure. The alternative times of first use are specified by a discrete distribution (see Table 8-1). The discrete probabilities for each year are: 2002, 0.125; 2003, 0.5; 2004, 0.25; and 2005, 0.125. The time of first use affects primarily the present value of savings nationwide, PVS_{ALL}, since it determines the number of years over which cost savings can accrue. This is because the end of the study period is fixed at 2015. Thus, if the year of first use is 2005, there are fewer years over which savings can accrue than for the baseline value (i.e., 2003). Notice that the measures of BFRL's influence are only slightly affected (i.e., the mean for each is approximately equal to the value calculated in the baseline analysis and the standard deviation for each is quite low). This is because BFRL's contribution is measured in terms of the savings occurring in the first seven years. The year of first use defines when the seven-year period begins. Thus, the differences from the value calculated in the baseline analysis are due to the timing of the savings, which, through the discount rate, affects the value of PVS_{BFRL}. Variations in the value of PVS_{BFRL} are responsible for variations in the values of $PVNS_{BFRL}$, SIR_{BFRL}, and $AIRR_{BFRL}$.

Table 8-5. Summary Statistics Due to Changes in the Input Variable Time of First Use

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
PVS_{ALL}	535.567	818.262	1,175.655	1,175.655	1,600.777	1,062.731	297.979
PVS_{BFRL}	78.744	84.564	90.727	90.727	98.652	88.754	5.455
PVC_{BFRL}	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$PVNS_{BFRL}$	67.269	73.089	79.252	79.252	87.177	77.279	5.455
SIR_{BFRL}	6.862	7.369	7.906	7.906	8.597	7.735	0.475
$AIRR_{BFRL}$	0.156	0.159	0.162	0.162	0.166	0.161	0.003

Table 8-6 shows how variations about the baseline value for the length of the delay (i.e., seven years) affect each economic measure. The alternative numbers of years for the

length of the delay are specified by a discrete distribution (see Table 8-1). The discrete probabilities for each length of delay are: 4 years, 0.016; 5 years, 0.047; 6 years, 0.187; 7 years, 0.5; 8 years, 0.187; 9 years, 0.047; and 10 years, 0.016. The length of delay only affects the measures of BFRL's influence. Thus, the computed value for PVS_{ALL} is equal to the value calculated in the baseline analysis. Reference to Table 8-6 reveals that the minimum value for each economic measure is lower than the corresponding minimum value for each of the four variables examined previously, and the maximum values are higher than the corresponding maximum value for each of the four variables examined previously. Although the range of values for each measure of BFRL's influence is quite wide, in every case BFRL's contribution is positive (i.e., $PVS_{BFRL} > 0.0$, $SIR_{BFRL} > 1.0$, and $AIRR_{BFRL} > 0.07$).

Table 8-6. Summary Statistics Due to Changes in the Input Variable Length of Delay

Economic Measure	Statistical Measure						
	Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
PVS_{ALL}	1,175.655	1,175.655	1,175.655	1,175.655	1,175.655	1,175.655	0.0
PVS_{BFRL}	14.522	90.727	90.727	90.727	407.606	103.894	63.411
PVC_{BFRL}	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$PVNS_{BFRL}$	3.047	79.252	79.252	79.252	396.131	92.419	63.411
SIR_{BFRL}	1.266	7.906	7.906	7.906	35.521	9.054	5.526
$AIRR_{BFRL}$	0.080	0.162	0.162	0.162	0.234	0.162	0.026

The results presented in Tables 8-7, 8-8, and 8-9 are related to the values of cost savings per square meter (*per square foot*). Table 8-7 summarizes the results of the Monte Carlo simulation of variations about the baseline value of energy cost savings of $1.71 per square meter (*$0.16 per square foot*). Reference to Table 8-7 reveals moderate variations about the values calculated in the baseline analysis for five of the six economic measures. For example, the value calculated in the baseline analysis for the SIR_{BFRL} is 7.9. In Table 8-7, the minimum value for the SIR_{BFRL} is 6.031, and the maximum value is 9.759.

Table 8-7. Summary Statistics Due to Changes in the Input Variable Energy Cost Savings Per Square Meter (*Per Square Foot*)

Economic Measure	Statistical Measure						
	Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
PVS_{ALL}	1,006.142	1,126.266	1,174.601	1,227.235	1,343.108	1,174.899	71.004
PVS_{BFRL}	69.208	84.457	90.593	97.275	111.985	90.631	9.014
PVC_{BFRL}	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$PVNS_{BFRL}$	57.733	72.982	79.118	85.800	100.510	79.156	9.014
SIR_{BFRL}	6.031	7.360	7.895	8.477	9.759	7.898	0.785
$AIRR_{BFRL}$	0.150	0.159	0.162	0.166	0.172	0.162	0.005

Table 8-8 summarizes the results of the Monte Carlo simulation of variations about the baseline value of maintenance cost savings of $1.60 per square meter (*$0.15 per square foot*). Table 8-8 reveals moderate variations about the values calculated in the baseline analysis for five of the six economic measures. This pattern is similar to the one resulting from per unit energy cost savings. For example, the minimum value for the SIR_{BFRL} is 6.122, and the maximum is 11.527. Note that the variability in these results is higher than for per unit energy cost savings (compare the two sets of entries under the heading Standard Deviation). This is because the triangular distribution used to model variations in per unit maintenance cost savings is positively skewed. Thus, the mean and the median for five of the six economic measures are higher (compare the two sets of entries for the mean and median values of SIR_{BFRL}) for per unit maintenance cost savings, since there is a small probability of maintenance cost savings exceeding $3.00 per square meter (*$0.28 per square foot*).

Table 8-8. Summary Statistics Due to Changes in the Input Variable Maintenance Cost Savings Per Square Meter (*Per Square Foot*)

Economic Measure	Statistical Measure						
	Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
$\mathbf{PVS_{ALL}}$	1,008.428	1,154.812	1,234.276	1,321.336	1,514.990	1,240.999	112.832
$\mathbf{PVS_{BFRL}}$	70.251	88.175	97.905	108.565	132.277	98.728	13.816
$\mathbf{PVC_{BFRL}}$	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$\mathbf{PVNS_{BFRL}}$	58.776	76.700	86.430	97.090	120.802	87.253	13.816
$\mathbf{SIR_{BFRL}}$	6.122	7.684	8.532	9.461	11.527	8.604	1.204
$\mathbf{AIRR_{BFRL}}$	0.150	0.161	0.166	0.171	0.180	0.166	0.007

Table 8-9 summarizes the results of the Monte Carlo simulation of variations about the baseline value of productivity cost savings of $4.20 per square meter ($0.39 per square foot). The results presented in Table 8-9 differ significantly from those presented in any of the previous tables in two important ways. First, the present value of cost savings nationwide, PVS_{ALL}, ranges from just over $250 million to nearly $2.1 billion in 1997 dollars. Thus, productivity cost savings are a key driver in estimating PVS_{ALL}. Second, the minimum values of three of the key measures of BFRL's influence (i.e., $PVNS_{BFRL}$, SIR_{BFRL}, and $AIRR_{BFRL}$[72]) indicate that BFRL's CBS-related investments may not be cost effective. To place the previous remark in context, it is important to recognize that this outcome corresponds to a few "low-probability" events. For example, the 25th percentile value of SIR_{BFRL} is 4.8, well above the minimum requirement of 1.0, and of $AIRR_{BFRL}$ is 13.9 percent, also well above the minimum requirement of 7 percent. How likely are "uneconomic" outcomes is a subject that will be explored more fully when all nine input variables are allowed to vary in combination.

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[72] The value of the AIRR is only defined for cases where the computed value of the SIR is non-negative. If the computed value of SIR_{BFRL} is negative, then the value of $AIRR_{BFRL}$ is listed as n.a.

Table 8-9. Summary Statistics Due to Changes in the Input Variable Productivity Cost Savings Per Square Meter (*Per Square Foot*)

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
PVS_{ALL}	258.125	884.554	1,169.202	1,446.833	2,094.076	1,172.358	380.455
PVS_{BFRL}	-21.620	55.083	89.937	123.932	203.184	90.323	46.585
PVC_{BFRL}	11.475	11.475	11.475	11.475	11.475	11.475	0.0
$PVNS_{BFRL}$	-33.095	43.608	78.462	112.457	191.709	78.848	46.585
SIR_{BFRL}	-1.884	4.800	7.838	10.800	17.706	7.871	4.060
$AIRR_{BFRL}$	n.a.	0.139	0.162	0.177	0.200	0.120	0.275

Table 8-10 shows how variations about the baseline value of the discount rate (7 percent (real)) affect each economic measure. The discount rate affects calculations in a number of ways. BFRL's CBS-related investment costs, PVC_{BFRL}, are affected by the discount rate. The present value of savings nationwide, PVS_{ALL}, and the present value of savings due to BFRL, PVS_{BFRL}, are also affected by the discount rate. Reference to Table 8-10 reveals that PVS_{ALL} is more sensitive to changes in the discount rate than are the key measures of BFRL's influence. This is because savings do not begin until 2003, whereas the base year is 1997. Thus, savings occurring in the out years (e.g., 2010 and beyond) benefit from a lower discount rate and are penalized by a higher discount rate. This explains the wide range in computed values for $PVS_{ALL,}$ a range that exceeds $1.0 billion in 1997 dollars. On the other hand, BFRL's CBS-related investments are largely clustered around 1997, and BFRL's savings occur between 2003 and 2009 (i.e., much earlier than the bulk of the savings used to calculate PVS_{ALL}). This explains why the key measures of BFRL's influence are less sensitive to changes in the discount rate than is PVS_{ALL}.

Table 8-10. Summary Statistics Due to Changes in the Input Variable Discount Rate

Economic Measure	Statistical Measure						
	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
PVS_{ALL}	772.835	1,041.206	1,173.724	1,328.731	1,811.587	1,198.829	216.187
PVS_{BFRL}	68.005	83.472	90.625	98.669	121.988	91.626	11.278
PVC_{BFRL}	10.952	11.313	11.473	11.648	12.128	11.490	0.246
$PVNS_{BFRL}$	57.053	72.159	79.152	87.021	109.860	80.136	11.031
SIR_{BFRL}	6.209	7.379	7.899	8.471	10.058	7.957	0.805
$AIRR_{BFRL}$	0.142	0.157	0.162	0.168	0.182	0.162	0.008

8.3.2 Changing All Nine Inputs in Combination

Table 8-11 summarizes the results of the Monte Carlo simulation in which all nine of the input variables were varied in combination. Reference to Table 8-11 reveals that both the present value of savings nationwide, PVS_{ALL}, and the present value of savings due to BFRL, PVS_{BFRL}, can be negative. This implies that there is some non-zero probability that BFRL's CBS-related investments are not cost effective. However, on the opposite extreme, $PVNS_{BFRL}$ may reach nearly $1.4 billion in 1997 dollars, and SIR_{BFRL} reaches 118.6.

The table also serves to highlight one of the merits of the median as a measure of central tendency. Comparison between the median value of each economic measure, recorded under the heading 50%, and the corresponding value calculated in the baseline analysis reveals that the two sets of values are remarkably close. The value computed in the baseline analysis for each economic measure (see Exhibit 7-1) is $1,175.6 million for PVS_{ALL}, $90.7 million for PVS_{BFRL}, $11.475 million for PVC_{BFRL}, $79.3 million for $PVNS_{BFRL}$, 7.9 for SIR_{BFRL}, and 0.162 for $AIRR_{BFRL}$. The mean values for PVS_{ALL}, PVS_{BFRL}, $PVNS_{BFRL}$, and SIR_{BFRL} tend to exceed the corresponding value calculated in the baseline analysis. This is because a small number of very large observations are pulling up the computed value of the mean.

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.

Table 8-11. Summary Statistics Due to Changes in All of the Input Variables

Economic Measure	Statistical Measure						
	Minimum	**25%**	**50%**	**75%**	**Maximum**	**Mean**	**Standard Deviation**
PVS_{ALL}	-2.503	611.492	1,168.482	1,552.634	5,820.787	1,215.738	822.988
PVS_{BFRL}	-29.834	40.649	90.886	172.463	1,402.408	136.714	157.107
PVC_{BFRL}	10.943	11.285	11.459	11.652	12.128	11.471	0.252
$PVNS_{BFRL}$	-41.424	29.058	79.484	161.109	1,390.585	125.243	157.065
SIR_{BFRL}	-2.574	3.548	7.896	15.287	118.616	11.873	13.543
$AIRR_{BFRL}$	n.a.	0.128	0.161	0.193	0.291	0.161	0.305

The graphical results of the sensitivity analysis where all nine input variables were varied in combination are shown in Figures 8-1 through 8-6. 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., SIR_{BFRL}) 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.

The tabular results of the sensitivity analysis are recorded in Table 8-12. The table lists each of the calculated percentiles from the resultant CDF. The range of percentiles included in the table go from the 1st to the 99th. For purposes of this analysis, the 0th percentile is set equal to the minimum value, and the 100th percentile is set equal to the maximum value. This enables a close coupling of the values recorded in Table 8-12 and the values used to plot each figure.

Table 8-12 includes for each percentile the computed value for PVS_{ALL}, PVS_{BFRL}, PVC_{BFRL}, $PVNS_{BFRL}$, SIR_{BFRL}, and $AIRR_{BFRL}$. 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. Readers interested in procedures for estimating percentiles are referred to the text by Ott.[73]

Figure 8-1 shows how present value cost savings nationwide, PVS_{ALL}, varies when all nine input variables are varied in combination. In analyzing Figure 8-1, it is useful to keep in mind that the value of PVS_{ALL} resulting from the baseline analysis was $1,175.6 million. As was seen in Table 8-11, the median value of the 1,000 observations was nearly equal to the value of PVS_{ALL} calculated in the baseline analysis. What the figure shows clearly is the considerable degree to which PVS_{ALL} varies—both above and below the median value.

To best understand the implications of these variations, it is useful to refer both to Figure 8-1 and the entries under the PVS_{ALL} column heading of Table 8-12. First, the lower limit shown on Figure 8-1 is approximately $0.0. However, the 1st percentile for PVS_{ALL} is $119.8 million. Thus, only 10 observations out of 1,000 are clustered between $0.0 and the 1st percentile ($119.8 million). Second, the CDF increases at a steady, almost linear rate between the 3rd percentile ($228.6 million) and the 75th percentile ($1,552.6 million). Third, above the 75th percentile, the CDF increases at a decreasing rate. This is shown by the way in which the CDF tails off as the calculated value of PVS_{ALL} gets large. Finally, the maximum value of PVS_{ALL} is nearly $6.0 billion. However, the 99th percentile is $3,791.3 million. Thus, only 10 observations out of 1,000 account for approximately $2.0 billion in the total range of values for PVS_{ALL}. This implies that the trace of the CDF for PVS_{ALL} is positively skewed.

[73] Ott, Lyman. 1984. *An Introduction to Statistical Methods and Data Analysis*. Boston, MA: Duxbury Press.

Figure 8-1. Present Value of Cost Savings Nationwide in Millions of 1997 Dollars

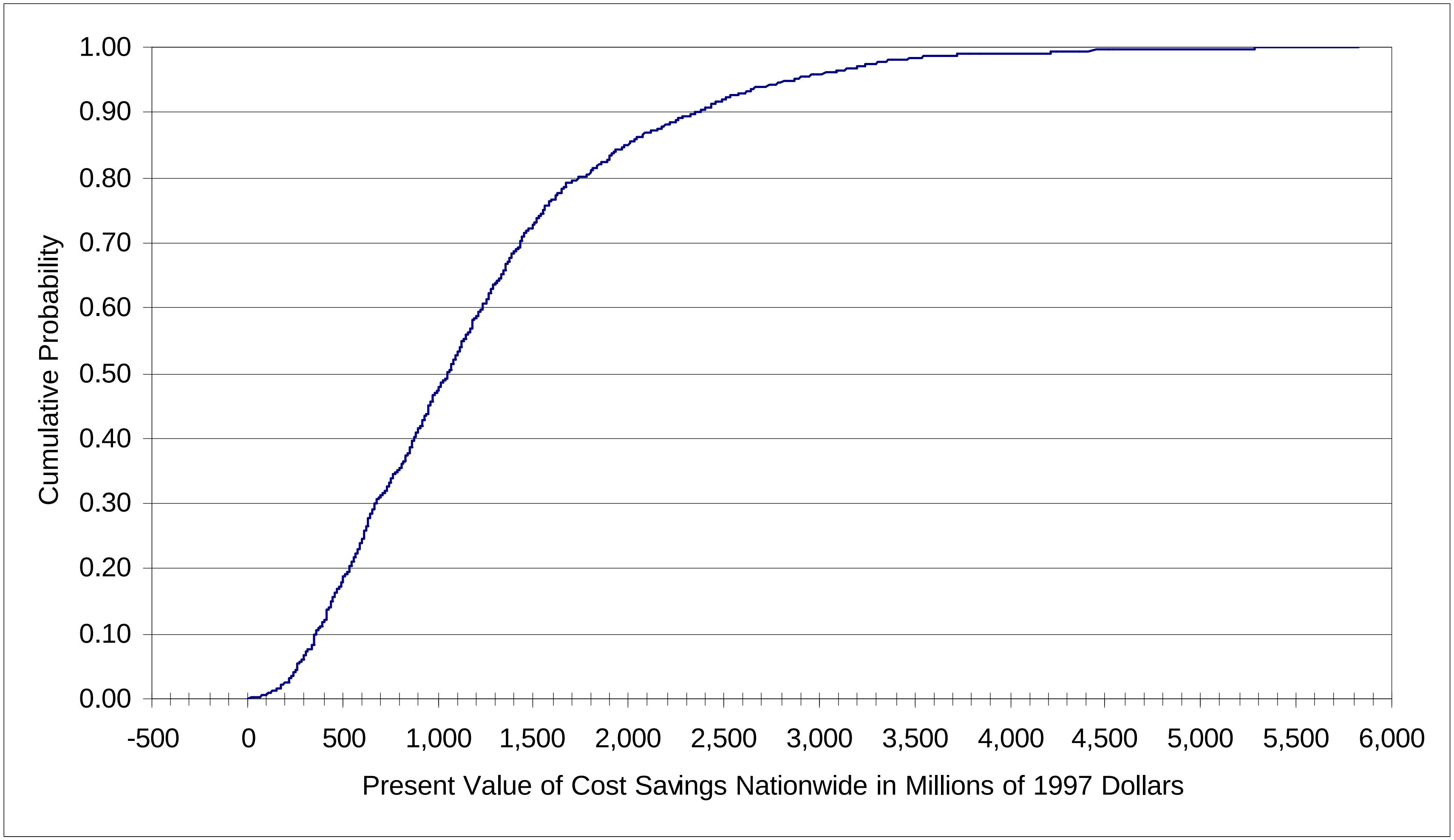


Table 8-12. Percentiles for Statistical Measures Due to Changes in All of the Input Variables

Percentile	Economic Measure					
	PVS_{ALL}	PVS_{BFRL}	PVC_{BFRL}	$PVNS_{BFRL}$	SIR_{BFRL}	$AIRR_{BFRL}$
1ST	119.824	-5.622	10.995	-16.763	-0.501	n.a.
2ND	183.241	1.006	11.013	-10.288	0.089	n.a.
3RD	228.621	4.670	11.040	-6.482	0.419	0.031
4TH	249.364	7.242	11.050	-4.436	0.624	0.049
5TH	265.328	9.377	11.066	-1.945	0.828	0.065
6TH	290.924	11.582	11.082	0.444	1.040	0.071
7TH	307.471	12.919	11.096	1.526	1.134	0.080
8TH	341.957	14.867	11.105	3.330	1.295	0.084
9TH	350.749	16.641	11.123	4.999	1.432	0.088
10TH	360.897	19.252	11.133	7.587	1.647	0.092
11TH	383.994	20.474	11.151	9.158	1.810	0.097
12TH	407.786	22.311	11.167	11.010	1.985	0.100
13TH	415.719	24.015	11.181	12.716	2.128	0.104
14TH	435.314	24.852	11.189	13.510	2.194	0.108
15TH	444.027	26.539	11.197	15.109	2.319	0.110
16TH	459.366	27.603	11.205	16.334	2.436	0.112
17TH	481.689	28.875	11.212	17.412	2.540	0.114
18TH	499.720	31.340	11.221	19.772	2.748	0.115
19TH	519.309	33.203	11.234	21.778	2.893	0.117
20TH	537.852	34.394	11.244	22.839	2.984	0.118
21ST	552.953	35.106	11.250	23.769	3.121	0.120
22ND	572.247	36.597	11.262	25.291	3.212	0.122
23RD	587.972	38.047	11.275	26.590	3.325	0.124
24TH	599.569	39.165	11.278	27.938	3.429	0.125
25TH	611.492	40.649	11.285	29.058	3.548	0.128
26TH	621.346	41.785	11.294	30.432	3.634	0.131
27TH	632.027	43.900	11.301	32.464	3.788	0.133
28TH	645.426	45.391	11.308	33.777	3.940	0.134
29TH	662.137	46.956	11.314	35.633	4.083	0.135
30TH	674.850	49.329	11.322	38.056	4.327	0.136
31ST	700.585	51.820	11.330	40.413	4.546	0.137
32ND	726.674	53.082	11.336	41.729	4.667	0.139
33RD	744.583	55.060	11.341	43.824	4.753	0.140

Table 8-12. Percentiles for Statistical Measures Due to Changes in All of the Input Variables (continued)

Percentile	Economic Measure					
	PVS_{ALL}	PVS_{BFRL}	PVC_{BFRL}	$PVNS_{BFRL}$	SIR_{BFRL}	$AIRR_{BFRL}$
34TH	764.498	56.212	11.347	44.613	4.949	0.141
35TH	786.522	57.707	11.354	46.088	5.061	0.143
36TH	816.554	59.391	11.361	47.958	5.179	0.143
37TH	832.884	61.827	11.369	50.242	5.363	0.144
38TH	851.606	63.081	11.374	51.513	5.512	0.146
39TH	865.486	65.212	11.381	53.720	5.705	0.146
40TH	879.298	68.613	11.387	57.464	5.949	0.147
41ST	890.950	70.302	11.394	58.765	6.147	0.148
42ND	917.081	71.690	11.399	60.203	6.257	0.150
43RD	924.849	74.395	11.405	62.774	6.411	0.151
44TH	947.165	76.049	11.416	64.455	6.622	0.152
45TH	955.129	79.162	11.422	67.755	6.934	0.153
46TH	974.491	81.761	11.430	70.236	7.168	0.154
47TH	993.461	85.661	11.442	74.181	7.429	0.156
48TH	1,016.152	87.430	11.448	76.013	7.574	0.157
49TH	1,036.961	88.958	11.454	77.690	7.751	0.159
50TH	1,048.482	90.886	11.459	79.484	7.896	0.161
51ST	1,070.888	91.926	11.465	80.348	8.045	0.162
52ND	1,087.093	94.554	11.473	82.742	8.150	0.165
53RD	1,104.631	96.329	11.477	85.184	8.409	0.166
54TH	1,120.000	99.246	11.486	87.704	8.672	0.167
55TH	1,137.351	101.390	11.497	89.943	8.864	0.169
56TH	1,154.523	104.005	11.503	92.563	9.134	0.171
57TH	1,175.424	107.686	11.512	96.026	9.295	0.172
58TH	1,185.143	109.186	11.516	97.810	9.608	0.173
59TH	1,213.544	112.739	11.525	101.168	9.809	0.175
60TH	1,231.675	115.968	11.534	104.512	10.134	0.176
61ST	1,252.945	120.408	11.539	109.143	10.491	0.177
62ND	1,269.792	122.643	11.548	111.249	10.716	0.178
63RD	1,287.812	126.465	11.551	114.951	11.031	0.179
64TH	1,306.804	128.389	11.559	116.953	11.223	0.180
65TH	1,337.499	130.092	11.565	118.690	11.390	0.181
66TH	1,351.516	133.183	11.572	121.630	11.564	0.182

Table 8-12. Percentiles for Statistical Measures Due to Changes in All of the Input Variables (continued)

Percentile	Economic Measure					
	PVS_{ALL}	PVS_{BFRL}	PVC_{BFRL}	$PVNS_{BFRL}$	SIR_{BFRL}	$AIRR_{BFRL}$
67TH	1,370.683	135.565	11.580	124.204	11.924	0.183
68TH	1,389.332	140.734	11.589	129.166	12.282	0.185
69TH	1,414.330	143.574	11.596	132.248	12.558	0.186
70TH	1,432.018	148.869	11.608	136.973	12.980	0.187
71ST	1,447.771	154.754	11.618	143.200	13.373	0.189
72ND	1,474.278	157.668	11.626	145.912	13.694	0.190
73RD	1,509.997	161.873	11.632	150.406	14.176	0.191
74TH	1,533.073	169.291	11.643	157.847	14.740	0.192
75TH	1,552.634	172.463	11.652	161.109	15.287	0.193
76TH	1,585.860	180.111	11.661	168.519	15.514	0.195
77TH	1,618.044	183.912	11.673	172.314	16.018	0.196
78TH	1,649.848	188.075	11.680	176.429	16.541	0.197
79TH	1,676.267	193.287	11.689	181.738	16.843	0.198
80TH	1,733.399	201.952	11.696	189.959	17.446	0.199
81ST	1,801.257	209.839	11.719	198.253	18.278	0.201
82ND	1,851.337	216.075	11.728	204.375	18.744	0.204
83RD	1,899.135	226.909	11.742	215.194	19.369	0.206
84TH	1,929.266	232.870	11.752	221.234	20.188	0.207
85TH	1,988.531	248.407	11.759	237.188	21.603	0.209
86TH	2,045.326	256.050	11.763	244.457	22.376	0.212
87TH	2,123.945	266.114	11.770	254.397	23.117	0.213
88TH	2,189.905	274.141	11.786	263.011	23.876	0.216
89TH	2,262.602	289.058	11.802	277.835	25.190	0.218
90TH	2,352.084	304.969	11.815	293.024	26.128	0.221
91ST	2,433.249	328.940	11.832	317.273	28.522	0.223
92ND	2,502.007	343.558	11.849	332.349	29.688	0.227
93RD	2,605.023	362.317	11.863	350.430	31.222	0.228
94TH	2,721.486	376.727	11.891	365.176	32.887	0.234
95TH	2,867.994	419.699	11.903	408.382	37.087	0.237
96TH	2,992.995	475.669	11.920	464.117	41.140	0.242
97TH	3,207.017	513.572	11.950	502.186	43.850	0.246
98TH	3,382.433	567.612	11.987	556.228	49.858	0.253
99TH	3,791.309	799.278	12.035	787.434	67.483	0.269

Figure 8-2 shows how present value savings due to BFRL, PVS_{BFRL}, varies when all nine input variables are varied in combination. In analyzing Figure 8-2, it is useful to keep in mind that the value of PVS_{BFRL} resulting from the baseline analysis was $90.7 million. As was seen in Table 8-11, the median value of the 1,000 observations was nearly equal to the value of PVS_{BFRL} calculated in the baseline analysis. Figure 8-2 exhibits a pattern similar to the pattern seen in Figure 8-1. There is, however, one important difference between the traces of the CDFs in the two figures. Figure 8-2 is much more positively skewed than Figure 8-1 (compare the upper tails of the two CDF traces).

To best understand the implications of these variations, it is useful to refer both to Figure 8-2 and the entries under the PVS_{BFRL} column heading of Table 8-12. First, note that the lower limit shown on Figure 8-2 extends below $0.0. Reference to Table 8-12 reveals that the 1st percentile for PVS_{BFRL} is still negative (-$5.6 million). However, by the 2nd percentile, the computed value of PVS_{BFRL} becomes positive ($1.0 million). Thus, less than 20 observations out of 1,000 are negative. Stated another way, there is at least a 98 percent probability that BFRL's CBS-related efforts will produce positive and measurable cost savings to building owners, managers, and occupants. Second, the CDF increases at a steady, almost linear rate between the 4th percentile ($7.2 million) and the 60th percentile ($116.0 million). Third, above the 60th percentile, the CDF increases at a decreasing rate. This is shown by the way in which the CDF tails off as the calculated value of PVS_{BFRL} gets large. Finally, the maximum value of PVS_{BFRL} is approximately $1.4 billion. However, the 99th percentile is $799.3 million. Thus, only 10 observations out of 1,000 account for approximately $600 million in the total range of values for PVS_{BFRL}.

Figure 8-3 shows how the present value of BFRL's CBS-related investment costs, PVC_{BFRL}, varies when all nine input variables are varied in combination. Because the only variable that produces variations in PVC_{BFRL} is the discount rate, the shape of Figure 8-3 differs from the shapes of all of the other figures presented in this section.

Reference to the figure and to Tables 8-11 and 8-12 reveals that the CDF for PVC_{BFRL} is very nearly symmetric. From Table 8-11 we see that the mean and median are nearly equal, the standard deviation is quite small, and the differences between the maximum and minimum values and the median are nearly equal. An examination of Figure 8-3 reveals that the trace of the CDF does not exhibit the same, sharp tailing off as was seen in the other figures. In fact, the trace of the CDF for PVC_{BFRL} is nearly linear between the 20th percentile ($11.244 million) and the 80th percentile ($11.696). Below the 20th percentile and above the 80th percentile the traces exhibit very similar patterns of non-linearity.

Figure 8-2. Present Value of Cost Savings Attributable to BFRL in Millions of 1997 Dollars

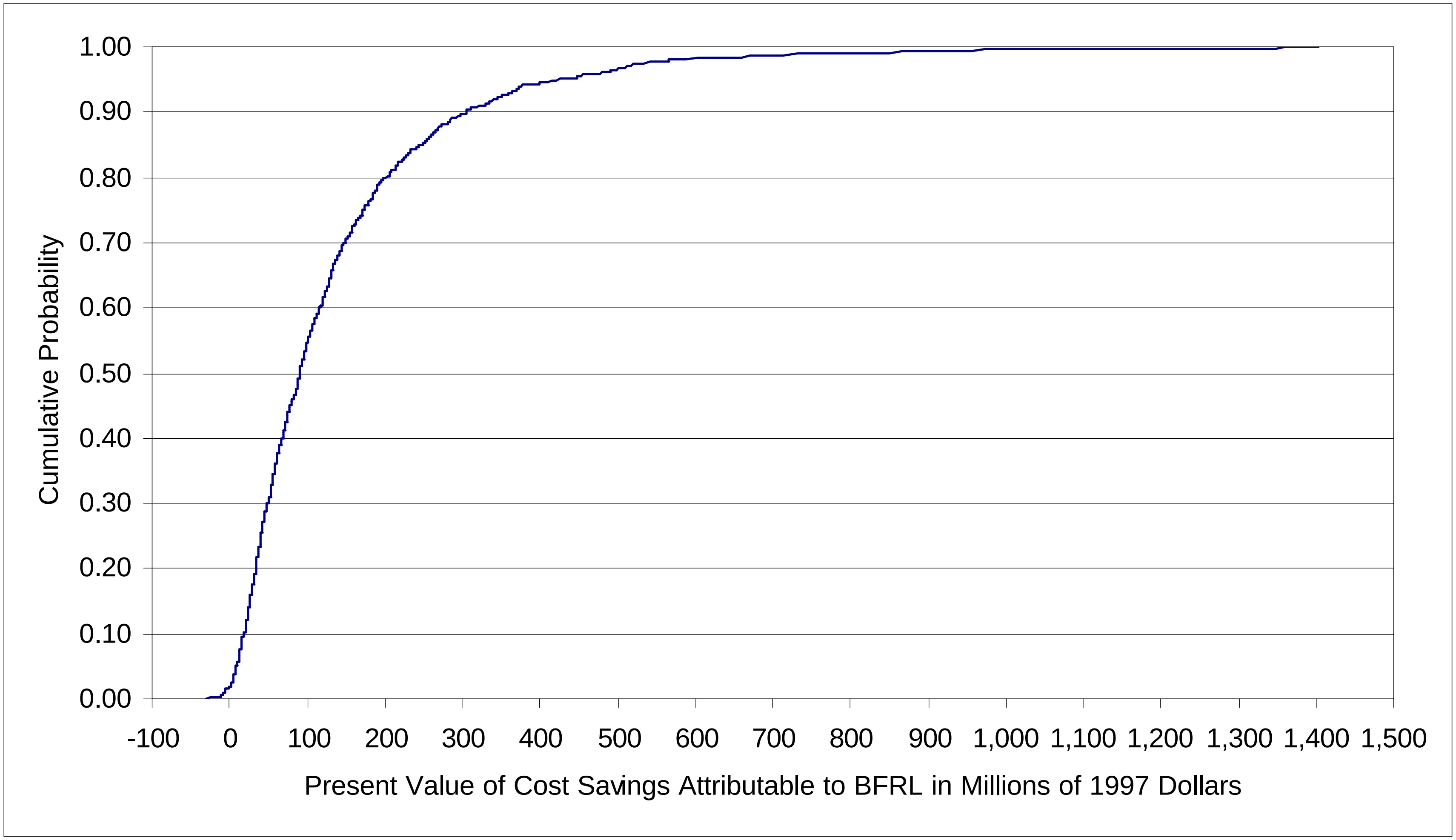


Figure 8-3. Present Value of BFRL's Investment Costs in Millions of 1997 Dollars

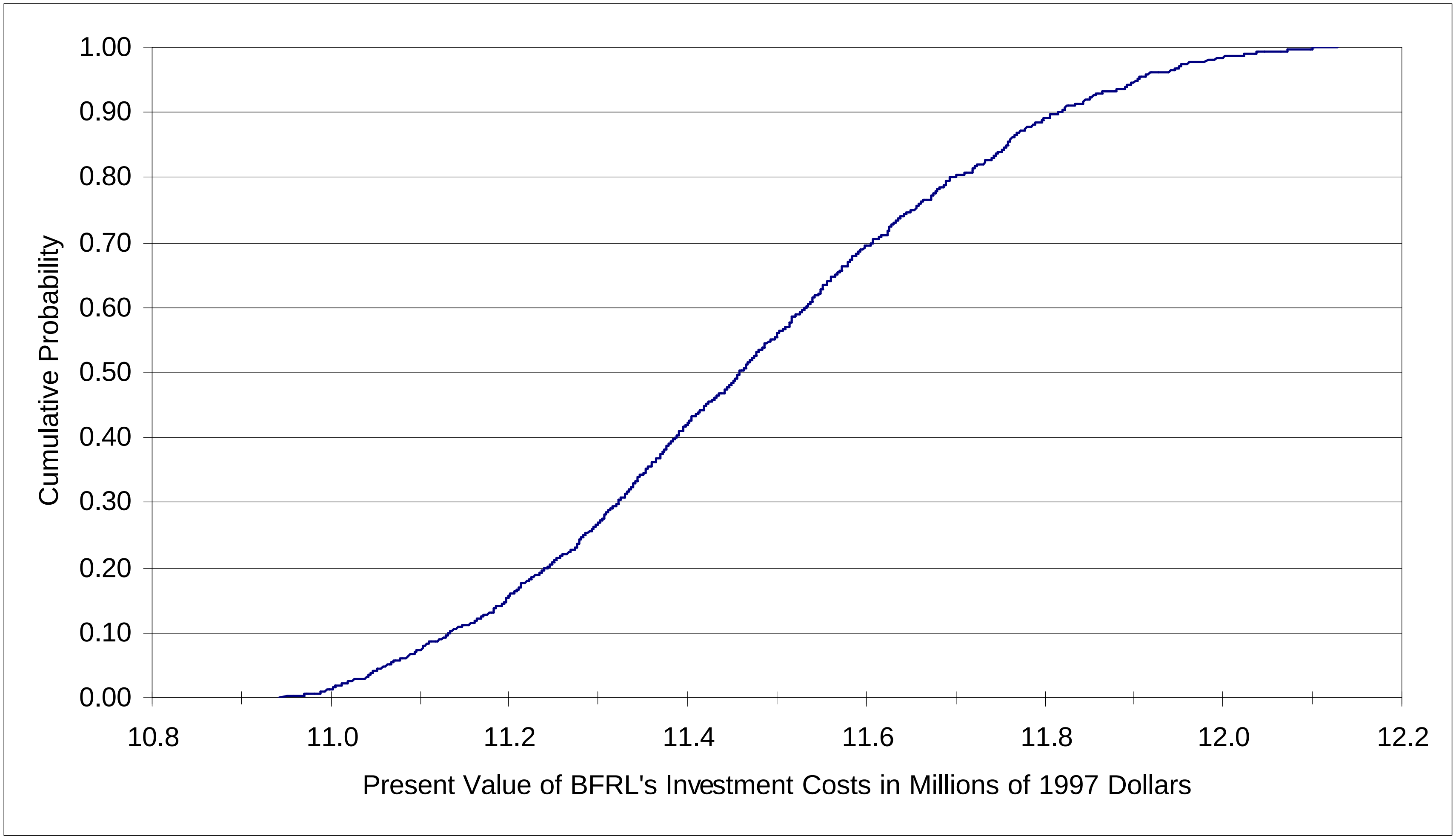


Figure 8-4 shows how present value net savings due to BFRL, $PVNS_{BFRL}$, varies when all nine input variables are varied in combination. In analyzing Figure 8-4, it is useful to keep in mind that the value of $PVNS_{BFRL}$ resulting from the baseline analysis was $79.3 million. As was seen in Table 8-11, the median value of the 1,000 observations was nearly equal to the value of $PVNS_{BFRL}$ calculated in the baseline analysis. Also, Figure 8-4 exhibits a pattern similar to the pattern seen in Figure 8-2. Note that both Figure 8-2 and Figure 8-4 are highly, positively skewed (compare the upper tails of the two CDF traces). In addition, both figures are defined over nearly identical ranges of values. This similarity is to be expected since the only difference between PVS_{BFRL} (see Figure 8-2) and $PVNS_{BFRL}$ is PVC_{BFRL} (see Figure 8-3). Recall that PVC_{BFRL} was defined over a very narrow range of values, and was also symmetric. Thus, throughout the range of values over which PVS_{BFRL} and $PVNS_{BFRL}$ are defined, the value of PVC_{BFRL} acts very much like a constant term.

As was the case for the previous figures, it is useful to refer both to Figure 8-4 and the entries under the $PVNS_{BFRL}$ column heading of Table 8-12. First, note that the lower limit shown on Figure 8-4 extends below $0.0. Reference to Table 8-12 reveals that the 1st percentile for $PVNS_{BFRL}$ is still negative (-$16.8 million). However, by the 6th percentile, the computed value of $PVNS_{BFRL}$ becomes positive ($0.4 million). Thus, less than 60 observations out of 1,000 are negative. Stated another way, there is at least a 94 percent chance that BFRL's CBS-related investments are cost effective. Second, the CDF increases at a steady, almost linear rate between the 10th percentile ($7.6 million) and the 50th percentile ($79.5 million). Third, above the 50th percentile, the CDF increases at a decreasing rate. This is shown by the way in which the CDF tails off as the calculated value of $PVNS_{BFRL}$ gets large. Finally, the maximum value of $PVNS_{BFRL}$ is nearly $1.4 billion. However, the 99th percentile is $787.4 million. Thus, only 10 observations out of 1,000 account for approximately $600 million in the total range of values for $PVNS_{BFRL}$.

Because there are so many similarities—very low values, very high values, and the CDF traces—between the results of the sensitivity analysis for PVS_{BFRL} and $PVNS_{BFRL}$, it is useful to analyze the underlying characteristics of both the upper and lower tails of the two CDF traces. This analysis was facilitated through the use of the @RISK software product. Specifically, the @RISK software product enables the random draw for each input variable for each of the 1,000 simulations to be stored in a spreadsheet. This produces a one-to-one correspondence between each simulation's input set and the resultant values of the economic measures.

As might be expected, the factors that contribute to very low values of PVS_{BFRL} and $PVNS_{BFRL}$ differ from those that contribute to very high values of PVS_{BFRL} and $PVNS_{BFRL}$. Consider first the very low values of PVS_{BFRL} and $PVNS_{BFRL}$. Two factors contribute to very low values of PVS_{BFRL} and $PVNS_{BFRL}$. One factor, the level of productivity cost savings, is always present. For this case, the level of productivity cost savings was always less than or equal to the 10th percentile of the parent probability distribution. The second factor was more complex; it operated in combination with the first. The second factor involved four different possible combinations. These

combinations resulted from either (1) per unit energy cost savings less than or equal to the 10th percentile, (2) maintenance cost savings less than or equal to the 10th percentile, (3) a value of α greater than or equal to the 90th percentile, or (4) a value of β less than or equal to the 10th percentile. Very high values resulted from either a 10-year delay or a combination of a delay of at least seven years and high values for productivity savings, β, or η, ***and*** relatively low values of α. For example, for the 50 highest values (i.e., the top 5 percent of the 1,000 observations), productivity savings exceeded their 90th percentile 14 times, β exceeded its 90th percentile 11 times, and η exceeded its 90th percentile 14 times. In addition, the value of α was less than the baseline value, 6.0, 47 times.

Figure 8-5 shows how the savings-to-investment ratio on BFRL's CBS-related investments, SIR_{BFRL}, varies when all nine input variables are varied in combination. In analyzing Figure 8-5, it is useful to keep in mind that the value of SIR_{BFRL} resulting from the baseline analysis was 7.9. As was seen in Table 8-11, the median value of the 1,000 observations was nearly equal to the value of SIR_{BFRL} calculated in the baseline analysis. Also, Figure 8-5 exhibits a pattern similar to the pattern seen in Figure 8-2. Note that both Figure 8-5 and Figure 8-2 are highly, positively skewed (compare the upper tails of the two CDF traces). This similarity in shapes is to be expected since SIR_{BFRL} is the ratio of PVS_{BFRL} to PVC_{BFRL}. Recall that PVC_{BFRL} was defined over a very narrow range of values, and was also symmetric. Thus, the value of PVC_{BFRL} acts very much like a constant term. Although the shapes of the two distributions are similar, the ranges of values are specified in different units.

As was the case for the previous figures, it is useful to refer both to Figure 8-5 and the entries under the SIR_{BFRL} column heading of Table 8-12. First, note that the lower limit shown on Figure 8-5 extends below 0.0. Reference to Table 8-12 reveals that the 1st percentile for SIR_{BFRL} is negative (-0.501). However, by the 6th percentile, the computed value of SIR_{BFRL} exceeds 1.0 (1.040). Thus, less than 60 observations out of 1,000 are less than 1.0. Stated another way, based on the calculated value of SIR_{BFRL}, there is at least a 94 percent chance that BFRL's CBS-related investments are cost effective. Second, the CDF increases at a steady, almost linear rate between the 10th percentile (1.647) and the 50th percentile (7.896). Third, above the 50th percentile, the CDF increases at a decreasing rate. This is shown by the way in which the CDF tails off as the calculated value of SIR_{BFRL} gets large. Finally, the maximum value of SIR_{BFRL} is nearly 120. However, the 99th percentile is 67.483. Thus, only 10 observations out of 1,000 account for approximately 50 units in the total range of values for SIR_{BFRL}.

Figure 8-6 shows how the adjusted internal rate of return on BFRL's CBS-related investments, $AIRR_{BFRL}$, varies when all nine input variables are varied in combination. In analyzing Figure 8-6, it is useful to keep in mind that the value of $AIRR_{BFRL}$ resulting from the baseline analysis was 0.162. As was seen in Table 8-11, the median value of the 1,000 observations was nearly equal to the value of $AIRR_{BFRL}$ calculated in the baseline analysis. Figure 8-6 exhibits a pattern different from those seen in the other figures. Note that Figure 8-6 is negatively skewed (compare the lower and upper tails of the CDF trace). Although the values for $AIRR_{BFRL}$ are a monotonic transformation of the values for SIR_{BFRL}, the shapes of the two CDFs are quite dissimilar. This is because the

$AIRR_{BFRL}$ is functionally related to $(SIR_{BFRL})^{1/25}$. This relationship is highly non-linear, explaining why the two CDF traces are so dissimilar.

As was the case for the previous figures, it is useful to refer both to Figure 8-6 and the entries under the $AIRR_{BFRL}$ column heading of Table 8-12. First, note that the lower limit shown on Figure 8-6 is 0.0. This is because a value of $AIRR_{BFRL}$ less than 0.0 has no economic meaning. In addition, to calculate $AIRR_{BFRL}$ for values of SIR_{BFRL} less than 0.0 involves taking the root of a negative number, a process that is only defined when the length of the study period in years is an odd number. Both such cases are designated by the term n.a. in Tables 8-11 and 8-12. Reference to Table 8-12 reveals that the 1st and 2nd percentiles for $AIRR_{BFRL}$ are n.a. These entries are reflected by the "step-up" in the CDF at 0.0. By the 6th percentile, the computed value of $AIRR_{BFRL}$ exceeds the seven-percent real discount rate. Thus, less than 60 observations out of 1,000 produce a value for the $AIRR_{BFRL}$ less than the discount rate. Stated another way, based on the calculated value of $AIRR_{BFRL}$, there is at least a 94 percent chance that BFRL's CBS-related investments are cost effective. Second, the CDF increases at a steady, almost linear rate between the 15th percentile (0.110) and the 85th percentile (0.209). Third, below the 15th percentile, the CDF increases at an increasing rate. Finally, above the 85th percentile, the CDF increases at a decreasing rate.

Note that the values of $PVNS_{BFRL}$, SIR_{BFRL}, and $AIRR_{BFRL}$ all indicated the regions of the appropriate CDF trace where BFRL's CBS-related investments were cost effective. In each case these economic measures defined the same break-even point in each of the CDF traces. The break-even point corresponds to a value of each economic measure just below the 6th percentile of its CDF. This point is noteworthy, since each measure provides a different perspective, but produces the same end result in terms of identifying the break-even point.

Figure 8-4. Present Value of Net Savings Attributable to BFRL in Millions of 1997 Dollars

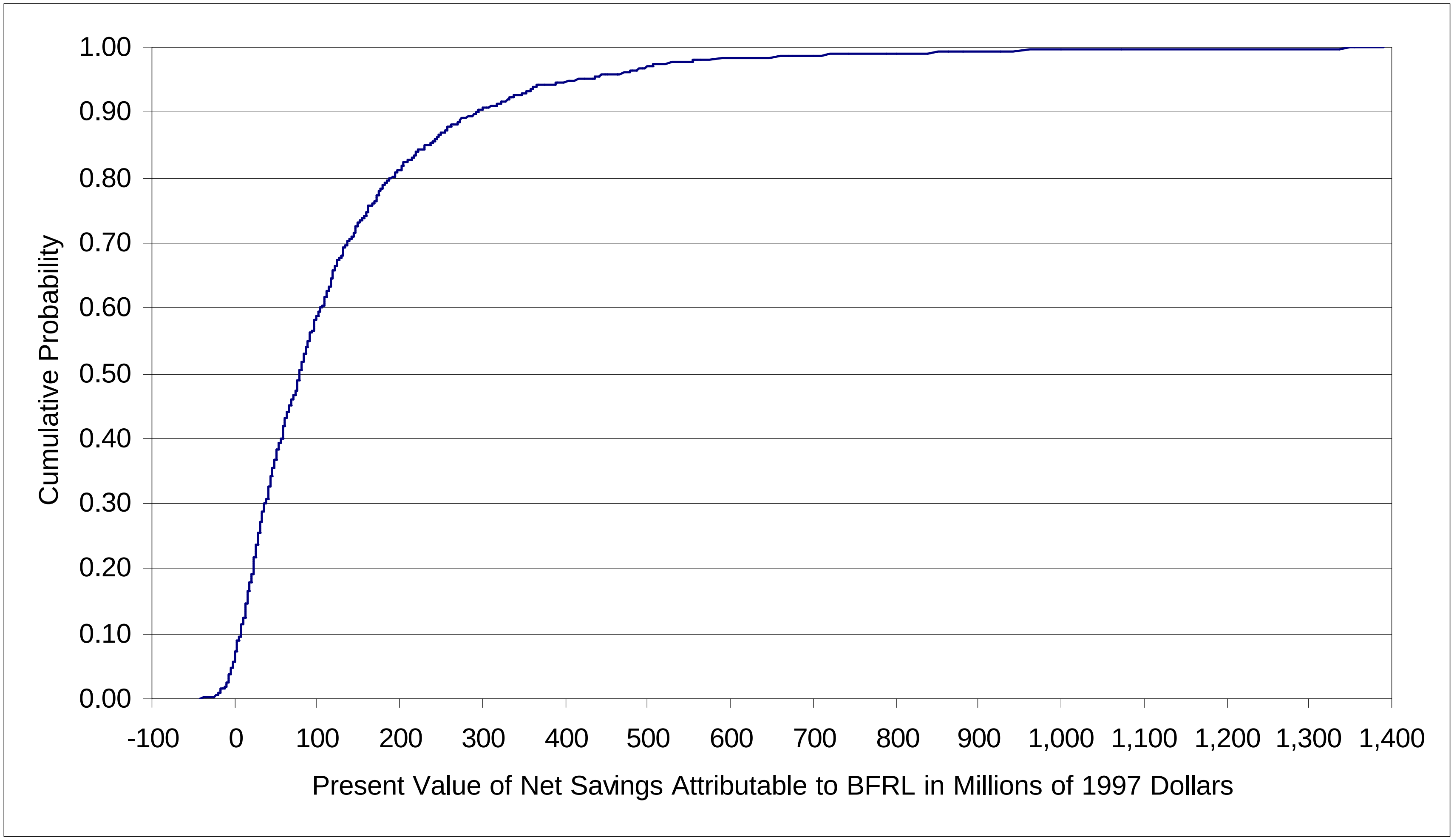


Figure 8-5. Savings to Investment Ratio on BFRL's Research and Development Investment

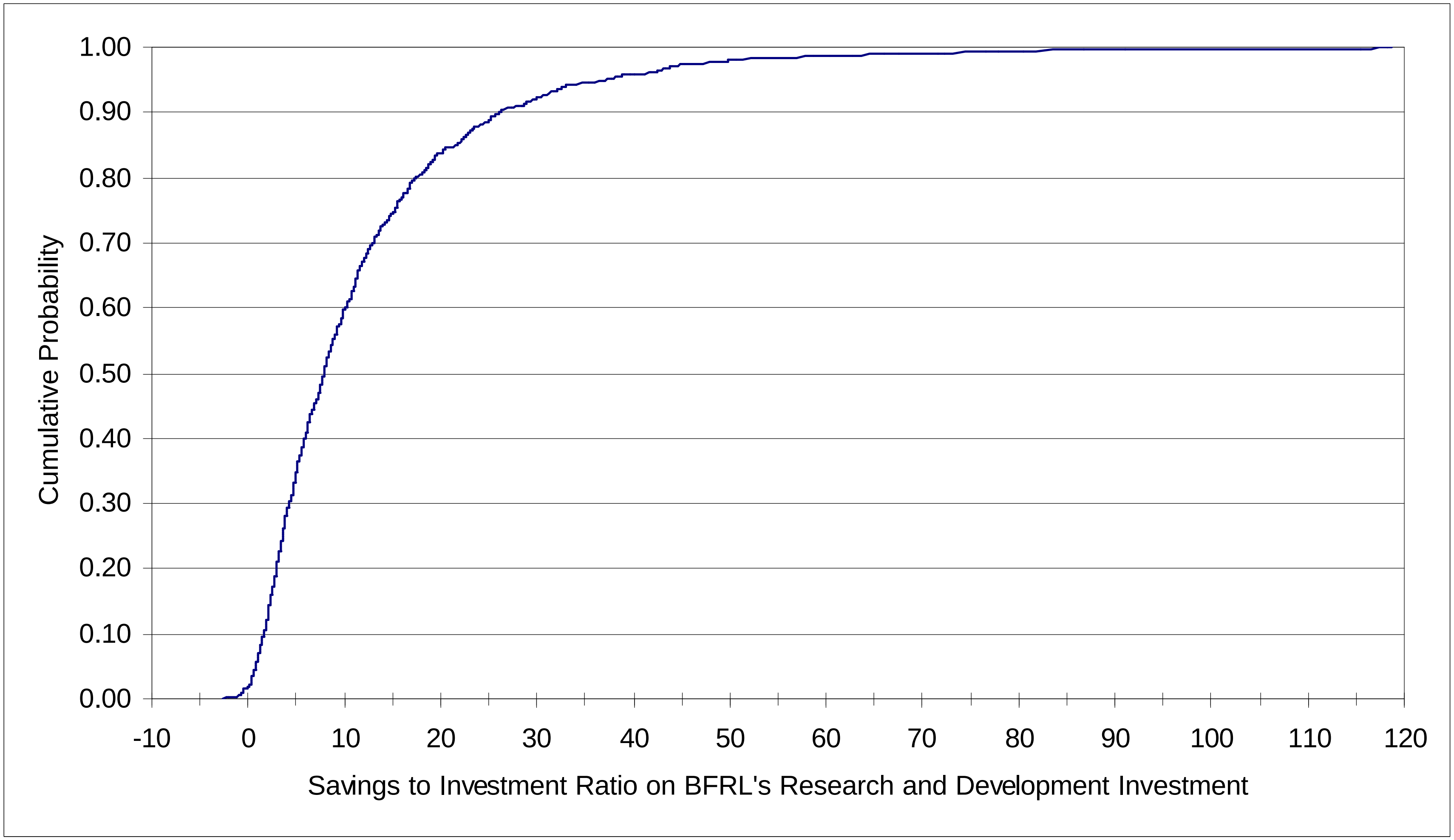
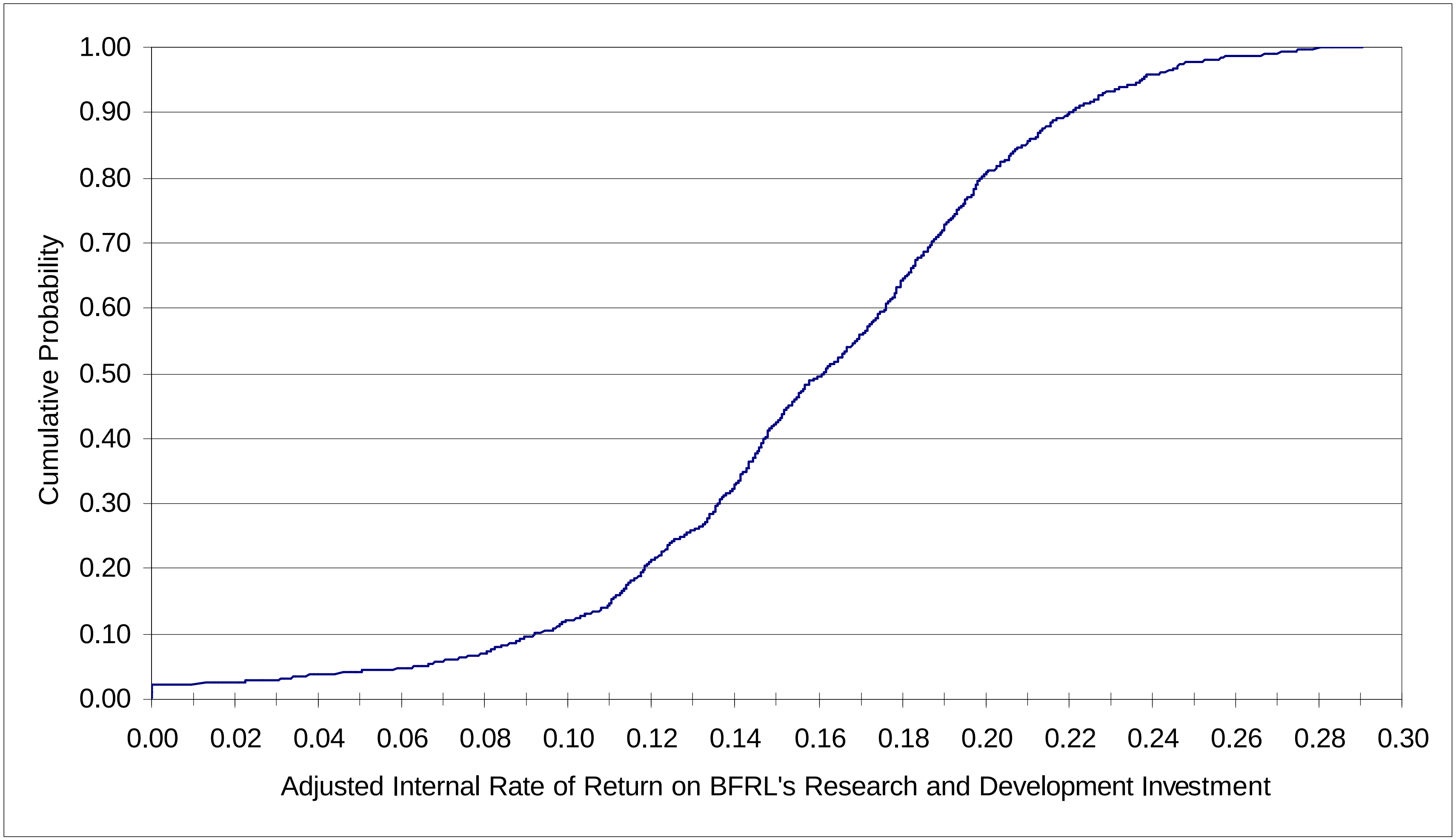


Figure 8-6. Adjusted Internal Rate of Return on BFRL's Research and Development Investment



9 Summary and Suggestions for Further Research

9.1 Summary

A formal resource allocation process for funding research is needed in both the public and private sectors. Research managers need guidelines for research planning so that they can maximize the payoffs from their limited resources. Furthermore, quantitative descriptions of research impacts have become a basic requirement in many organizations for evaluating budget requests.

There are several reasons for measuring the economic impacts of a federal laboratory's research program. First, economic impact studies are a management tool; they help set priorities and point to new research opportunities. Second, as federal laboratories become more customer oriented, by revealing the "voice of the customer," such studies will strengthen the ties to industry and identify opportunities for leveraging federal research investments. Finally, changing requirements, such as the Government Performance and Results Act, will affect how federal research funds are allocated. Increasingly, federal agencies and laboratories that fail to demonstrate that their research efforts complement those of industry and that they are having a positive impact on society will be at a disadvantage when competing for federal research funds.

The National Institute of Standards and Technology (NIST), a scientific research agency of the U.S. Department of Commerce's Technology Administration, is improving its resource allocation process by doing "microstudies" of its research impacts on society. This report is the third in a series of microstudies prepared by NIST's Building and Fire Research Laboratory (BFRL).[74, 75] It focuses on a critical analysis of the economic impacts of past, ongoing, and planned BFRL research for developing and deploying cybernetic building systems (CBSs) in office buildings.

The CBS research, development, and deployment effort within BFRL is aimed at producing a suite of products that integrate a wide variety of building systems. Building systems targeted for incorporation into CBS products and services include energy management, fire and security, fault detection and diagnostics, the real-time purchase of electricity, and the aggregation of building stock for multi-facility operations. A CBS is defined as a multi-system configuration that is able to communicate information and control functions simultaneously and seamlessly at multiple levels. Pressure to increase building systems performance and reduce costs has created a potential market for CBS

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[74] The first report focuses on two building technology applications: (1) ASHRAE Standard 90-75 for residential energy conservation; and (2) 235 shingles, an improved asphalt shingle for sloped roofing. See Chapman, Robert E., and Sieglinde K. Fuller. 1996. *Benefits and Costs of Research: Two Case Studies in Building Technology*. NSTIR 5840. Gaithersburg, MD: National Institute of Standards and Technology.
[75] The second report focuses on a fire technology application: the Fire Safety Evaluation System for health care facilities. See Chapman, Robert E., and Stephen F Weber. 1996. *Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System*. NSTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology.

products and services. BFRL is collaborating with industry on the development of CBS products and services and is providing a forum for conducting interoperability testing.

This case study of BFRL's CBS-related research, development, and deployment effort illustrates how to apply in practice a series of standardized methods, referred to as economic measures, to evaluate and compare the economic impacts of alternative research investments. It is presented in sufficient detail to understand the basis for the economic impact assessment and to reproduce the results. It is based on past, ongoing, and planned research efforts. Thus, it includes CBS-related investment costs that have already occurred along with estimates of future investment costs and cost savings due to the use of CBS products and services.

The CBS economic impact assessment was carried out in two stages. In the first stage, a baseline analysis was performed. In the baseline analysis, all input variables used to calculate the economic measures are set at their likely values. It is important to recognize that the term baseline analysis is used to denote a complete analysis in all respects but one; it does not address the effects of uncertainty. In the second stage, nine input variables were varied both singly and in combination according to an experimental design. Monte Carlo simulations are employed to evaluate how changing the value of these variables affects the calculated values of the economic measures.

The results of the baseline analysis demonstrate that the use of CBS products and services will generate substantial cost savings to the owners, managers, and occupants of office buildings across the nation. The present value of cost savings nationwide expected from the use of CBS products and services in office buildings exceeds $1.1 billion ($1,176 million in 1997 dollars). Furthermore, because of BFRL's role as a facilitator and developer of key CBS enabling technologies, CBS products and services are expected to become available commercially in 2003. Without BFRL's participation, the commercial introduction of CBS products and services would likely be delayed until 2010, and potential cost savings accruing to the owners, managers, and occupants of office buildings over the period 2003 until 2010 would have been foregone. These cost savings are $90.7 million in 1997 dollars. These cost savings measure the return on BFRL's CBS-related investment costs of approximately $11.5 million. Stated in present value terms, every public dollar invested in BFRL's CBS-related research, development, and deployment effort generates $7.90 in cost savings to the public. The annual percentage yield from BFRL's CBS-related investments over the 25-year study period is 16.2 percent.

The objective of the sensitivity analysis was to evaluate how uncertainty in the values of each of the nine input variables, both singly and in combination, translates into changes in each of the six economic measures. The six economic measures evaluated in the sensitivity analysis are: (1) the present value of savings nationwide, PVS_{ALL}; (2) the present value of savings due to BFRL, PVS_{BFRL}; (3) the present value of BFRL's CBS-related investment costs, PVC_{BFRL}; (4) the present value of net savings due to BFRL, $PVNS_{BFRL}$; (5) the savings-to-investment ratio on BFRL's CBS-related investments, SIR_{BFRL}; and (6) the adjusted internal rate of return on BFRL's CBS-related investments,

$AIRR_{BFRL}$. The major advantage of the sensitivity analysis is that it produces results that can be tied to probabilistic levels of significance for each economic measure (e.g., the probability that $PVNS_{BFRL}$ is greater than or equal to zero, SIR_{BFRL} is greater than or equal to 1.0, or $AIRR_{BFRL}$ is greater than or equal to the discount rate, each of which would indicate that BFRL's CBS-related investments were cost effective).

The results of the sensitivity analysis serve to validate the results of the baseline analysis. For example, the Monte Carlo simulation in which all nine of the input variables were varied in combination produced 1,000 observations for each of the six economic measures. The median value for each economic measure was almost identical to the value calculated in the baseline analysis for that measure. Results from this Monte Carlo simulation reveal that the present value of net savings due to BFRL, $PVNS_{BFRL}$, can be negative. This implies that there is some non-zero probability that BFRL's CBS-related investments are not cost effective. However, on the opposite extreme, $PVNS_{BFRL}$ may reach nearly $1.4 billion in 1997 dollars.

The fact that the range of values for an economic measure is so wide prompted an in-depth examination of the results of this Monte Carlo simulation for three of the six economic measures. These measures are particularly helpful in understanding BFRL's contribution, since each measure provides a different perspective. The first, the present value of net savings due to BFRL, is a magnitude measure; it shows a dollar value to the public net of BFRL's CBS-related investments. The second, the savings-to-investment ratio on BFRL's CBS-related investments, is a multiplier; it shows, in present value terms, how many dollars the public receives for each public dollar spent. The third, the adjusted internal rate of return on BFRL's CBS-related investments, is a rate of return; it shows the annual return on the public monies going into the development of CBS products and services throughout the 25-year study period.

For each of the three economic measures, less than 60 observations out of 1,000 were responsible for the observed "uneconomical" outcome. Stated another way, there is at least a 94 percent chance that BFRL's CBS-related investments are cost effective. This underscores the importance of using multiple measures that ensure consistency in decision making.

9.2 Suggestions for Further Research

The background work for this report uncovered additional areas of research that might be of value to government agencies and other institutions that are concerned with an efficient allocation of their research budgets. These areas of research are concerned with: (1) the development of a standard classification of research benefits and costs; (2) factors affecting the diffusion of new technologies; (3) conducting *ex ante* evaluations with scheduled follow-ups; and (4) evaluations based on multiattribute decision analysis.

9.2.1 The Development of a Standard Classification of Research Benefits and Costs

A survey by the Civil Engineering Research Foundation shows that expenditures for research and development efforts in the areas of construction, building, and disaster mitigation technologies were over $2.1 billion in 1992.[76] Private industry, trade association, university, and government research bodies would like to know what are the economic impacts of these investments. The standardized evaluation methods employed in this report are appropriate for measuring these economic impacts. However, there is no systematic and comprehensive classification of research benefits and costs to guide analysts who must identify the benefits and costs associated with new construction, building, and disaster mitigation technologies that are used in these standardized evaluation methods. Such a classification, if developed, refined, and adopted as a standardized classification, could be used in several ways.[77] First, the classification will help researchers and research managers identify potential benefits and costs associated with candidate research projects and thereby help them choose those with maximum net benefits (maximum net savings). Second, the classification will provide a standardized basis for identifying benefits and costs in research proposals. Finally, the classification will make possible a consistent treatment of benefits and costs in *ex ante* evaluations of new technologies and in *ex post* evaluations of completed building- and fire-related research projects.

9.2.2 Factors Affecting the Diffusion of New Technologies

Reliable estimates of the data input values for the standardized evaluation methods cannot be made without some relatively sound basis for predicting the rate of diffusion and the ultimate level of adoption of a new technology. The rate of diffusion and the ultimate level of adoption of a new technology depend on many factors. Uncertainty about how a new technology will perform affects both its rate of diffusion and its ultimate level of adoption.

Two factors over which a research laboratory exerts some control and which have the potential to reduce uncertainty about new technologies are: (1) the research laboratory's information dissemination efforts; and (2) the research laboratory's participation in standards-making organizations. Additional research on these two factors is warranted for a number of reasons. First, the characteristics of information are changing dramatically. With the advent of the World Wide Web and the increased acceptance of electronic media, the fruits of research may be quickly and widely disseminated. The reliance on printed reports sent to a targeted audience as the sole vehicle for communication is being eclipsed by other means of information dissemination. This

[76] Civil Engineering Research Foundation. 1993. *A Nationwide Survey of Civil Engineering-Related R&D.* Report no. 93-5006. Washington, DC: Civil Engineering Research Foundation.

[77] Although the standardized classification would be focused on identifying benefits and costs associated with building- and fire-related research projects, it would be generic to the extent that scientific research in general produces types of benefits and costs that are similar across technology areas. Thus the standardized classification will be applicable to many non-building- and non-fire-related technologies as well.

transition needs to be studied to ensure that the information dissemination strategy that emerges is tailored to the needs of the research laboratory's customer base. Second, research results in the form of technical reports often provide the basis for standards. Consequently, information dissemination efforts may be used to leverage private-sector activities aimed at standardization. Finally, standards are an important means for disseminating information on expected levels of performance and for measuring key performance characteristics (e.g., through the use of standard practices, specifications, and test methods). For new technologies, acceptance by a standards-making organization should lead both to higher rates of diffusion and to higher levels of adoption. Consequently, research on how a research laboratory's participation in standards-making organizations (e.g., those concerned with building codes and standards) affects the rates of diffusion and levels of adoption of new technologies will enable it to improve the efficiency with which it allocates staff and other resources to these activities.

9.2.3 Conducting *Ex Ante* Evaluations with Scheduled Follow-ups

From an analysis perspective, an *ex ante* evaluation of a new technology poses several challenges which are absent in an *ex post* evaluation of a completed research project. The biggest challenge involves the diffusion of a new technology (i.e., predicting the rate of diffusion and the ultimate level of adoption). Although two of the factors affecting the diffusion of a new technology were discussed in the previous suggestion for further research, much can be learned about the diffusion process by performing *ex ante* evaluations with the understanding that scheduled follow-up evaluations will be conducted.

The follow-up evaluation focuses on answering several key questions. These questions are aimed at learning more about the research laboratory's role and ability to move research results towards the market place *and* about the way in which firms and households (i.e., the intended users of the new technology) adopt and make use of the new technology. First, did the new technology become available to the intended users when anticipated in the *ex ante* evaluation? Second, is the new technology being adopted at the rate anticipated? Third, are the users that adopt the new technology experiencing the types of changes anticipated (e.g., cost savings, increased durability, and increased reliability)? Finally, are the types of users that adopt the new technology the same as anticipated? If these questions are asked and the answers are reviewed, critiqued, and fed back to research managers, *ex ante* evaluations will become a key link in the research laboratory's continuous improvement efforts.

Because *ex ante* evaluations are more complex than *ex post* evaluations, it is not always possible to quantify all of the relevant benefits and costs going into the evaluation. Such was the case in this economic impact assessment. Specifically, estimates of the cost savings due to enhanced fire safety performance and estimates of the cost savings due to the ability to respond to real-time electricity price changes and to aggregate building stock for multi-facility operations are not included. Similarly, estimates of the investments required to develop, test, and market CBS products and services by the vendor tier (see Figure 3-1) are not included. These challenges and others are being

addressed through the design and creation of a database for compiling information on CBS-related impacts. This database is currently under development by BFRL's Office of Applied Economics (OAE). Once the database is in place, OAE will monitor outcomes and compile information on CBS-related impacts in preparation for the follow-up CBS economic impact assessment.

9.2.4 Evaluations Based on Multiattribute Decision Analysis

Many research 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 research investments, 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 research investments. A class of methods that can accommodate non-monetary benefits and costs is multiattribute decision analysis.[78]

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.[79]

The AHP and its associated software represent a powerful and versatile management tool. How to apply this management tool most productively in a research environment suggests additional research in two areas. First, what will be the relationship between the AHP software and the standard classification proposed earlier? Second, how will the AHP be used to assess fit to mission, to set priorities, or to evaluate performance against some other management goal?

If research is conducted on the two topics just outlined, the AHP-based tool which emerges will provide a format for: (1) efficiently and reliably screening and selecting among alternative research investments (e.g., by embedding information from the standard classification of research benefits and costs, information on fit to mission, and on research priorities); (2) selecting research projects for in-depth analyses, either of the *ex ante* or *ex post* type of evaluation; and (3) selecting and scheduling follow-up evaluations.

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[78] 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.
[79] American Society for Testing and Materials. 1998. *Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems.* E 1765. Philadelphia, PA: American Society for Testing and Materials.

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