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Benefits and Costs of Research: A Case Study of Construction Systems Integration and Automation Technologies in Industrial Facilities

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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 research on BFRL's construction systems integration and automation technologies (CONSiAT) major product. The CONSiAT major product is an interdisciplinary research effort within BFRL—in collaboration with the Construction Industry Institute, the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies, standard communication protocols, and advanced measurement technologies needed to deliver fully-integrated and automated project process (FIAPP) products and services to the construction industry.

This case study of BFRL's CONSiAT-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 CONSiAT-related investment costs that have already occurred along with estimates of future investment costs and cost savings due to the use of FIAPP products and services.

The results of this study demonstrate that the use of FIAPP products and services will generate substantial cost savings to industrial facility owners and managers and to contractors engaged in the construction of those facilities. The present value of savings nationwide expected from the use of FIAPP products and services is in excess of $2.0 billion (measured in 1997 dollars). Furthermore, because of BFRL's involvement, FIAPP products and services are expected to be commercially available in 2005. If BFRL had not participated in the development of FIAPP products and services, the commercial introduction of FIAPP products and services is expected to be delayed until 2009. Consequently, potential cost savings accruing to industrial facility owners and managers and to contractors over the period 2005 through 2008 would have been foregone. The present value of these cost savings is approximately $150 million. These cost savings measure the value of BFRL's contribution for its CONSiAT-related investment costs of approximately $30.1 million. Stated in present value terms, every public dollar invested in BFRL's CONSiAT-related research, development, and deployment effort is expected to generate $4.95 in cost savings to the public.

Keywords

Building economics; construction; delivery time; economic analysis; impact evaluation; industrial facilities; integration and automation; life-cycle costing; safety

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
AHP	Analytical Hierarchy Process
AIRR	Adjusted Internal Rate of Return
AISC	American Institute for Steel Construction
AP	Application Protocol
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BCR	Benefit-to-Cost Ratio
BFRL	Building and Fire Research Laboratory
BLS	Bureau of Labor Statistics
CAD	Computer-Aided Design
CADD	Computer-Aided Design and Drafting
CAM	Computer-Aided Manufacturing
CDF	Cumulative Distribution Function
CII	Construction Industry Institute
CONSiAT	Construction Systems Integration and Automation Technologies
CPI	Consumer Price Index
ECS	Emissions Control System
EDI	Electronic Data Interchange
EPC	Engineer-Procure-Construct
ERP	Enterprise Resource Planning
FIAPP	Fully-Integrated and Automated Project Process
FIATECH	Fully-Integrated and Automated Project Processes Technologies
FY	Fiscal Year
GPS	Global Positioning System
GUI	Graphical User Interface
HVAC	Heating, Ventilation, and Air-Conditioning
IAI	International Alliance for Interoperability
IEC	International Electrotechnical Commission
IEEE	Institute of Electronics and Electrical Engineers
IFC	Industry Foundation Classes
IFMA	International Facilities Management Association
IRS	Internal Revenue Service
ISO	International Organization for Standardization
IT	Information Technology
LCC	Life-Cycle Cost

LIDAR	LIght Detection and Ranging
LWCIR	Lost Workday Case Incidence Rate
MARR	Minimum Attractive Rate of Return
NIST	National Institute of Standards and Technology
NLS	Non-Line-of-Sight
NSTC	National Science and Technology Council
OAE	Office of Applied Economics
OMB	Office of Management and Budget
PDU	Protocol Data Unit
PLIB	Parts LIBrary
PVB	Present Value of Benefits
PVC	Present Value of Non-Investment Costs
PVC	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
R&D	Research and Development
RFID	Radio Frequency Identification
RIR	Recordable Incidence Rate
ROI	Return on Investment
SIC	Standard Industrial Classification
SIR	Savings-to-Investment Ratio
STEP	Standard for the Exchange of Product
TV	Terminal Value
VRML	Virtual Reality Modeling Language

Executive Summary

This report is the fourth in a series of impact studies prepared by BFRL.[i] It focuses on BFRL's construction systems integration and automation technologies (CONSiAT) major product. The CONSiAT major product is an interdisciplinary research effort within BFRL—in collaboration with the Construction Industry Institute, the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies, standard communication protocols, and advanced measurement technologies needed to deliver fully-integrated and automated project process (FIAPP) products and services to the construction industry.

This case study of BFRL's CONSiAT-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 CONSiAT-related investment costs that have already occurred along with estimates of future investment costs and cost savings due to the use of FIAPP products and services in industrial facilities.

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 CONSiAT-related research, development, and deployment effort and each of its seven key areas of research. The CONSiAT effort within BFRL is

[i] The first report in the series 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). 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*. NISTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology). The third report focuses on the research, development, deployment, and adoption and use of cybernetic building systems in office buildings (see Chapman, Robert E. 1999. *Benefits and Costs of Research: A Case Study of Cybernetic Building Systems*. NISTIR 6303. Gaithersburg, MD: National Institute of Standards and Technology).

aimed at producing a suite of products and services that integrate a wide variety of planning, design, and construction activities. How these products and services perform in a "synergistic" and reliable manner is at the heart of BFRL's CONSiAT major product. The goal of BFRL's CONSiAT major product is to produce FIAPP products and services that will result in significant reductions in ***both*** the delivery time of constructed facilities ***and*** the life-cycle costs of those facilities. These products and services are being developed for use by building owners and operators, construction contractors, architects, engineers, and other providers of professional services.

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 FIAPP 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 industrial sector is then presented to focus on its importance within the overall construction industry and to define its key components. Special emphasis is then placed on identifying and detailing the key characteristics of the industrial sector. Detailing the key characteristics of the industrial sector is crucial, because investments in FIAPP products and services affect not only new construction activities but additions and alterations and maintenance and repair activities as well.

A strategy for identifying, collecting, and measuring FIAPP-related benefits and costs is presented in Chapter 5. The strategy identifies key stakeholders (e.g., industrial facility owners and managers), presents comprehensive lists of FIAPP-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 CONSiAT team. Second, the lists were refined and organized into a suite of "classification" hierarchies. Third, the classification hierarchies were distributed to the BFRL CONSiAT project leaders and, upon their review of the classification hierarchies, critiqued in a series of meetings. The meetings with the BFRL CONSiAT 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 FIAPP products and services in industrial facilities. The goal of Chapter 6 is fourfold. First, it establishes the sources and validity of the data used in the CONSiAT economic impact assessment. Second, it defines the base case and the FIAPP 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 1993 through 2017. The discount rate is 7 % (real). The base year is 1997, and all dollar amounts are calculated in present value 1997 dollars

The CONSiAT 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, eleven 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 FIAPP products and services will generate substantial cost savings to industrial facility owners and managers and to contractors engaged in the construction of those facilities. The present value of savings nationwide expected from the use of FIAPP products and services is in excess of \$2.0 billion (measured in 1997 dollars). Furthermore, because of BFRL's involvement, FIAPP products and services are expected to be commercially available in 2005. If BFRL had not participated in the development of FIAPP products and services, the commercial introduction of FIAPP products and services is expected to be delayed until 2009. Consequently, potential cost savings accruing to industrial facility owners and managers and to contractors over the period 2005 through 2008 would have been foregone. The present value of these cost savings is approximately \$150 million. These cost savings measure the value of BFRL's contribution for its CONSiAT-related investment costs of approximately \$30.1 million. Stated in present value terms, every public dollar invested in BFRL's CONSiAT-related research, development, and deployment efforts is expected to generate \$4.95 in cost savings to the public (i.e., an SIR of 4.95). The annual percentage yield (AIRR) from BFRL's CONSiAT-related investments over the study period is 14.1 %.

Chapter 8 covers the sensitivity analysis. The objective of the sensitivity analysis was to evaluate how uncertainty in the values of each of the eleven 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 CONSiAT-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 CONSiAT-related investments, SIR_{BFRL}; and (6) the adjusted internal rate of return on BFRL's CONSiAT-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 CONSiAT-related investments were cost effective).

The results of the sensitivity analysis serve to validate the results of the baseline analysis. For example, each Monte Carlo simulation in which a single input variable was varied produced 1,000 observations for each of the six economic measures. Ten of the 11 such

simulations produced values for the median and mean that were nearly identical to the corresponding value calculated in the baseline analysis for that measure. The final Monte Carlo simulation, in which all eleven of the input variables were varied in combination, also produced 1,000 observations for each of the six economic measures. In this case, the median and mean values for each economic measure were less than the corresponding value calculated in the baseline analysis for that measure. In addition, the 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 CONSiAT-related investments are not cost effective. On the opposite extreme, however, $PVNS_{BFRL}$ may reach nearly $1.0 billion in 1997 dollars.

The range of values for an economic measure is so wide that it prompted an in-depth examination of the results of the final 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 CONSiAT-related investments. The second, the savings-to-investment ratio on BFRL's CONSiAT-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 CONSiAT-related investments, is a rate of return; it shows the return on the public monies going into the development of FIAPP products and services throughout the 25-year study period.

For each of the three economic measures, less than 160 observations out of 1,000 were responsible for the observed "uneconomical" outcome. Stated another way, there is at least an 84 percent probability that BFRL's CONSiAT-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 continually 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 following 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 assist 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; and building materials.

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. Seven goals to enhance the competitiveness of the U.S. construction industry are explicit in the mission of the Subcommittee.[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.

Information and automation technologies are core components of the strategic plans of the U.S. construction industry. Advances in information and automation technologies have been identified as key components for achieving the National Construction Goals. The U.S. chemical industry identifies information systems as a key technical discipline in its *Technology Vision 2020*[5] and predicts achieving the smooth flow of information—from concept through design to construction and into plant maintenance and operation—will promote the use of automation and improve economic competitiveness. The *1999 Strategic Plan* of the Construction Industry Institute (CII) identifies six major industry trends that will shape the construction industry in the next century.[6] CII identified fully-integrated and automated project processes (FIAPPs) as the most significant trend and predicts it will revolutionize the construction industry.[7] Characteristics of FIAPP products and services include one-time data entry; interoperability with design, construction, and operation processes (e.g., virtual construction and construction automation); and user friendly input/output techniques. Significant economic impacts are anticipated from the adoption and use of FIAPP products and services within the construction industry.

1.2 Purpose

This report is the fourth in a series of impact studies prepared by BFRL.[8] It focuses on BFRL's construction systems integration and automation technologies (CONSiAT) major

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[3]For a detailed description of these goals and how the Subcommittee on Construction and Building is approaching 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] American Chemical Society. 1996. *Technology Vision 2020*. Washington, DC: American Chemical Society.

[6] Construction Industry Institute. 1999. *1999 Strategic Plan*. Austin, TX: Construction Industry Institute.

[7] *Ibid*. p. 15.

[8] The first report in the series 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*

product. The CONSiAT major product is an interdisciplinary research effort within BFRL—in collaboration with CII, the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies, standard communication protocols, and advanced measurement technologies needed to deliver FIAPP products and services to the construction industry.

BFRL's CONSiAT major product is aimed at producing a suite of products and services that integrate a wide variety of planning, design, and construction activities. How these products and services perform in a "synergistic" and reliable manner is at the heart of BFRL's CONSiAT major product.

The goal of BFRL's CONSiAT major product is to produce products and services that will result in significant reductions in ***both*** the delivery time of constructed facilities ***and*** the life-cycle costs of those facilities. These products and services are being developed for use by building owners and operators, construction contractors, architects, engineers, and other providers of professional services.

1.3 Scope and Approach

FIAPP products and services help all four construction industry sectors—industrial, commercial/institutional, public works, and residential. This report employs standardized methods to evaluate the expected economic impacts of the adoption and use of FIAPP products and services in industrial facilities only (i.e., original equipment manufacturing facilities and other types of industrial facilities manufacturing products and/or commodities). The decision to focus first on the industrial sector was based both on the desire of key industrial sector stakeholders to partner with BFRL and on data-related issues. A subsequent impact assessment focusing on the commercial/institutional sector is planned as a follow-up to the industrial impact assessment.

The "case study" approach employed here illustrates how to evaluate and compare the economic impacts of research investments. Standardized methods are used in this report and others in the series to ensure consistency in the measurement of economic impacts. The measurement methods employed here are applicable to other programs in BFRL, in NIST, and in other research laboratories.

The report has eight chapters in addition to the Introduction. The methodology and the standardized methods employed in the study to measure the CONSiAT major product's economic impacts are described in Chapter 2. Standardized methods are used to define

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Studies in Building Technology. NISTIR 5840. Gaithersburg, MD: National Institute of Standards and Technology). 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*. NISTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology). The third report focuses on the research, development, deployment, and adoption and use of cybernetic building systems in office buildings (see Chapman, Robert E. 1999. *Benefits and Costs of Research: A Case Study of Cybernetic Building Systems*. NISTIR 6303. Gaithersburg, MD: National Institute of Standards and Technology).

the key measures of the economic impacts of research investments. A format for summarizing the economic impacts of research investments is also presented.

The body of this report, Chapters 3 through 8, consists of a case study of fully-integrated and automated project process systems and technologies in industrial facilities. The approach is to present all CONSiAT-related information in sufficient detail *both to understand* the basis for the economic impact assessment *and to make it possible for the reader to reproduce* the results of the economic impact assessment. The CONSiAT case study is *ex ante* (i.e., prospective) in that it estimates impacts from on-going and planned research as well as past research.

The CONSiAT case study estimates the economic impacts to the industrial sector from BFRL's research effort aimed at the development and introduction of a suite of FIAPP products and services. Chapter 3 describes BFRL's CONSiAT major product. Both the overall CONSiAT research and development effort and the seven 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 FIAPP products and services is defined. A strategy for measuring FIAPP-related benefits and costs is presented in Chapter 5. The strategy identifies key stakeholders (e.g., building owners and managers), presents comprehensive lists of FIAPP-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 FIAPP products and services in industrial facilities are necessary to measure the economic impacts of fully-integrated and automated project process systems and technologies. 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 FIAPP products and services in industrial facilities 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 CONSiAT 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 CONSiAT major product in industrial facilities. 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 fully-integrated and automated project process systems and technologies in industrial facilities. 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.[9] 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 applications. Office of Management and Budget *Circular A-94* recommends sensitivity

[9] 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 case where the median is used as the measure of central tendency is clearly indicated in the text. Consequently, if no explicit reference is made to the measure of central tendency, the measure used is the mean.

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 baseline values. Readers interested in a comprehensive survey on methods for dealing with uncertainty for use in government and private-sector applications are referred to the study by Marshall[10] and the subsequent video[11] and workbook.[12]

2.2 Overview of Evaluation Methods

Several methods of economic evaluation are available to measure the economic performance of a 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.[13] Detailed descriptions of each of the standardized methods are given in Chapman and Fuller.[14] Readers interested in an excellent, in-depth survey covering these as well as other methods are referred to Ruegg and Marshall.[15]

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;

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[10]Marshall, Harold E. 1988. *Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Building Investments.* NIST Special Publication 757. Gaithersburg, MD: National Institute of Standards and Technology.
[11]Marshall, Harold E. 1992. *Uncertainty and Risk—Part II in the Audiovisual Series on Least-Cost Energy Decisions for Buildings.* Gaithersburg, MD: National Institute of Standards and Technology.
[12]Marshall, Harold E. 1993. *Least-Cost Energy Decisions for Buildings—Part II: Uncertainty and Risk Video Training Workbook*. NISTIR 5178. Gaithersburg, MD: National Institute of Standards and Technology.
[13]American Society for Testing and Materials (ASTM). Fourth Edition, 1999. *ASTM Standards on Building Economics*. West Conshohocken, PA: American Society for Testing and Materials.
[14]Chapman and Fuller, *Two* Case *Studies in Building Technology*, pp. 27-37.
[15]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 expressed as a decimal.

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 ($PV\underline{\mathbf{C}}$), 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).[16] By treating savings like revenue benefits, the PVNB method may be reformulated as the PVNS method.

[16]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:

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

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:

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

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 construction systems integration and automation technologies (CONSiAT) 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:

$$BCR^{a^*} = \left(PVB^{a^*} - PVC^{a^*}\right) / PVI^{a^*}$$

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

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

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

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

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 CONSiAT 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), 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.[17] The most convenient procedure for calculating the AIRR is based on its relationship to the BCR (SIR). This 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 CONSiAT case study (see Chapters 7 and 8).

2.2.4 Summary of Methods[18]

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.

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

[18]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).

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 (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.[19] 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,

[19]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.

when used appropriately, ensure consistency in both setting priorities and selecting projects for funding. The results from the CONSiAT case study presented in Chapters 7 and 8 illustrate the importance of multiple measures of economic performance.

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 CONSiAT 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 CONSiAT 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 CONSiAT Major Product

3.1 Fully-Integrated and Automated Project Processes: What They Are and What They Will Do

Information technologies have transformed many aspects of our daily lives and revolutionized industries in both the manufacturing and service sectors. Within the construction industry, the changes have so far been less radical. However, the use of information technologies offers a clear potential for revolutionary change in the effectiveness with which construction-related processes are executed and the value they add to construction industry stakeholders. Recent exponential growth in computer, network, and wireless capabilities, coupled with improved 3D CAD (computer-aided design) and object-oriented software tools, have made it possible to apply information technologies in all aspects of the facility life cycle—design, construction, commissioning, operation, and decommissioning.

Computer, automobile, and aircraft manufacturers have taken the lead in improving the integration of design and manufacturing, harnessing automation technology, and in using electronic standards to replace paper for many types of documents. Unfortunately, the construction industry has not yet used information technologies as effectively to improve and automate its design, construction, and operational processes. There is still widespread use of paper as a medium to capture and exchange information among project participants, and relatively little use of design and automation tools that depend on computer-readable product descriptions.

The Construction Industry Institute (CII) predicts that fully-integrated and automated project processes (FIAPPs) will be a vehicle for transforming the way construction projects are designed, built, and operated.[20] FIAPPs will result in significant reductions in both the delivery time and life-cycle costs of constructed facilities. FIAPPs are also expected to result in reductions in construction-related accidents. Characteristics of FIAPP products and services include one-time data entry; interoperability with design, construction, and operation processes (e.g., virtual construction and construction automation); and user friendly input/output techniques.

The context within which FIAPP products and services are defined is shown schematically in Figure 3-1. Figure 3-1 is a stylized information flows model for a typical industrial facility; it spans the entire facility life cycle—from concept through disposition.

The information flows model is configured as a four-tiered set of activities. Each activity is represented by a rectangle. Interactions between activities (i.e., information flows) are represented by arrows. It is important to note that each activity shown in Figure 3-1 can

[20] Construction Industry Institute. 1999. *1999 Strategic Plan*. Austin, TX: Construction Industry Institute.

be subdivided into sub-activities and used to highlight information flows between sub-activities. These information flows, although not shown, are treated as implicit in Figure 3-1. In several cases, interactions with feedback are made explicit. This is done to highlight the most significant feedback loops between activities. In principle, there is substantial feedback between many of the activities shown in Figure 3-1.

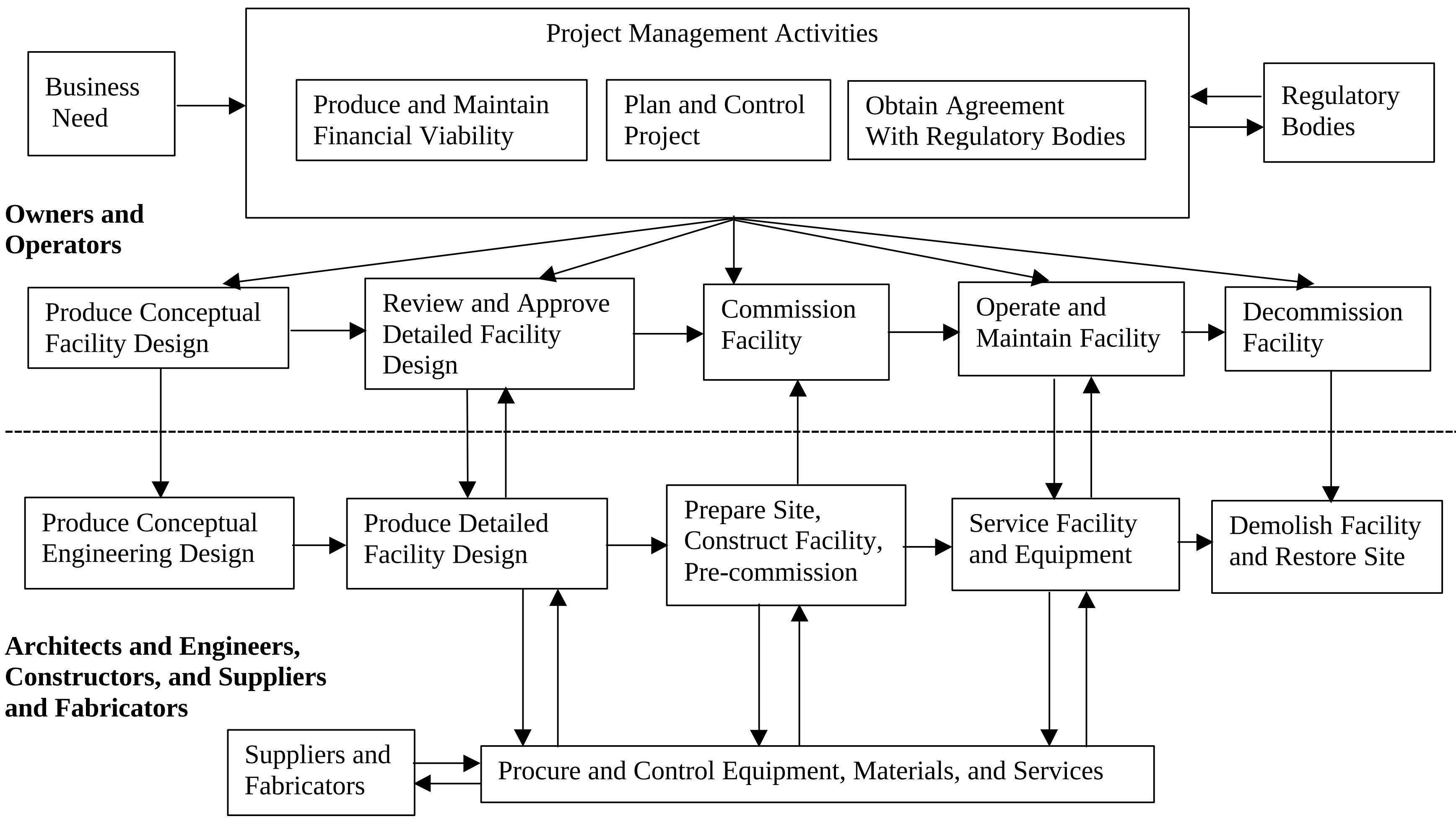
Business need provides the impetus for planning, designing, constructing, operating, and disposing of an industrial facility. Consequently, business need is placed at the left-hand side of the uppermost tier (i.e., the first tier). Project management activities are placed on the first tier because they span all phases in the life cycle of the facility. Regulatory bodies are also placed on the first tier.

The activities on the second and third tiers are laid out in sequential order. Interactions between these two tiers are closely coupled. A dashed line is placed between the second and third tier; it is used to separate functions performed by the two major groups of participants: (1) owners and operators—the first and second tiers; and (2) architects and engineers, constructors, and suppliers and fabricators—the third and fourth tiers. The key participants are designated in bold face font. The fourth tier is limited to suppliers and fabricators; it spans most of the phases in the facility life cycle.

A closer examination of Figure 3-1 reveals an interesting outcome. The entire construction phase is shown as a single activity in Figure 3-1: Prepare Site, Construct Facility, Pre-Commission. As will be seen in Sections 3.2 and 3.3, much of the interest in FIAPP products and services is concerned with the construction phase. However, as is shown in Figure 3-1, there are many information flows going into or coming out of the construction phase. Thus, to better understand the value of FIAPP products and services, it is useful to review what these information flows represent.

The information flows model is a mapping of project processes during an industrial facility's life cycle. Integrating and automating these project processes involves managing and manipulating information flows within and between the activities shown in Figure 3-1. Thus, a FIAPP consists of a data warehouse with a real-time capability enabling information to be passed, operated upon, and retained for future reference. This information could be used to control the position of construction equipment, specify a set of work tasks, or electronically store the "as built" status of a building element. The data warehouse component of a FIAPP includes design data, supplier data, project data, site data, resource data, and codes and standards data. The real-time capability is supported through two key enabling technologies—the Construction Site Measurement System and the Project Information Management System. Linkages between the enabling technologies, the data warehouse, and other FIAPP components rely on standard interoperability and communication protocols and advanced measurement technologies (see Section 3.3).

Figure 3-1. Information Flows Model for Industrial Facilities



3.2 The FIATECH Consortium: A Vehicle for Delivering Fully-Integrated and Automated Project Processes to the Construction Industry

The FIATECH Consortium is envisioned as a CII affiliated, collaborative, not-for-profit, research consortium established to conduct leveraged research and development to accelerate the deployment of FIAPP products and services in the commercial marketplace. Specifically, the FIATECH Consortium is needed to make FIAPP real for CII members and the rest of the construction industry.

The construction industry faces special challenges in reaping the full benefits of the information technology revolution that has brought and continues to bring rich rewards to many industries. These challenges include low R&D investment, fragmentation, and its unique project-oriented character. Recognizing these challenges, CII has made FIAPP a top priority.

The FIATECH Consortium will seek to achieve breakthrough, technology-intensive process changes. First, it will enable the seamless integration and management of project information within the context of an entire facility life cycle and enterprise-wide resource planning system. And second, it will bring live wireless data from the construction site into the project management information loop.

The FIATECH Consortium will conduct leveraged R&D in partnership with suppliers, with firms in the software/information technology industries, and within the public sector. In addition to NIST, likely public sector partners include the Department of Transportation, the U.S. Army Corps of Engineers, and the General Services Administration.

NIST's participation in the FIATECH Consortium focuses on providing the measurements, standard interoperability and communication protocols, and information technology tools to enable FIAPP along with economic assessments to quantify its impact. Consortium-developed products and services will be tested and demonstrated in a distributed testbed environment.

The Consortium-developed products and services, when fully deployed, will enable significant cycle time and life-cycle cost reductions in the delivery of capital projects by digitally linking all facets of the design, fabrication, and construction process. Drawing on documented economic success in industries such as manufacturing, the FIATECH Consortium will develop and adopt open interoperability and communication standards to achieve significant cycle time and life-cycle cost reductions.

Specifically, the goals of the FIATECH Consortium are to:

- Reduce design changes and rework through concurrent engineering;
- Enable better control of project schedule and cost;
- Improve supply chain management, including tracking of materials, components, and labor;

- Rapidly detect and rectify differences between intended design and actual construction; and
- Capture the "as-built" status of a project for later use in facility operation, maintenance, and renovation.

To achieve these goals, the FIATECH Consortium has established a framework of guiding principles and primary purposes. The guiding principles of the Consortium are twofold. First, the Consortium will be an industry-driven, not-for-profit, collaborative research consortium with dues-paying member companies. Second, it will maintain a "safe harbor" environment with third party independence where companies can come together and: achieve mutually beneficial results by pooling talent; substantially leverage their scarce R&D dollars; spread risks and achieve robust solutions; collaborate broadly with diverse partners—public, private, and academe; and create alliances.

The primary purposes of the Consortium are to:

- Conduct, sponsor, fund, direct, and otherwise promote research, development, and demonstration of technologies and practices for significant cycle time and life-cycle cost reductions in the delivery, operation, and maintenance of capital projects;
- Assist in the implementation of such technologies and practices;
- Provide a forum for the examination and discussion of technical issues having a significant impact on cycle time and life-cycle costs of capital projects;
- Serve as a national clearinghouse, library, and data source for information in these areas; and
- Publish or sponsor articles, press releases, newsletters, and other publications on these topics.

3.3 Key Components of BFRL's CONSiAT Major Product

BFRL is working towards a prototype suite of FIAPP systems and technologies being tested and deployed by 2004. To achieve this goal, BFRL is working with facility owners, contractors, equipment and systems manufacturers and service providers, software developers, facility operators, trade associations, professional societies, standards organizations, university researchers, and other government agencies. Strategic partnerships for the overall CONSiAT research, development, and deployment effort will employ the FIATECH Consortium (see Section 3.2).

BFRL's CONSiAT-related research, development, and deployment effort is multi-year and multi-tiered. Throughout this effort, BFRL will employ field demonstration projects. These projects are by design collaborative activities, since they seek to gain early involvement of key construction industry stakeholders to insure that the products and services developed are focused on stakeholder needs and address explicitly any potential barriers to adoption. BFRL's major milestones for these collaborative activities include field demonstrations of: (1) key FIAPP system components and associated information technology (IT) protocols/tools; (2) FIAPP subsystems and associated IT protocols/tools for earthwork, foundation, and the structural steel delivery process and the pipe spools

and piping systems delivery process; (3) first-generation prototype FIAPP system and associated IT protocols/tools based largely on the innovative use of proven technologies; (4) advanced site measurement systems and innovative uses of information technologies; and (5) second-generation prototype FIAPP system and associated IT protocols/tools that build on advanced site measurement systems and innovative uses of information technologies.

The first generation prototype FIAPP system, targeted for completion in 2002, will demonstrate feasibility, focusing on innovative process changes based largely on the integration of robust/proven technologies. The second generation prototype system, targeted for completion in 2004, will integrate advanced functional capabilities, building on new measurement systems and innovative uses of information technology.

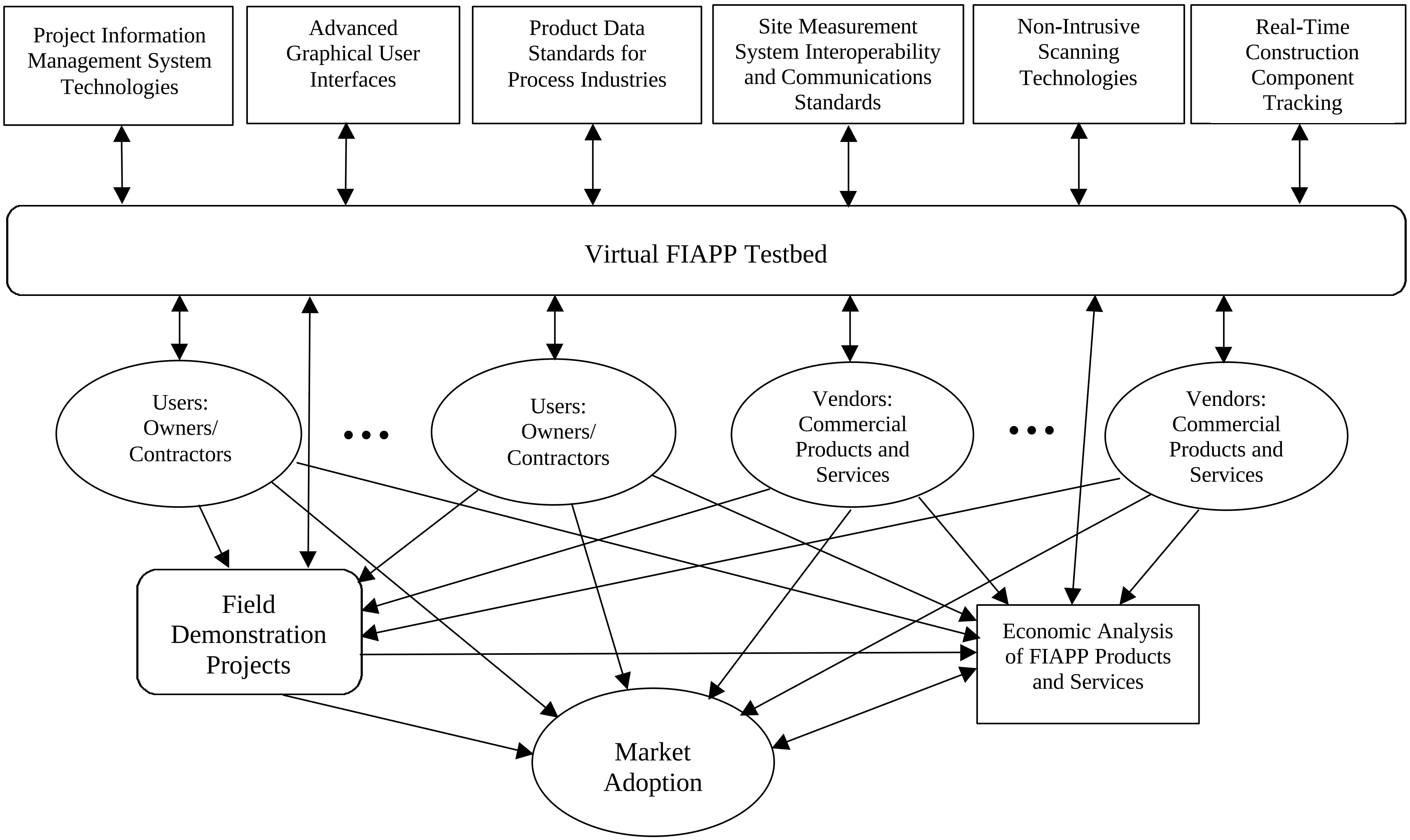
The overall CONSiAT research, development, and deployment effort is built around seven key projects (see Sections 3.3.1 through 3.3.7). In addition, the overall effort includes a Virtual FIAPP Testbed and a series of full-scale field demonstration projects.

A schematic for how the seven key projects fit together and how BFRL will work with industry to develop FIAPP products and services is shown in Figure 3-2. Each of the seven key projects is represented by a rectangle in the figure. These activities are undertaken and funded primarily by NIST. Those activities undertaken by private sector entities are represented by ovals in the figure. The Virtual FIAPP Testbed and the field demonstration projects are a hybrid activity, involving a broad cross-section of participants; they are represented in the figure by the rectangles with rounded edges. Unidirectional arrows or bi-directional arrows (i.e., including a feedback mechanism) represent information flows between activities. Coordination of and feedback between the BFRL projects and the private sector entities is facilitated by BFRL's CONSiAT Product Manager.

Figure 3-2 includes a user/vendor tier. Owners and contractors are classified as users of FIAPP products and services. Vendors include equipment and systems manufacturers and service providers and software developers. Because many different users will adopt and install FIAPP products and services and 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 users and the number of vendors in the user/vendor tier.

Figure 3-2 shows the importance of the field demonstration projects to BFRL's efforts. Once the field 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 FIAPP products and services diffuse throughout the marketplace.

Figure 3-2. Schematic Diagram of BFRL's CONSiAT Major Product



BFRL will produce a series of intermediate outputs prior to the deployment of a prototype suite of FIAPP products and services. These outputs are described briefly in the series of bullets that follow:

- Develop enabling technologies aimed at producing a Construction Site Measurement System and a Project Information Management System.

- Develop standard interoperability and communication protocols for the open exchange of information among facility owners, designers, construction products and equipment manufacturers and suppliers, contractors, and facility managers. Protocols being developed include:
    - Data exchange protocol for piping design, fabrication, installation, and inspection;
    - Identification and fiducial marking protocols for discrete components; and
    - *LiveView* construction site management system interoperability protocols.

- Develop advanced measurement technologies, including:
    - Ability to compare “as-is” and “as-designed” geometry, location, and orientation of construction objects incorporating advanced VRML (Virtual Reality Modeling Language) techniques;
    - Ability to characterize LIDAR (LIght Detection And Ranging) measurement accuracy as a function of range, surface texture, and reflectivity for a range of conditions anticipated at construction sites;
    - Mobile scanning system with wireless transport of range data to a remote site;
    - Robust post-processing technique for registration and volumetric calculations of LIDAR-acquired terrain data; and
    - Integration of project information management system with construction metrology systems using *LiveView* to enable all data communications.

- Construct a Virtual FIAPP Testbed—an open, distributed system environment with modular (plug-and-play) architecture—in the laboratory to facilitate the development and evaluation of new products and systems by manufacturers and external service providers.

- Develop a Consortium of facility owners, contractors, construction products and equipment manufacturers, and service providers interested in producing, testing, demonstrating, and buying and selling FIAPP products and services.

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

- Demonstrate the integration of FIAPP products, services, and concepts in real construction projects.

3.3.1 Project Information Management System Technologies

An effective project delivery process depends on the availability of current and correct information for all the participants, wherever they are and whenever they need it. Achieving the seamless integration of project information has become a primary goal for many organizations associated with the building and construction industries, ranging from CII to the Construction and Building Subcommittee of the President's National Science and Technology Council. Ongoing benchmarking studies by organizations like the Business Roundtable and CII confirm the business stake in this goal.

BFRL's CONSiAT major product envisions a number of technology developments that will make more and richer information available to project participants. These developments, and the information resources associated with them, include: (1) more complete descriptions of the project design itself and of the products and services procured for the project; (2) large amounts of previously unavailable spatio-temporal information supporting the realization of the project design on the construction site; and (3) comprehensive commissioning procedures tied to the "as-built" condition of the resulting facility.

Integrating and managing these information resources presents significant technical challenges. Two very different approaches have emerged during this decade. The first is a data-driven approach based on the evolution of computer-aided design systems. Open system standards such as the International Organization for Standardization's STandard for the Exchange of Product model data (ISO/STEP) and Parts LIBrary (ISO/PLIB) and the International Alliance for Interoperability's Industry Foundation Classes (IAI/IFC) are being developed to capture the complex, deep-structured technical data created using computerized tools. These standards allow the exchange and sharing of information in such a way that it remains as functional in the receiving system as it was in the originating system, with integration taking place at the level of individual information elements.

However, neither the standards nor the systems based on them yet cover all the functionality needed in a typical project, and especially not throughout the entire delivery process. This has led to a second, document-driven approach based on the evolution of the Internet and the World Wide Web. Frequently called project extranets, systems based on this approach collect and distribute project information, ranging from long-lived design drawings to transitory email requests, as configuration-controlled documents, with integration taking place at the level of hyperlinks among the documents. Compared to the first approach, the information exchanged in this approach is shallow-structured and superficially integrated. Because the basic unit of information is a document, however, these systems automatically cover all the functionality needed in a traditional document-centric project. Consequently, their use is beginning to make a difference in the U.S. construction industry.

As the technologies envisioned in the CONSiAT major product emerge, the need to merge these two approaches to the integration and management of project information

will become acute. The objective of this project is to develop the standards-based open-system technologies needed in next-generation project information management systems and demonstrate them in prototype systems.

To enable the capture of technical project information, BFRL will implement selected portions of emerging product data standards in experimental databases. The ISO/STEP and PLIB standards suites and the IAI/IFC are relevant starting points. Because several CONSiAT projects share an interest in the fabrication, delivery, and erection of structural steelwork, BFRL will collaborate in this project with the American Institute for Steel Construction (AISC) as its members begin implementing the CIMSteel Integration Standard CIS(2), which is based on STEP technology and is the precursor of the STEP Application Protocol 230 on structural steelwork. In following years, this project will widen its focus to include other systems, such as piping and HVAC, and their associated controls.

To deal with the spatial-temporal information envisioned to be streaming to the project information system from on-site construction metrology systems, this project will document candidate use cases in collaboration with the companion project (see Section 3.3.4); assess the state of the art in temporal database research; and implement a suitable data model in experimental databases. Many such models are available, and none is considered to be universally applicable, so this task is expected to be an iterative implement-and-test cycle that continues over several years.

In the first year, this project will deal only with the information needed by other CONSiAT projects to track certain work processes relating to the fabrication and erection of steelwork, and the creation of experimental supporting databases. In following years, BFRL will install a commercial project extranet system and couple it with the experimental databases. In addition, coupling and integration mechanisms will be developed to account for additional work processes and other systems.

NIST construction projects, most notably the addition of a new emissions control system (ECS) to Building 205 at the NIST Gaithersburg site, will be used as the source of information for populating and testing the experimental databases coupled to a project extranet system. The resulting system will be used to provide information management support for other CONSiAT projects as they test emerging construction metrology systems.

3.3.2 Advanced Graphical User Interfaces for Construction Project Delivery Systems

The technical challenges faced in integrating and managing project information were addressed in the previous subsection. Once available, however, accessing and viewing this information presents additional technical challenges. Traditional presentation mechanisms are based on static views of tabular data extracted from databases and stored two-dimensional drawings and documents. These mechanisms have been carried directly

into the graphical user interface (GUI), based on Web browser technology, used in document-based project extranet systems. While the industry has a decade of experience in developing graphical user interfaces for 3-dimensional project models, these were typically based on proprietary CAD-system data structures and presented static design models with only limited access to non-geometric information.

As the technologies envisioned in the CONSiAT major product emerge, the user will be challenged to deal with increasing volumes of increasingly complex information, and the need for facile and intuitive graphical user interfaces will increase dramatically. The objective of this project is to develop standards-based, open-system technologies for accessing and viewing construction project information and demonstrate them in prototype systems.

BFRL will build on the work begun in fiscal year (FY) 1999 to model typical construction products using the Virtual Reality Modeling Language (VRML) 97 specification developed by the Web3D Consortium and promulgated as ISO/IEC 14772. The use of VRML continues to offer an advantage because any user can employ widely available Web browser technology to access and display the results. The construction object definitions that were developed using VRML programming capabilities will be extended and enhanced to include more functionality. Techniques for improving performance will be explored, for example, by reimplementing critical JavaScript code as Java applets. Additional Java applets tied to the VRML External Authoring Interface will be used to import project information to the VRML model from external information sources based on standard data representations. Techniques for creating intuitive links from the VRML model to non-geometric information will be explored, as well as innovative techniques for accessing and displaying non-geometric information using VRML directly. Techniques for dealing with spatio-temporal information (e.g., time sequences of equipment movements on the construction site) will be explored. Techniques for comparing different geometry models representing, for example, the as-designed and as-built conditions of some item of interest, will be explored. The emerging third-generation VRML specification, tentatively called X3D, will be reviewed and critiqued for its applicability to construction applications.

Because several CONSiAT projects share an interest in the fabrication, delivery, and erection of structural steelwork, BFRL will collaborate in this project with the AISC as its members begin implementing the CIMSteel Integration Standard CIS(2), which is based on ISO/STEP technology and is the precursor of the STEP Application Protocol 230 on structural steelwork. The STEP geometry representations chosen by AISC will be mapped to VRML.

Exemplary models will be built using NIST construction projects, most notably the Building 205 ECS at the NIST Gaithersburg site, as the source of information. The results will be evaluated in terms of their ability to support typical user work processes.

3.3.3 Product Data Standards for the Process Plant Industries

The U.S. process plant industries are seeking to improve the design and delivery of constructed facilities through advanced uses of information technologies—CADD, CAM, ERP (computer-aided design and drafting, computer-aided manufacturing, enterprise resource planning)—and the integration of information systems (e.g., automation of the exchange and sharing of information among systems). Although many of the leading engineering organizations have adopted 3D modeling and information integration technologies, the capabilities and benefits of these technologies are not being exploited fully in the fabrication, inspection, and construction phases of projects.

The many computerized systems in use for the design and construction of facilities can be integrated only at great cost because of their incompatible proprietary representations of information. Standard, neutral information representations and exchange methods are needed that allow system vendors to be innovative and yet allow system users to exchange and share information about industrial facilities automatically. The evolving international standard ISO 10303, Product Data Representation and Exchange, known as STEP, is providing a base technology for developing information exchange protocols.

Leading organizations in the U.S. process plant industries recognize the potential benefits of STEP application protocols (APs) and are working with NIST to develop protocols that meet the needs of the process plant industries. The shipbuilding industry has adopted CAM technologies for improvements in the fabrication and assembly of piping. These CAM successes and lessons from improvements in ship piping fabrication could be useful to advancing the capabilities of the U.S. process plant industries. Additionally, the piping delivery process could be improved with the use of advanced component tagging technologies. U.S. industry needs data exchange protocols, test cases, and guidance for fully leveraging CADD and CAM technologies and progressing toward achievement of FIAPP capabilities. This project works with the chemical, pharmaceutical, power, engineering and construction, CADD/CAM, shipbuilding, and pipe fabrication industries to resolve these challenges.

Many of the current applications of CADD/CAM tools focus on automating the documentation of engineering decisions. These applications have improved the productivity of the engineering phase of industrial projects, but have not been used to improve the fabrication, inspection, installation, and commissioning phases of industrial projects.

Industry studies show that the piping delivery process is often one of the most inefficient of all construction activities. In a CII study,[21] the average amount of rework on piping systems for industrial projects exceeds 3 percent of the project's total installed cost.

Beyond documenting procedures for reducing potential rework costs, this project will investigate improvements in the fabrication, delivery, and installation of piping systems.

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[21] Construction Industry Institute. 1989. *Costs of Quality Deviations in Design and Construction*. RS10-1. Austin, TX: Construction Industry Institute.

The primary use of CADD for piping fabrication is still focused on replicating the drafting of isometric drawings and spool drawings to illustrate the configuration, shapes, and connections of piping components. Large savings in labor, time, and errors are possible by reducing the need for the piping engineer to develop intermediate isometric drawings for the piping fabricator. Rather, this project will develop a piping fabrication protocol for conveying the piping 3D design information directly to the piping fabricator for automated pipe spool definition and materials management. This protocol will also be useful for conveying spool and installation information to the project information systems and back to the piping engineer, when necessary. PlantSTEP, PIEBASE, and the CII Research Team 152 (3D CADD in the Fully-Integrated and Automated Project Process) identified piping fabrication and installation as construction tasks which could be improved with the reliable exchange of 3D piping model information.

3.3.4 Site Measurement System Interoperability and Communication Standards

There is presently little in the way of live information from a construction job site that flows back into the design, planning, fabrication, and transportation stages of a project. Because these facets of project management are not automatically linked, it is extremely difficult to take advantage of recent advances in information technology to speed construction delivery time through concurrent engineering. Lack of information closure with the job site specifically precludes: (1) comparison of "as-is" with "should-be" to avoid and rapidly rectify differences between the intended design and the actual construction; (2) construction site control and resource management to avoid delays by tracking material, equipment, and labor to meet schedule while ensuring quality; and (3) capturing "as-built" status of a completed project for use in operation and maintenance over the facility life cycle. In order to bring construction into the information loop, a myriad of real-time sensors and human feedback must find a means to be wirelessly brought from the job site to a digital storehouse—a temporal database—that can be mined and used to facilitate work process modeling and construction management. This project seeks to develop the standard interoperability language and protocols that will make possible this transfer of information.

One of the significant problems facing developers of new construction metrology systems is the difficulty of interfacing to a wide variety of subsystems and integrating them into a useful whole. Furthermore, the subsystems are often numerous, and the "best" for any task can change rapidly. At present, there is no generally accepted approach for software subsystems in a construction site measurement system to use for exchanging data with one another. As a result, significant effort in implementing such systems goes into creating different software interfaces for each sensor, actuator, GUI, and database. Since there is often little prospect of interface-software reuse (because there is so little standardization), system developers are often hesitant to change, upgrade, or experiment with new subsystems. To avoid this productivity loss, a standard, broadly accepted means to communicate information between construction site measurement subsystems is needed. Ideally, this interface should work whether the subsystems reside on the same

computer, or on different ones. Also, ideally, this protocol should be designed to provide maximum flexibility of physical networks capable of realizing the protocol.

Research at NIST is predicated on the availability of live spatial data—the position and orientation of all objects on site. This includes the geometry of amorphous[22] objects, which are not neatly classified as "components," as well as task and component-specific knowledge. We are using many state-of-the-art and emerging sensing technologies to achieve this, including phase differential GPS (global positioning system), fanning lasers, NLS (non-line-of-sight) tracking systems, and LIDAR. We must consider how one is to mine this wealth of chronological data and present it to the various consumers: project/ construction managers, crew foremen, laborers, engineers, fabricators, building owners, and automated machinery.

Unlike modern manufacturing plants (and our most complex laboratory experiments) the every day construction site represents a highly unstructured environment. Stated simply: there can be no wires leading to the thousands of sensors, displays, and machines which must be integrated to make the system work. Current technologies to realize a wireless solution are low bandwidth, especially when compared to modern wire-based systems. Thus a standard protocol will have to take into account lower bandwidth availability yet anticipate improvements in wireless technology. BFRL has already begun looking at the issues surrounding wireless data communication from the construction site.[23]

Our present effort, focused around the BFRL Construction Metrology and Automation Group's *LiveView* protocol, deals with interoperability protocols. Consider a field agent that provides a state update (who/what/where/when) for a static object encountered (e.g., reading the bar code from a girder on a construction site). After the field agent has identified the object and determined the object's position, it is necessary to broadcast any updates to the data consumers. In this case, the facilities for entity creation and managing entity information, provide a common data exchange to enable communication between the field agent and the data consumers.

Development work on *LiveView* proposed for FY 2000 includes:

- The creation of a partial *LiveView* implementation that can be used to enable initial full-scale tests at construction sites employing a limited number of sensor systems for the purposes of tracking excavation and the erection of steel frame structures.

- Development of recommended practice documents for applying *LiveView* to construction automation and metrology tasks. These documents will provide system integrators with a complete picture of how a working system is put

[22] Amorphous objects are items which do not fall under the category of engineered components. They include such things as excavation topography; status of a concrete pour; piles of raw materials; and the status of a paving operation.
[23] Pfeffer, L.E., and Latimer, D.T., "Toward Open Network Data-Exchange Protocols for Construction Metrology and Automation: LiveView," *Proceedings of the International Conference on Automation and Robotics in Construction (ISARC-99), Madrid, Spain, September 22-24, 1999*.

together. Additionally, such a document provides vendors of specific systems a model to follow for how their products could be used. Specifically, in FY 2000, this will include the introduction of component tracking via GPS, fanning laser, and LIDAR; excavation tracking and general field range data via LIDAR and GPS; and bar code and RFID (radio frequency identification) related information.

- Field testing of *LiveView* at an actual construction site on the NIST grounds. Tentatively, pending contract issuance, this will be the 205 ECS.

Future work will seek to provide "Quality of Data" estimates with measurements. Currently, due to the nature of simulation in IEEE 1278, which assumes perfect accuracy of reporting positions, if an entity reports a position, there is no reason to question the potential error in that message. However, field methods for measuring position have limited accuracy. The data quality might be represented with a simple confidence-band, or a more complex function. Issues in how to represent and transport information of this nature need to be investigated further. Finally, the issue of security and access rights in *LiveView* will have to be addressed. Current research in security for distributed systems needs to be evaluated and applied to the *LiveView* system. Ultimately this will lead to the proposal of *LiveView* as an IEEE standard.

3.3.5 Non-Intrusive Scanning Technologies for Construction Status Assessment

Recent evaluations by the construction industry indicate that timely knowledge of project status—where things are, what has been done, what needs to be done—is the single most important issue facing construction managers today. For example, excavation companies spend considerable sums on site layout and verification. Each verification (stakeout) requires a survey team to be hired. A waiting line for surveying services is not uncommon. During the wait, money is lost. If an error is discovered, the re-work can multiply the cost significantly. Excavation is just one example of a broad class of construction status monitoring tasks that are complicated by the amorphous nature of the item to be tracked. Concrete placement, paving operations, and determining quantities of raw materials such as sand and gravel are all further extensions to this theme. Even more powerful, however, will be the ability to automatically capture the "as-built" condition of an existing structure, or to capture and decipher a complex construction operation as it happens and to provide real-time feedback to those conducting the operations. All of these are complex situations where traditional metrology techniques are simply not effective, due to the massive quantities of data needed to describe the environment. This project focuses on the use of new fast laser ranging technologies and three-dimensional analysis to automatically and non-intrusively scan a construction site and to extract useful information from these data for project planning purposes. This versatile capability will directly address both the BFRL CONSiAT major product and the National Construction Goal of reducing delivery time by 50 percent.

BFRL's Construction Metrology and Automation Group in collaboration with NIST's Information Technology Laboratory and BFRL's Computer Integrated Construction

Group has made significant strides during FY1999 in the use of interactive LIDAR for rapidly assessing the status and quantitative change of amorphous objects on a construction site. Specifically, BFRL has succeeded in live acquisition of 3D earthmoving topography, transmission of this data to a remote host, registering the live data with extant data from other, previous LIDAR sweeps, and developed the subsequent post-processing technology to produce both a 3D representation of the changed state of the terrain following excavation ***and*** quantitative information concerning such measures as the amount of material removed and the amount remaining.

NIST is focusing significant research efforts towards becoming a world leader in laser-based site metrology. BFRL's work has been focused on the development of an automated system for the assessment of earthmoving activities at a construction site. The approach involves capturing multiple LIDAR scene images that completely cover all viewable facets of the terrain. A typical LIDAR image looks much like a computer screen image, and in fact is acquired in a similar fashion—by sweeping the laser beam across the site in a line and then stepping the lines down through the field of view in a raster-like fashion. Each line may represent thousands of range measurements as well as returned intensity measurements. Unlike traditional survey instruments, there are no retro-reflector stations involved with LIDAR surveys. The laser beam reflects off dirt and construction components and is received at the instrument that utilizes sensitive coherent radiation sensors to detect the returned signal. Once a complete circuit of an earthmoving site has been made the various LIDAR images are registered to the site coordinate system. The result is a point cloud of three-dimensional locations which discretely (but at very high density) defines the geometry of the construction site. These points can subsequently be meshed and, through various mathematical approaches, used to derive cut and fill requirements, quantities of material placed or removed, and rates of material removal, all of which are of significant interest to excavation subcontractors, primes, and owners. Although the laboratory demonstrations utilized a small sand pile, the same technology and algorithms will work on a construction site measuring hundreds of meters on a side. This technology has drawn international interest and collaborative projects are currently being planned with several companies.

Development work proposed for FY 2000 includes:

- Develop more robust processing of scan data to deal with most terrain features such as vertical surfaces and undercuts.

- Conduct site visits with earthmoving subcontractors, general site contractors, and facility owners to determine their information specific management needs with regard to excavation work at a construction site.

- Develop a mobile scanning system with wireless transport of geometric data to a remote database.

Future work will focus on a demonstration of a complete prototype information management system integrated with automated earthwork tracking systems and a

subsequent field demonstration of a second-generation prototype project information management system incorporating advanced earthwork tracking techniques, including real-time extraction of in-scene machinery.

3.3.6 Real-Time Construction Component Tracking

Inordinate amounts of time are spent every day on construction sites across the United States in efforts to locate and identify components, sub-assemblies, and tools. Finding a needed item is only part of the problem. Once a component or assembly has been incorporated into the building or plant, other questions need to be answered: (1) was the component the right one for that location? (2) where was it finally positioned and what was its orientation? (3) were there any problems associated with the component or with its placement into the structure? and (4) do the appropriate managers, engineers, and planners know this information? Knowledge of this information, in a quick and accurate fashion, would dramatically improve productivity and lower construction costs. The goals of this project are to develop standards for part ID and tracking that the construction industry will adopt; to develop means for real-time tracking of these items and wirelessly transmitting that information to a construction project database; and, finally, to demonstrate the utility of these techniques on full-scale construction sites.

This project will address the problem of identifying, registering, and tracking discrete construction components and sub-assemblies on a construction site, specifically steel frame components. BFRL's approach uses a customized, interactive web site operating on a field-portable computer as the field agent interface. Peripherals, such as a laser-based real-time spatial positioning system, a bar code and RFID scanning system, and a wireless data link, are integrated seamlessly through the browser. The field inspector uses either the bar code scanner or RFID reader to determine the part identification. Then an interactive session begins in which the field computer queries, by means of the wireless link, a remote job site database that then returns information concerning the part. The returned information also includes a three-dimensional model of the component. In the current NIST laboratory work, the new component location data is automatically sent to a Virtual Site Simulator that allows contractors, engineers, and owners to independently view the job site in 3D and to observe the status of construction, including the current position and orientation of every component. In this fashion an automated "as-built" database is constructed in the course of routine quality control tracking. The system is powerful enough to permit real-time tracking of construction machinery as well as other mobile capital assets.

This project will work with industry to develop realistic business cases for deployment of the technologies based on the standards. Collaborations will be sought with construction industry partners to ensure that the standards being developed are responsive to industry needs and are compatible with other industry standardization efforts.

The technology developed in this project will be tested at the Building 205 ECS project on the NIST, Gaithersburg campus.

3.3.7 Economic Analysis of FIAPP Products and Services

FIAPP products and services are one means to improve the performance of the project delivery process by reducing cycle time, construction costs, and construction-related accidents. But investments in and the use of FIAPP 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 FIAPP products and services will encourage their acceptance and use. Economic support for the overall CONSiAT effort addresses the need for information on the economic consequences of investing in FIAPP 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 CONSiAT-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 CONSiAT-related impacts. Once the database is in place, OAE will monitor outcomes and compile information on CONSiAT-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 FIAPP 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 FIAPP 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 FIAPP products and services and traditional products and services will accelerate the introduction and acceptance of FIAPP 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 FIAPP 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 FIAPP 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.[24]

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 FIAPP products and services is defined. The chapter contains two sections.

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 five year period 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 places special emphasis on identifying and detailing the key characteristics of the industrial sector. Detailing the key characteristics of the industrial sector is crucial, because investments in FIAPP 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 FIAPP-related benefits and costs are discussed in Chapter 6.

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.[25] 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

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[24] 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).

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

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).

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.[26] Reference to Table 4-1 reveals that total

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[26] 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*

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 of subcomponents. Both the two major components and the 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.

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.

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

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.[27] 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[28]

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

Table 4-4. Value of Construction Put in Place: Sector Totals and Sum Total in Millions of Current Dollars[29]

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.

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[27] 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.

[28] 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.

[29] 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.

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.

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

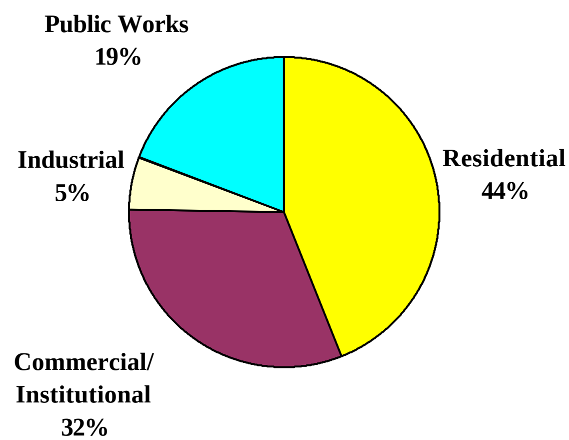

Figure 4-1 provides a useful perspective on the potential market for FIAPP products and services. Consider the four following issues in developing a statement of market scope. First, the use of FIAPP products and services is more likely in the non-residential sectors, where construction establishments tend to be larger. Thus, slightly more than half of the U.S. construction industry serves as a potential market for FIAPP products and services. However, the relatively larger size of construction establishments engaged in non-residential construction activities is only an indicator of market potential. Second, the "owner" plays a vital role in choosing whether or not to employ FIAPP products and services. In fact, the ultimate choice of which technologies to use—traditional or FIAPP—rests with the owner. Third, the relative importance of cost—both first costs and life-cycle costs—and schedule considerations are key drivers of whether or not to use

FIAPP products and services. These considerations tend to reflect more of an owner perspective than a contractor perspective. However, much has been done in recent years to bring these two perspectives into alignment. This brings us to the fourth issue. Finally, the method of contracting and the use of strategic alliances between owners and contractors affect the efficacy with which new technologies can be deployed. Specifically, the engineer-procure-construct (EPC) method of contracting that is used broadly within the industrial sector and, more recently, the design-build method of contracting used in all three non-residential sectors promote a "partnership" environment rather than the adversarial environment that often prevailed under the traditional design-bid-build method of contracting. Furthermore, large industrial organizations (e.g., many of the members of the Construction Industry Institute) have actively pursued strategic alliances to promote increased cooperation and reduced confrontation between owners and contractors.

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, two factors that are of particular importance to decision makers considering investments in new technologies are the ability of those technologies to reduce costs and to reduce the delivery time of constructed facilities. Clearly, cost reductions have an immediate impact on the bottom line and thus are reflected on the "corporate" balance sheet. In the case of industrial facilities, construction expenditures and expenditures for facility operations and for maintenance and repair activities are dwarfed by manufacturing/process-related expenditures (e.g., production workers' wages).[30] Thus, any investments which have the potential ***both*** to reduce construction expenditures and expenditures for facility operations and for maintenance and repair activities ***and*** to reduce manufacturing/ process-related expenditures will have a doubly beneficial impact on the bottom line. Conversely, any investments that result in reductions in delivery time will bring the facility on-line sooner and into a revenue-generating status. Reductions in delivery time may also translate into a significant advantage for a manufacturing establishment's products/commodities. Manufacturing establishments that are consistently able to reduce the delivery time of their constructed facilities will more likely be the first to market their new products/commodities. This strategy is likely to result in increased market share, a significant market advantage for any manufacturing establishment.

As is shown in Chapter 5, FIAPP products and services offer such opportunities in the industrial sector. Although such a doubly beneficial impact will probably result for the other non-residential sectors of the construction industry, the industrial sector is considered a more likely candidate for early adoption of FIAPP technologies. Consequently, this impact assessment adopts a conservative approach in defining the scope of the market for FIAPP products and services to be the industrial sector. The next section defines the size of the market for FIAPP products and services by detailing information on the industrial sector.

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[30] 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.

4.2 Characteristics of the Industrial Sector

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.

The industrial sector, defined in economic terms, consists of establishments that manufacture products and/or commodities. Defined in this way, the industrial sector is extremely varied. It includes chemical manufacturing, oil refining, pulp and paper production, pharmaceuticals manufacturing, electronics manufacturing, automotive manufacturing, consumer products manufacturing, and miscellaneous manufacturing.

Expenditures by establishments in the industrial sector for the built environment include construction expenditures (e.g., new construction and additions and alterations) as well as expenditures for facility operations and for maintenance and repair activities. The market for FIAPP 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 industrial facilities that affect these expenditures. This approach is aimed at producing a better understanding of the market for FIAPP products and services within the industrial 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.

Facility operations include all non-process or end-product related activities required to operate a building or structure (e.g., energy and water consumption, trash removal/ environmental costs, cleaning services/janitorial, and security services/life safety costs), with the exception of maintenance and repair activities. 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.

New construction expenditures in 1997 for the industrial sector were $32.4 billion in current dollars (see Table 4-4). Total construction expenditures include both new construction expenditures and expenditures for additions and alterations. Unfortunately, the C30 report figures do not include an estimate of expenditures for additions and

alterations for any of the non-residential sectors. However, data from the 1992 Census of the Construction Industry can be used to estimate a value for expenditures for additions and alterations in 1997. Data from the 1992 Census of the Construction Industry reveal that expenditures for additions and alterations within the industrial sector average 45 % of expenditures for new construction. Applying this percentage to the 1997 value in Table 4-4 produces the desired estimate. Thus, expenditures for additions and alterations in the industrial sector in 1997 are estimated to be $14.6 billion.

A report by Chapman and Rennison presented and analyzed information on operations, maintenance, and energy costs.[31] The industrial sector figured prominently in these analyses. Readers interested in an in-depth discussion and analysis of operations, maintenance, and energy costs in the industrial sector are referred to the report by Chapman and Rennison.[32]

Based on data presented in Table 7-9 of Chapman and Rennison,[33] estimates of industrial facility operations costs[34] and the total cost for repair of industrial buildings and structures can be produced. These estimates are based on data from the 1992 Census of the Construction Industry updated to 1997. Each estimate may be framed as a percentage of expenditures for new construction. The resultant estimate of industrial facility operations costs updated to 1997 is $5.2 billion. The resultant estimate of the total cost for repair of industrial buildings and structures updated to 1997 is $6.4 billion.

Information on maintenance and repair costs per unit of floor area is available from a variety of sources. However, information from the International Facilities Management Association (IFMA) provides guidance on the relative costs of repair versus preventive maintenance. 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,[35] published in 1994 is the result of a 1993 survey of IFMA members. The report presents benchmarking data derived from 283 survey questionnaires. Combining this information[36] with the estimated costs for repair of industrial buildings and structures produces an estimate of the costs of preventive maintenance for industrial buildings and structures. The resultant estimate of the costs of preventive maintenance for industrial buildings and structures for 1997 is $3.8 billion.

Total expenditures for maintenance and repairs may be estimated in either of two ways. First, sum the estimated 1997 expenditures for repair of industrial buildings and the

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[31] Chapman and Rennison, *An Approach for Measuring Reductions in Operations, Maintenance, and Energy Costs*.
[32] *Ibid.*, pp. 183-225.
[33] *Ibid*., pp. 222-223.
[34] Because it is difficult to separate manufacturing-related consumption of energy and water from facility-related consumption, all costs for energy and water consumption are allocated to manufacturing-related activities.
[35] International Facilities Management Association. 1994. *Benchmarks II*. Research Report #13. Houston, TX: International Facilities Management Association.
[36] *Ibid*., p. 35.

estimated 1997 expenditures for preventive maintenance to get the estimated value of expenditures for maintenance and repairs in the industrial sector in 1997. The resultant sum is $10.2 billion. Second, use data from the 1992 Census of the Construction Industry to determine for the industrial sector what percentage of expenditures for new construction is spent for expenditures on maintenance and repairs and apply it to the 1997 value in Table 4-4. These data reveal that expenditures for maintenance and repairs within the industrial sector average 38 % of expenditures for new construction. Thus, expenditures for maintenance and repairs in the industrial sector in 1997 by the second method are estimated to be $12.3 billion.

Reference to Table 4-3 reveals that new construction expenditures for the industrial sector—measured in constant 1992 dollars—have hovered around $30 billion per year in recent years. Because expenditures for additions and alterations, for facility operations, and for maintenance and repair activities may be estimated as "fixed proportions" of expenditures for new construction, investments in and expenditures for buildings and structures in the industrial sector—expressed in constant dollar terms—are remaining fairly constant. This finding is of particular importance in defining the size of the market for FIAPP products and services for two reasons.

First, the market for FIAPP 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 FIAPP 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 FIAPP products and services will be employed both as retrofits to existing buildings and as initial installations in new buildings.

Second, this finding implies that the sum total of all construction/facility-related expenditures for the entire industrial sector have remained fairly constant for an extended period of time. If this trend continues, as seems likely, then total expenditures will continue to remain constant. Thus, the potential market for FIAPP products and services in the industrial sector may be modeled as a constant dollar volume for which FIAPP products and services compete with traditional products and services.

This section's approach to characterizing the market for FIAPP products and services and detailing the market in terms of total dollar expenditures for construction, facility operations, and maintenance and repair activities sets the stage for the impact assessment. By focusing on total dollar expenditures as the potential target market, the calculation of FIAPP-related costs and benefits is driven by expenditure-related considerations. This is fortuitous because the industrial sector is geared towards processing information presented in terms of total expenditures (e.g., total installed cost). By casting the economic impact assessment in terms of total expenditures, this study will be able to denominate all key inputs in terms of percent changes from a baseline (e.g., percent reduction in total installed cost). This approach will promote a better understanding of the findings of this study and its implications for the construction industry.

5 Strategy for Identifying, Collecting, and Measuring FIAPP-Related Benefits and Costs

The strategy outlined in this chapter was developed through an iterative process. First, information was solicited from members of the BFRL CONSiAT team. This information was used to develop candidate lists of key stakeholder classes (e.g., building owners) and general types of FIAPP-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 CONSiAT project leaders and, upon their review of the classification hierarchies, critiqued in a series of meetings with the project leaders. The meetings with the BFRL CONSiAT 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 FIAPP 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 FIAPP products and services.

Since individual stakeholder classes evaluate the benefits and costs of FIAPP 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 FIAPP 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 five classes of individual stakeholders: construction workers, general contractors, specialty trade contractors, trade associations, and wholesale/retail trade/supply. 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 FIAPP products and services to society. BFRL's assessment of FIAPP-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 FIAPP-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 six stakeholder groups are listed in a ***bold-italics*** typeface. The classes of individual stakeholders are listed in alphabetical order beneath each stakeholder group.

Table 5-2 is arranged as a checklist; it assigns each of the 31 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 Classification of FIAPP-Related Benefits and Cost Savings

Stakeholders invest in FIAPP 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 identify FIAPP-related benefits and cost savings from society's frame of reference (i.e., across all stakeholder groups).

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

The first tier of the hierarchy lists generic types of FIAPP-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 15 first tier elements are listed in a ***bold-italics*** typeface. Examples of first tier benefits and cost savings are increased/new sales for system design/integration/optimization services, lower first costs, and lower operations and maintenance costs.

Table 5-1. Hierarchy of FIAPP Stakeholders by Groups and Classes of Individual FIAPP Stakeholders

Building Owners and Managers

- Building Managers
- Building Owners

Codes, Standards, and Support Services

- Building Owners
- Building Permitting and Inspection
- Code Officials
- Code Organizations
- Construction Products/Equipment Manufacturers
- Professional Societies
- Product Certification Services
- Product Evaluation Services
- Research Organizations
- Standards Organizations
- Trade Associations

Construction and Associated Support Services

- Construction Workers
- General Contractors
- Specialty Trade Contractors
- Trade Associations
- Wholesale/Retail Trade/Supply

Other

- Building Occupants
- Special Interest Groups
- Third Parties

Manufacturing Interest Group

- Construction Products/Equipment Manufacturers
- Customer Service Operations
- Product/Equipment/Software Designers
- Product/Equipment/Software Innovators
- Product/Equipment/Software Marketing, Sales, and Distribution Services
- Professional Societies
- Research Organizations
- Testing Laboratories
- Testing Services
- Trade Associations

Professional and Financial Services

- Architects
- Designers
- Engineering Consultants
- Insurance Companies
- Investment Banking Services
- Warranty Companies

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

Individual Stakeholder Class	Stakeholder Group					
	Building Owners & Managers	Codes, Standards, & Support Services	Manufacturing Interest Group	Construction & Associated Support Services	Professional & Financial Services	Other
Architects					✓	
Building Managers	✓					
Building Occupants						✓
Building Owners	✓	✓				
Building Permitting and Inspection		✓				
Code Officials		✓				
Code Organizations		✓				
Construction Products/Equipment Manufacturers		✓	✓			
Construction Workers				✓		
Customer Service Operations			✓			
Designers					✓	
Engineering Consultants					✓	
General Contractors				✓		
Insurance Companies					✓	
Investment Banking Services					✓	
Product Certification Services		✓				
Product/Equipment/Software Designers			✓			

Table 5-2. Assignment of Classes of Individual FIAPP Stakeholders to FIAPP 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	Other
Product/Equipment/Software Innovators			✓			
Product/Equipment/Software Marketing, Sales, and Distribution Services			✓			
Product Evaluation Services		✓				
Professional Societies		✓	✓			
Research Organizations		✓	✓			
Special Interest Groups						✓
Specialty Trade Contractors				✓		
Standards Organizations		✓				
Testing Laboratories			✓			
Testing Services			✓			
Third Parties						✓
Trade Associations		✓	✓	✓		
Warranty Companies					✓	
Wholesale/Retail Trade/Supply				✓		

Table 5-3. FIAPP-Related Benefits (or Cost Savings) for All Stakeholders

Improved Company Capabilities and Flexibility for New Project Opportunities

- Access to Live Data Stream from Construction Site Allows Construction Management to be Conducted Remote from the Job Site
    - Automated Generation of Material Orders and Payments
    - Pre-Programming and Simulating the Following Day's Activities for Optimum Efficiency
- Tele-Present Machine Operation Allows for Remote Operation of Machinery

Improved Feedback Mechanisms on Performance of New Tools and Processes

Increased/New Sales for System Design/Integration/Optimization Services

- Automated Construction Machine Maintenance and Fleet Management
- Automated Construction Machine Programming and Task Execution
- Construction Simulation/Visualization
- Facility Operations
- Materials Management, Tracking, and Scheduling

Increased Net Income for Contractors

- Better Control of Cost Growth
- Better Design Evaluation and Checking
- Better Document Control
- Better Materials Management
- Better Scheduling of Construction-Site Operations
- Improvements in Productivity
- Smoother Start-Up Operations

Increased Revenues Due to Earlier Start-Up of Primary Functions

- Earlier Revenue Stream from Sale of Products/Services
- Faster Return on Investment

Increased Sales of Selected Product/Equipment Lines and Associated Services

Increased Sales of Construction Products/Equipment/Services with New Features

Table 5-3. FIAPP-Related Benefits (or Cost Savings) for All Stakeholders (Continued)

Lower First Costs

- Better Control of Cost Growth
  - Earlier Bill of Materials and Procurement Analysis Reduces Risks of Non-Availability of Parts
  - Fewer Project Development and Scope Changes
  - Less Design Rework
  - Less Field Rework
- Better Component Selection Process
- Better Design Evaluation and Checking
- Better Document Control
- Better Materials Management
- Better Scheduling of Construction-Site Operations
- Early Payment on Bill of Materials Gets Discount Price
- Lower Financing Costs Due to Earlier Start-Up of Primary Functions
- Optimization of Project Team and Plan
  - Better Coordination Between Owner, Prime Contractor, and Subcontractors
  - Better Opportunity for Supply Chain Management
  - Earlier Optimization of Design and Project Plan
  - Improved Procurement, Supply, and Contractor Management
- Smoother Start-Up Operations

Lower Operations and Maintenance Costs

- Availability of Electronic "As Built" Information 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
- Improvements in Compliance Monitoring
- Increased Functionality and Performance
- Reduced Down Time
- Use of On-Part Information Systems (RFID) Reduces Certification and Calibration Costs

Table 5-3. FIAPP-Related Benefits (or Cost Savings) for All Stakeholders (Continued)

Lower Repair, Replacement, and Decommissioning Costs

- Availability of Electronic “As Built” Information Enables Faster Response to and Resolution of Many Repair Problems
- Availability of Electronic “As Built” Information Reduces the Costs of Addition and Modernization Projects
- Availability of Electronic “As Built” Information Reduces the Costs of Decommissioning “Out-of-Date” Plant and Equipment
- Longer Equipment Life Due to Better Operating Conditions
- On-Part Information Systems (RFID) Identify “Generic” Replacement Components and Sources
- Reduced Down Time
- Use of Electronic Data Interchange Promotes Faster Delivery of “Out-of-Stock” Parts

Reductions in Construction-Related Accidents and Injuries

- Availability of Electronic “As Built” Information Increases Safety During Normal Operations and Emergency Situations
- Fewer Lost Workdays
- Fewer Recordable Incidents
- Improved Safety Through Automated Tracking and Event Logging
    - Fewer Machine-Worker Accidents
    - Identification of High-Risk Employees
    - Identification of High-Risk Machinery
- Less Down Time
- Lower Medical Costs
- Lower Workman’s Compensation Insurance Premiums

Reductions in Costs of Code Compliance Due to New Ways of Designing, Constructing, and Maintaining Buildings

- New Ways of Communicating With Code Officials
    - Automated Inspection Requests
- New Ways of Demonstrating Code Compliance
    - Pre-Certified Automated Procedures
    - Remote Certification (Tele-Presence Inspection)
- New Ways of Demonstrating Operating Compliance
    - Autonomous Remote Sensing to Code Official

Table 5-3. FIAPP-Related Benefits (or Cost Savings) for All Stakeholders (Continued)

Reductions in Delivery Time

- Better Control of Schedule Growth
  - Automated Field Inspection Reports
  - Automated Utility Avoidance
  - Fewer Project Development and Scope Changes
  - Less Design Rework
  - Less Field Rework
  - Earlier Bill of Materials and Procurement Analysis Reduces Risks of Non-Availability of Parts
- Better Document Control
  - Automated Updates of As-Built Information
- Better Scheduling of Construction-Site Operations
  - Dynamic Database Allows for Identification of Non-Obvious Critical Path Activities and Automated Rescheduling
  - New Ideas/Task Sequencing Can be Explored with 3D Simulations
  - Output of 3D Simulations Can be Used to Drive Machinery for Automated Processes
- Earlier Start-Up of Primary Functions
- Faster Task Completion
  - Ability to Employ Automated Processes and "Measureless" Construction
  - Automated Tracking of Parts and Processes
- Optimization of Project Team and Plan
  - Better Coordination Between Owner, Prime Contractor, and Subcontractors
  - Better Opportunity for Supply Chain Management
  - Earlier Optimization of Design and Project Plan
  - Improved Procurement, Supply, and Contractor Management
- Smoother Start-Up Operations

Reductions in Warranty Costs

Reductions in Waste and Pollution

The second tier lists specific types of benefits and cost savings associated with its "parent" first tier element. The second tier elements are listed in alphabetical order as a series of bullets under the parent first tier element. An example of a second tier element for lower first costs is better control of cost growth. Not all generic types of benefits and cost savings have a second tier (e.g., reductions in warranty costs).

The third tier lists specific types of benefits and cost savings associated with its "parent" second tier element. The third tier elements are listed in alphabetical order as a series of bullets under the parent second tier element. Two of the third tier elements, fewer project development and scope changes and less field rework, are concerned with better control of cost growth. These cost savings are of central importance to BFRL and its industry collaborators.

The classification hierarchy presented as Table 5-3 has been limited to three tiers. Because Table 5-3 and Table 5-4 (see Section 5.3) are used to measure the "benefits" and "costs" sides of FIAPP-related impacts, the end product of these classification hierarchies is a collection of economic data. In the case of FIAPP-related benefits and cost savings, the depth of the hierarchy (i.e., the number of tiers) is equal to three. In principle, the depth of these data-related classification hierarchies could be equal to one, to two, to three, or to some number greater than three. 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 FIAPP-related benefits and cost savings, three tiers were considered adequate.

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 FIAPP-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.

5.3 Classification of FIAPP-Related Cost Increases and Benefit Reductions

Costs are at the heart of any investments in new products.[37] For the CONSiAT economic impact assessment, costs are incurred at several points in the "product" life cycle. Specifically, FIAPP-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

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

"traditional" products. These cost increases 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 FIAPP-related cost increases and benefit reductions. The list is considered to be exhaustive and self-evident. The six first tier elements are listed in a ***bold-italics*** typeface. Examples of first tier cost increases and benefit reductions are increased costs for new standards development, increased investments by construction products/equipment manufacturers and hardware/software developers, and new-technology introduction costs.

The last element, new-technology introduction costs, merits a closer examination. Ehlen and Marshall[38] 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.[39]

The second tier lists specific types of cost increases and benefit reductions associated with its "parent" first tier element. The second tier elements are listed in alphabetical order as a series of bullets under the parent first tier element. One example of a second tier element for increased investments by construction products/equipment manufacturers is increased research and development costs. Another example of a second tier element for new-technology introduction costs is increased training costs. Not all generic types of costs and benefit reductions have a second tier (i.e., increased costs for new standards development and reduced sales of selected product/equipment lines and associated services).

The third tier elements are concerned with increased research and development costs and with two of the four second tier elements for new-technology introduction costs—increased marketing, advertising, and distribution costs by construction products/ equipment manufacturers and hardware/software developers ***and*** increased training costs. The costs associated with these three second tier elements are of central importance to both BFRL and its industry collaborators. Consequently, it was desirable to increase the depth of the FIAPP-related costs and benefit reductions classification hierarchy to three. Information on increased research and development costs is presented and discussed in Section 6.3.2.1. Examples of increased research and development costs are increased costs for product development and increased costs for product testing/ simulation. Information on new-technology introduction costs is presented and discussed in Section 6.3.2.2.

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[38] 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.
[39] *Ibid.*, p. 15.

Table 5-4. FIAPP-Related Cost Increases (or Benefit Reductions) for All Stakeholders

Increased Costs for New Standards Development

Increased Costs of Hardware and Software Installation to Provide Infrastructure Support

- Additional Construction-Site Systems Infrastructure Needed to Monitor and Control Systems and Components
- Additional Information Technology Costs for Program Management and Procurement
- Increased Costs of Installing Hardware and Software for Use by Building Owners and Managers
- Increased Costs of Installing Hardware and Software in Building Code Offices
- Increased Costs to Modify the Current Inspection/Certification Process to Accommodate New Hardware/Software Capabilities

Increased Costs to Properly Maintain Hardware and Software

- Additional Costs Associated with Parts Replacement and Software Upgrades
- Additional Costs Associated with Periodic Calibration and Certification of New Technology Products
- Additional Costs to Insure that the Current Information Transfer Protocols Are Being Used
- Additional Costs to Insure that the Hardware and Software Incorporate the Most Recent Set of Building Code Information

Increased Investments by Construction Products/Equipment Manufacturers and Hardware/Software Developers

- Additional Costs for New Intellectual/Material Inputs
- Conversion Costs for Installing New Production Processes in Existing Facilities
- Increased Costs for Copyright/Trademark Registration/Defense
- Increased Research and Development Costs
    - Increased Costs for Product Development
    - Increased Costs for Product Testing/Simulation

Table 5-4. FIAPP-Related Cost Increases (or Benefit Reductions) for All Stakeholders (Continued)

New-Technology Introduction Costs

- Increased Costs of Adapting New Construction Technologies, Products, Equipment, and Practices to Industry Use
- Increased Marketing, Advertising, and Distribution Costs by Construction Products/Equipment Manufacturers and Hardware/Software Developers
  - Increased Costs Associated with Market Positioning Efforts
  - Increased Costs to Develop New Distribution and Service Channels
  - Intermediate Requirement to Maintain Redundant Services and Distribution Channels
- Increased Risk Exposure and Uncertainty Due to Construction with New Technologies, Products, Equipment, or Practices
- Increased Training Costs
  - Increased Costs for Instruction on How to Incorporate New Technologies, Products, Equipment, and Practices into the Design Process
  - Increased Costs for Training Building Owners and Managers on New Operations and Maintenance Processes and Techniques
  - Increased Costs for Training Construction Workers on New Construction Processes and Techniques
  - Increased Costs for Training Public Officials on Hardware/Software Capabilities

Reduced Sales of Selected Product/Equipment Lines and Associated Services

5.4 How FIAPP-Related Benefits and Costs Accrue to Stakeholders

Recall that BFRL's assessment of FIAPP-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 FIAPP 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 FIAPP-related benefits and cost savings and FIAPP-related cost increases 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 two stakeholder groups—building owners and managers *and* professional and financial services—are beneficiaries of lower operations and maintenance costs (see the cells beneath the "stakeholder group" column headings in Table 5-5 with check marks (✓)), then we can focus our "operations and maintenance cost" data collection effort on these two 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 FIAPP 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 FIAPP product versus a traditional product, they need to know if the life-cycle cost over the proposed study period of the FIAPP 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 six of the 15 types of benefits and cost savings. Examples of specific types of benefits and cost savings accruing to building owners and managers are lower first costs, lower operations and maintenance costs, and reductions in delivery time. Reference to Table 5-6 shows that building owners and managers bear four types of increased costs. They are the costs associated with new standards development, increased costs of hardware and software to provide infrastructure support, increased costs to properly maintain hardware and software, and new-technology introduction 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 FIAPP product under consideration.

Table 5-5. Types of FIAPP-Related Benefits (or 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	Other
Improved Company Capabilities and Flexibility for New Project Opportunities			✓	✓	✓	
Improved Feedback Mechanisms on Performance of New Tools and Processes			✓	✓	✓	
Increased/New Sales for System Design/ Integration/Optimization Services			✓	✓	✓	
Increased Net Income for Contractors				✓	✓	
Increased Revenues Due to Earlier Start-Up of Primary Functions	✓					
Increased Sales of Selected Product/ Equipment Lines and Associated Services			✓	✓	✓	
Increased Sales of Construction Products/ Equipment/Services with New Features		✓	✓	✓	✓	
Lower First Costs	✓	✓	✓	✓	✓	
Lower Operations and Maintenance Costs	✓				✓	
Lower Repair, Replacement, and Decommissioning Costs	✓		✓	✓	✓	
Reductions in Construction-Related Accidents and Injuries	✓			✓	✓	✓
Reductions in Costs of Code Compliance Due to New Ways of Designing, Constructing, and Maintaining Buildings	✓	✓	✓	✓	✓	✓
Reductions in Delivery Time	✓	✓	✓	✓	✓	✓
Reductions in Warranty Costs	✓		✓	✓		
Reductions in Waste and Pollution	✓		✓	✓		✓

Table 5-6. Types of FIAPP-Related Cost Increases (or Benefit Reductions) Classified by Stakeholder Group

Type of Cost Increase or Benefit Reduction	Stakeholder Group					
	Building Owners & Managers	Codes, Standards, & Support Services	Manufacturing Interest Group	Construction & Associated Support Services	Professional & Financial Services	Other
Increased Costs for New Standards Development	✓	✓	✓	✓	✓	✓
Increased Costs of Hardware and Software to Provide Infrastructure Support	✓	✓		✓	✓	
Increased Costs to Properly Maintain Hardware and Software	✓	✓	✓	✓	✓	
Increased Investments by Construction Products/Equipment Manufacturers			✓			
New-Technology Introduction Costs	✓	✓	✓	✓	✓	✓
Reduced Sales of Selected Product Lines and Services			✓	✓	✓	✓

6 Data and Assumptions for the CONSiAT Economic Impact Assessment

This chapter describes the data and assumptions used to evaluate the economic impacts expected from the adoption and use of FIAPP products and services in the industrial sector. The goal of this chapter is fourfold. First, it establishes the sources and validity of the data used in the CONSiAT economic impact assessment. Second, it defines the base case and the FIAPP 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 CONSiAT 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 CONSiAT 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.[40] 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 seven 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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[40] 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.

Two reports by Chapman and Rennison provide detailed sets of baseline measures for National Construction Goal 1,[41] reductions in delivery time, and National Construction Goal 2,[42] reductions in operations, maintenance, and energy costs. A third report by Chapman provides a detailed set of baseline measures for National Construction Goal 7,[43] reductions in construction worker illnesses and injuries. Goals 1, 2, and 7 were identified as the highest priority National Construction Goals by the construction industry.

The baseline measures for Goals 1, 2, and 7 for the industrial sector were the starting point for collecting the data and information needed to conduct the CONSiAT economic impact assessment. Specifically, the values of the baseline measures are reference data against which the values contained in this report can be compared. In addition, all three reports 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 industrial 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 The CII Benchmarking and Metrics Database

Information from CII is used to produce estimates for three key data items: (1) reductions in construction costs; (2) reductions in delivery time; and (3) reductions in construction-related accidents. The first data item is needed to estimate the percent cost savings for a typical industrial sector project. The second data item provides the basis for estimating the potential for increased sales revenues due to earlier start-up of production operations. The third data item is needed to estimate cost savings resulting from improved safety performance. Anecdotal information is also presented which is useful in estimating a fourth data item—reductions in maintenance and repair costs.

CII is an internationally-recognized research consortium focused on advancing the capital projects industry. CII draws its membership primarily from companies involved in the operation or construction of chemical manufacturing, oil refining, pulp and paper, or similar industrial facilities. CII membership is nearly equally split between owner members and contractor members. CII data are used in this document because CII has committed itself to an annual cycle of surveying its member companies, collecting data on an individual project basis, analyzing these data, and publishing its findings.

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[41] Chapman, Robert E., and Roderick Rennison. 1998. *An Approach for Measuring Reductions in Delivery Time: Baseline Measures of Construction Industry Practices for the National Construction Goals*. NISTIR 6189. Gaithersburg, MD: National Institute of Standards and Technology.
[42] 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.
[43] Chapman, Robert E. 2000. *An Approach for Measuring Reductions in Construction Worker Illnesses and Injuries: Baseline Measures of Construction Industry Practices for the National Construction Goals*. NISTIR 6473 (in press). Gaithersburg, MD: National Institute of Standards and Technology.

Research by the author indicates that CII is one of the few organizations in the US that is systematically collecting construction project data in a manner conducive to estimating the benefits and costs of employing innovative methods for using existing design and information technologies. CII has agreed to provide NIST with aggregated data from its database, which will enable NIST to develop an extensive set of benefit and cost measures associated with the use of design and information technologies.[44] At the same time, NIST's analyses of the CII data will provide CII with valuable insights into the performance of its member companies, which will be of direct benefit to its membership.

All information presented in this subsection is based on the results of a research collaboration between NIST and CII.[45] The focus of this research collaboration was on quantifying the value of using design/information technologies within the non-residential sectors of the construction industry. Although the evolution and deployment of design/information technologies will undoubtedly play an important role in the future of the construction industry, many stakeholders are unsure of the economic value of using these technologies. A detailed, authoritative, and readily accessible set of information is needed to enable construction industry stakeholders to make cost-effective investment decisions among established, new, and innovative design/information technologies. The CII Benchmarking and Metrics database, which is composed exclusively of actual project execution experiences, is the product from which this set of information was developed.

This collaborative research effort uses the CII Benchmarking and Metrics database to evaluate the use of design/information technology and relate its use to project performance. Results from this collaborative research effort are used to identify, document, and develop estimates for the benefits and costs of using FIAPP products and services in the industrial sector.

The CII Benchmarking and Metrics Committee[46] established the CII Benchmarking and Metrics database in 1996. The CII Benchmarking and Metrics database is based on survey data collected from CII member companies. The Benchmarking and Metrics Committee is responsible for the design of the survey instrument, the training of benchmarking associates from member companies, and the compilation and analysis of respondent data.

The survey instrument focuses on information on project size, cost, schedule, overall performance, as well as on details of project execution. The survey instrument is designed to collect information both on performance metrics—cost, schedule, and safety—and on the use of CII-endorsed best practices. Perhaps most importantly, CII's analysis of respondent data seeks to quantify the impacts of best practice usage on the values of performance metrics (e.g., how the use of best practices translates into

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[44] All data provided to NIST by CII have been aggregated in a manner that precludes identification of an individual company's or project's performance.

[45] Thomas, Stephen R. 1999. *Impacts of Design/Information Technology on Project Outcomes*. NIST GCR 99-786. Gaithersburg, MD: National Institute of Standards and Technology.

[46] The Benchmarking and Metrics Committee was chartered by CII's Board of Advisors in November 1993. The Benchmarking and Metrics Committee is composed of representatives from both owner and contractor companies; it met for the first time in February 1994.

reductions in project delivery time). Detailed information is collected on 6 CII-endorsed best practices: (1) safety;[47] (2) pre-project planning;[48] (3) team building;[49] (4) constructability;[50] (5) project change management;[51] and (6) design/information technology.[52] These data are used to construct a series of indices for measuring the degree of usage both for individual best practices (e.g., design/information technology) and for the overall set. Having data which links best practice use (e.g., design/information technology) to project outcomes (e.g., reductions in project delivery time) is a valuable tool for identifying performance improvement opportunities.

Information from 297 projects totaling $13.0 billion (installed cost) has been collected, compiled, analyzed, and made available to NIST.[53] Figure 6-1 summarizes the project data received from both CII owners and contractors. Note that nearly two-thirds of the projects came from owners.

The Benchmarking and Metrics Committee uses four construction industry groups and allows for categorization of the database by these groups. The four industry groups are: (1) buildings; (2) heavy industrial; (3) infrastructure; and (4) light industrial. Figure 6-2 reports the distribution of projects in the database by industry group. Data on both owner respondent projects and contractor respondent projects are shown in Figure 6-2. The heavy industrial group comprises approximately two thirds of the database. The remainder of the projects is distributed among the other three industry groups as follows: 50 building projects; 14 infrastructure projects; and 39 light industrial projects. Throughout this document buildings are classified under the commercial/institutional sector, both heavy industrial projects and light industrial projects are classified under the industrial sector, and infrastructure projects are classified under the public works sector.

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[47] Safety practices include the site-specific program and efforts to create a project environment and state of consciousness embracing the concept that all accidents are preventable and that zero accidents is an obtainable goal.

[48] Pre-project planning involves the process of developing sufficient strategic information with which owners can address risk and decide to commit resources to maximize the chance for a successful project.

[49] Team building is a process that brings together a diverse group of project participants and seeks to resolve differences, remove roadblocks, and proactively build and develop the group into an aligned, focused, and motivated work team that strives for a common mission for shared goals, objectives, and priorities.

[50] Constructability practices seek to achieve overall project objectives through the optimum use of construction knowledge and experience in planning, design, procurement, and field operations. Constructability is achieved through the effective and timely integration of construction input into planning and design as well as field operations.

[51] Project change management practices seek to promote a balanced change culture, recognize change, evaluate change, implement change, and continuously improve from lessons learned.

[52] Design/information technology practices involve the use of data integration programs, 3D CAD modeling, electronic data interchange (EDI), and bar coding.

[53] Information compiled from the CII Benchmarking and Metrics database was limited to data from US domestic projects. Contractor data was used only for those projects on which contractors performed both design and construction tasks. Although the CII Benchmarking and Metrics database contains data for three versions of its questionnaire, only data from versions 2.0 and 3.0 were included. The version 1.0 questionnaire did not address design/information technology use.

Figure 6-1.   CII Database by Respondent Type

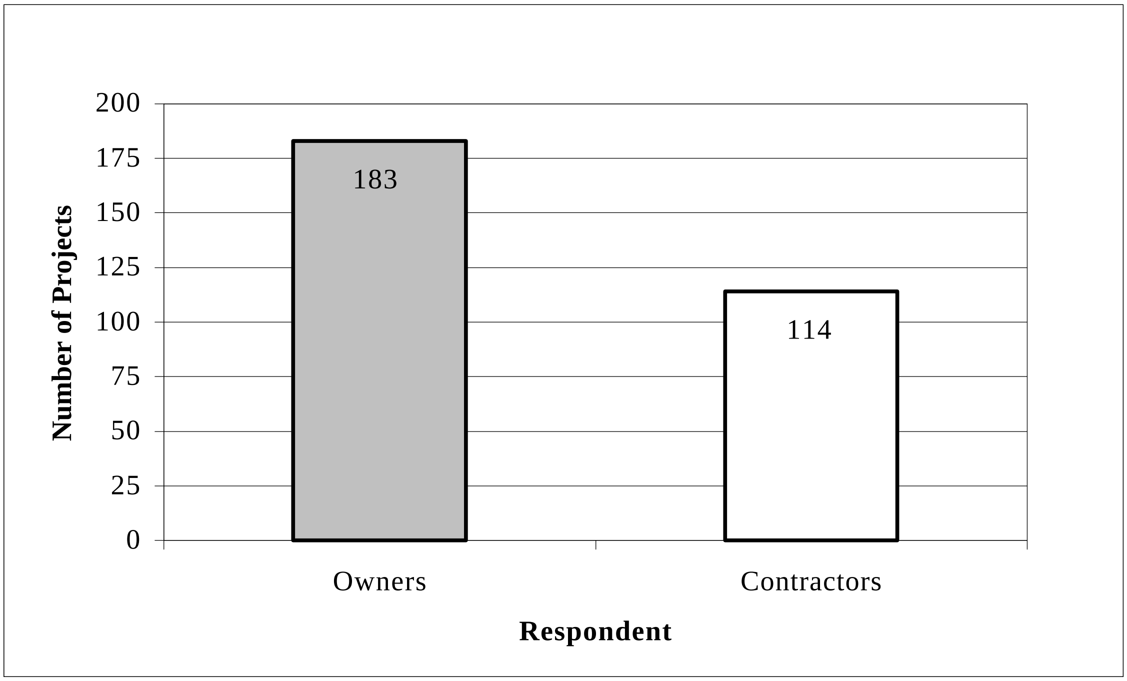
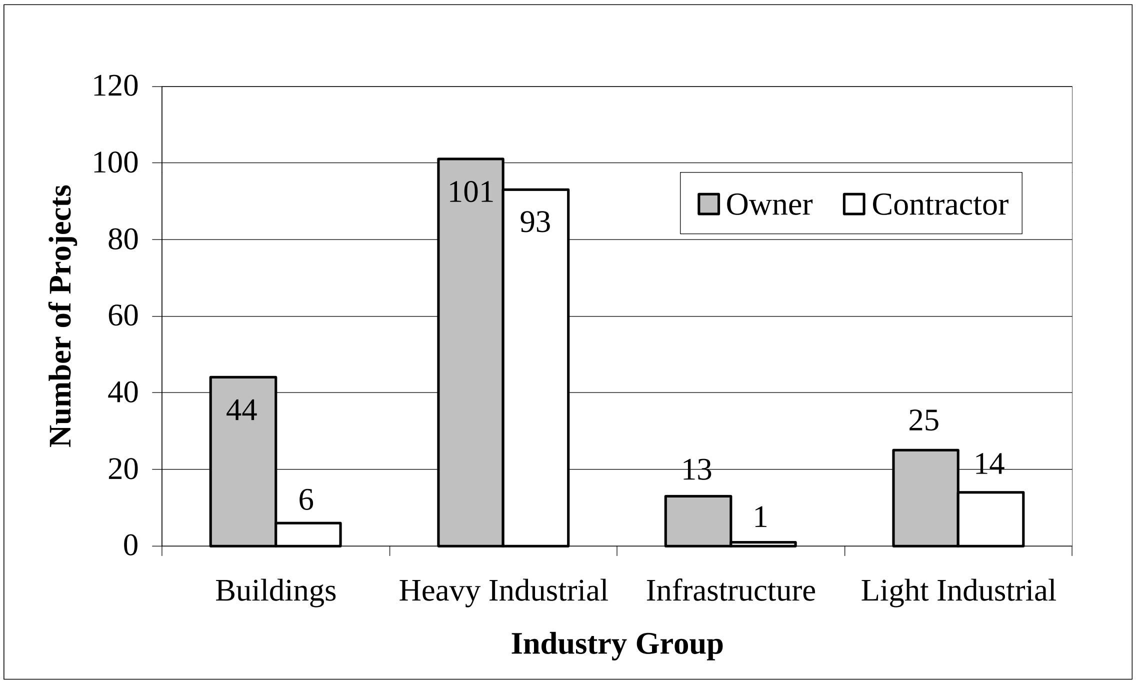


Figure 6-2.   CII Database by Industry Type



The CII database currently represents a broad range of project size as measured by cost. As shown in Figure 6-3, approximately one-half of the projects have a cost of less than $15 million, one-third have a cost between $15 and $50 million, and one-sixth have a cost in excess of $50 million. The individual project costs range from slightly below $5 million to in excess of $500 million, with an average cost of approximately $45 million. Data on both owner and contractor respondent projects are shown in Figure 6-3.

Projects in the CII database can be identified and categorized by the nature of the project. Project nature indicates to which of the three categories a project belongs: (1) grassroots; (2) addition; and (3) modernization. The survey instrument defined grass roots as a new facility. An addition was defined as a new facility component that ties in to an existing facility, often intended to expand capacity. Modernization was defined as a facility for which a substantial amount of the equipment or structure is replaced or modified, and which may expand capacity. For purposes of this document, grassroots projects are classified under the heading of new construction, and addition and modernization projects are classified under the heading of additions and alterations. Figure 6-4 shows how the projects in the database are distributed among the three categories of project nature. The projects are approximately equally distributed among all three categories. Data on both owner respondent projects and contractor respondent projects are shown in Figure 6-4.

The results of the statistical analyses of the CII project data are summarized in Table 6-1. The table records two cost metrics, two schedule metrics, and two safety metrics. The two cost metrics are project cost growth[54] and construction cost growth. The two schedule metrics are total project duration[55] (in weeks) and construction phase duration (in weeks). The two safety metrics are the recordable incidence rate[56] (RIR) and the lost workday case incidence rate[57] (LWCIR).

Performance improvements due to the extensive use of design/information technology practices (Column 3) are computed as the difference between average project performance for that metric (Column 1) and the value of that metric for that subset of projects which made extensive use of design/information technology practices (Column 2). The calculated values recorded in Column 3 of Table 6-1 provide the starting point for estimating FIAPP-related benefits and cost savings derived in Subsection 6.3.1. Anecdotal information collected as part of a series of in-depth analyses of a select set of exemplary projects provided the basis for estimating reductions in maintenance and repair costs (see Subsection 6.3.1).

[54] Project cost growth equals {(actual total project cost – initial predicted project cost) / initial predicted project cost}, where actual total project cost equals total installed cost at turnover to the user (excluding land costs), and initial predicted project cost equals the project's budget at the start of detailed design.
[55] Total project duration equals the elapsed time from the start of detailed design to turnover to the user.
[56] The RIR represents the number of injuries and illnesses per 100 full-time workers. It is calculated as (N/EH)x200,000, where N = the number of injuries and illnesses, EH = the total hours worked by all employees during the calendar year, and 200,000 = the base for 100 full-time workers (working 40 hours per week, 50 weeks per year).
[57] The LWCIR is a measure of more serious injuries; it records those cases which result in days away from work or restricted work activity.

Figure 6-3. CII Database by Cost Category

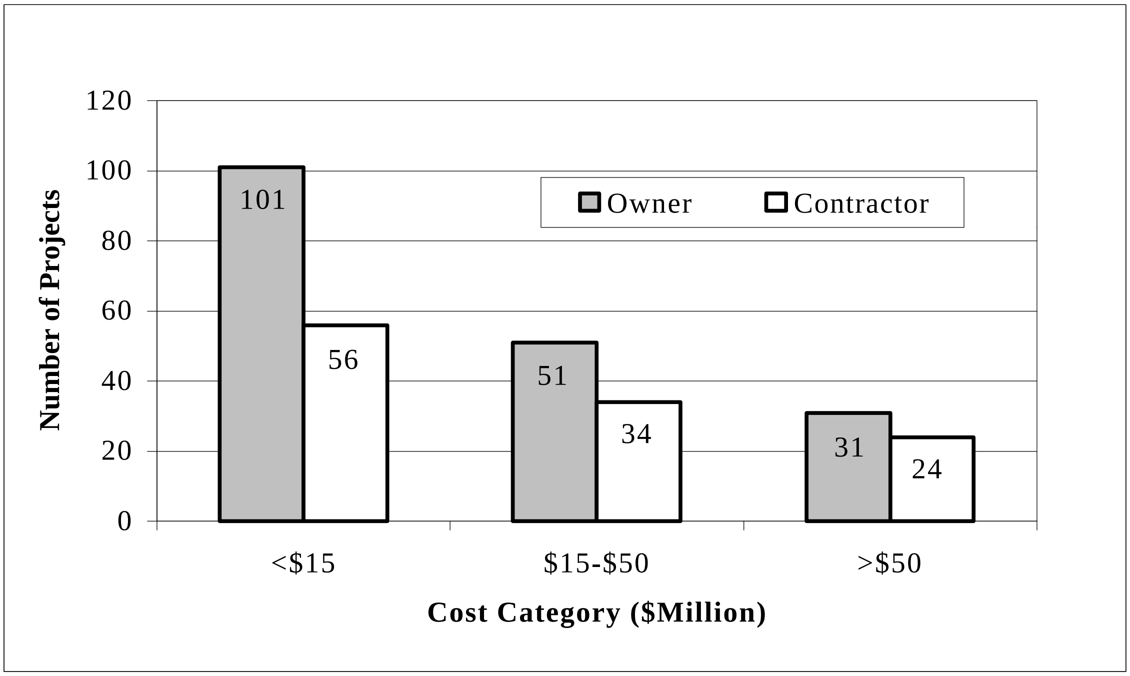


Figure 6-4. CII Database by Project Nature

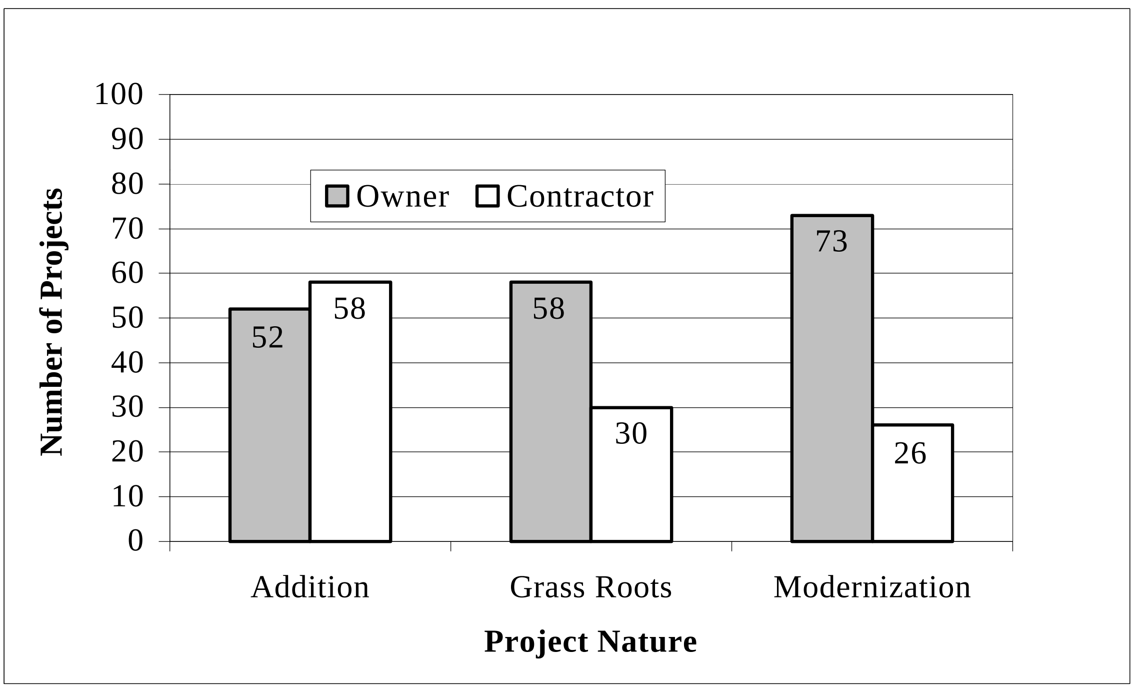


Table 6-1. Summary of Selected Results from the Statistical Analyses of the CII Project Data

Metric	Design/Information Technology Use		Measured Performance Improvement
	Average Col. (1)	Extensive Col. (2)	Col. (3)
Project Cost Growth	-2.0 %	-3.4 %	1.4 %
Construction Cost Growth	-0.2 %	-4.7 %	4.5 %
Total Project Duration	96 weeks	80 weeks	16 weeks
Construction Phase Duration	58 weeks	50 weeks	8 weeks
Recordable Incidence Rate	2.184	1.439	0.745
Lost Workday Case Incidence Rate	0.585	0.238	0.347

Source: Thomas, *Impacts of Design/Information Technology on Project Outcomes*, pp. 3-12.

6.1.3 Other Data Sources

In addition to the information extracted from the CII Benchmarking and Metrics database, information on the value of construction put in place, maintenance costs, repair costs, safety statistics, the book value and replacement cost of industrial facilities, and net income from manufacturing were needed. The focus of this subsection is on identifying the data sources for these key data items. How this information is used to develop estimates of benefits and cost savings in the industrial sector is described in detail in Subsection 6.3.1.

Data from the US Bureau of the Census

The value of construction put in place in the industrial sector is based on data published in the *Current Construction Reports* series *C30* publication (see Table 4-4 in Section 4.1) supplemented by information from the *1992 Census of the Construction Industry* (see Section 4.2). The *C30* publication provides an estimate of the value of new construction put in place ($32.4 billion in 1997). Information from the *1992 Census of the Construction Industry* is used to estimate the value of construction put in place for additions and alterations as a “fixed proportion” of expenditures for new construction. The resultant value for additions and alterations is $14.6 billion (measured in 1997 dollars). Thus, the value of construction put in place (i.e., new construction plus additions and alterations) for the industrial sector is $47.0 billion (measured in 1997 dollars).

The US Bureau of the Census also carries out a number of surveys that are specific to the industrial sector. Two of these surveys used in preparing this report are the *Census of Manufacturers* and the *Annual Survey of Manufacturers*.

The *Census of Manufacturers* provides detailed information on selected characteristics of the industrial sector. The survey is carried out every five years in years ending with 2 and 7; data are currently available for the 1992 Census. The *1992 Census of Manufacturers* includes all establishments with one paid employee or more, which are primarily engaged in manufacturing. This includes approximately 380,000 establishments. Manufacturing is defined as the mechanical or chemical transformation of substances or materials into new products. The assembly of component parts of products is also considered to be manufacturing. The *1992 Census of Manufacturers* covers 20 major industry groups with two-digit SIC codes 20 through 39 inclusive.

The *Annual Survey of Manufacturers* presents manufacturing establishments statistical data for years when the *Census of Manufacturers* is not carried out. It is a less detailed sample survey of establishments with payroll.

Two key data elements are obtained from the surveys. These data elements are the cost of purchased services for the repair of industrial facilities and other structures and the gross book value of industrial facilities and other structures. The first data element is a direct measure of annual repair costs for industrial facilities. It is used as the starting point for estimating potential annual repair cost savings due to the use of FIAPP products and services. The first data element is also used, in conjunction with data from the International Facilities Management Association, as the basis for estimating annual maintenance costs for industrial facilities. The second data element is used as the basis for estimating the replacement cost of industrial facilities, a term which is used as a deflator in the estimation procedure for placing a dollar value on potential increases in sales revenue due to early start-up (i.e., reductions in delivery time).

Data from the International Facilities Management Association

The International Facilities Management Association (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,[58] published in 1994 is the result of a 1993 survey of IFMA members. The report presents benchmarking data derived from 283 questionnaires. While the IFMA report presents summary data based on a relatively small sample size; it is one of the few reports which analyzes the relationship between maintenance and repair costs. In addition, the IFMA report contains information on both the mean values (i.e., average values) and the distribution (i.e., range of values and the ordering of these values) of each type of cost (i.e., repair costs and maintenance costs). This information may be used to develop a "weighting" factor for allocating aggregated costs into each of

[58] International Facilities Management Association. 1994. *Benchmarks II*. Research Report #13. Houston, TX: International Facilities Management Association.

the two cost categories. This factor is used to derive directly from Census data on the cost of purchased services for the repair of industrial facilities and other structures an estimate of annual maintenance costs for industrial facilities (see Section 4.2).

Data from the US Bureau of Labor Statistics

The US Bureau of Labor Statistics (BLS) disseminates data in a continuous series of annual releases from the BLS safety and health statistical series. The BLS *Survey of Occupational Injuries and Illnesses* provides data on injuries and illnesses that are derived from population samples. In cooperation with State agencies, BLS collects information from employers[59] on the number and incidence of nonfatal work-related injuries and illnesses. Each year the *Survey* provides estimates by industry and by State of the number of workplace injuries and illnesses, and also by the number of injuries and illnesses that involve lost work time. The average number of days away from work and the percent distribution of days away from work by industry are also given.

By recording the days away from work, the *Survey* provides a measure of the "seriousness" of injuries and illness. For workers with injuries and illnesses involving time away from work, the *Survey* estimates the number and percent distribution of injuries and illnesses by occupation, sex, age, race, and length of service. Numbers, percent distributions, and incidence rates are also calculated by detailed nature of injury and illness, part of body affected, source of the injury or illness, and type of event or exposure leading to the incident. Cross tabulations of the worker characteristics and injury/illness circumstances are also available. The median and percent distribution of days away from work are estimated for each worker and case characteristic.

BLS data on the recordable incidence rate (RIR) and the lost workday case incidence rate (LWCIR) are used to construct key trends in safety performance. Information on trends is necessary because safety performance in the construction industry has been improving over the last decade. Consequently, it is necessary to separate safety improvements due to industry-wide trends from improvements due to the use of FIAPP products and services.

US Internal Revenue Service

The US Internal Revenue Service (IRS) publishes financial data for all business enterprises. These data appear in the *Statistics of Income*, *Corporation Income Tax Returns*, and the *Statistics of Income Bulletin*. IRS data on net income[60] is used as one component in the estimation procedure for placing a dollar value on potential increases in sales revenue due to early start-up (i.e., reductions in delivery time).

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[59] Construction establishments with no employees (i.e., self-employed construction workers) are not covered by the *Survey*.

[60] Net income equals total taxable receipts less business deductions. Net income is before income tax.

6.2 Defining the Base Case and the FIAPP Alternative

The purpose of this section is to define the base case and the FIAPP alternative to the base case. This "definition step" is done to draw two key distinctions between the base case and the FIAPP 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 FIAPP products and services will be employed in both the construction of new industrial facilities and for the renovation of existing industrial facilities. Verification that the FIAPP products and services employed are performing "as stipulated" is done as part of a formal project execution process. If the FIAPP alternative is not chosen, the same process applies for industrial facilities employing the base case. Thus, for new industrial facilities, either the base case or the FIAPP alternative is employed during "grass roots" construction. Similarly, for existing industrial facilities, either the base case or the FIAPP alternative is employed while the facility is undergoing renovation.

Both the base case and the FIAPP alternative (i.e., both configurations) have features against which costs, savings, and performance are measured. These features include the equipment and software required for design, construction, and facility operations. It is important to recognize that both configurations must meet all facility-related performance requirements. This "performance requirement" constraint is needed to ensure that both configurations are reliable, serviceable, safe, and at a minimum, neutral with regard to design aesthetics.[61] The performance requirement applies both to either configuration employed during the construction of a new industrial facility and to either configuration employed during the renovation of an existing industrial facility.

Throughout the remainder of this report, the term base case is used to represent the configuration that maintains the *status quo* (i.e., the "average" use of traditional design, information, and construction technologies). The FIAPP 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 FIAPP given in Section 3.1.

Based on the definitions of the base case and the FIAPP alternative, there are two key differences between the two configurations. First, the degree to which construction activities (e.g., materials management) and facility service features (e.g., maintenance and repair procedures) are integrated, automated, and controlled is significantly higher in the FIAPP alternative. The second difference is that the FIAPP alternative has the potential to achieve enhanced performance for selected construction activities (see Table 6-1) and facility service features (see Subsection 6.3.1.2). These differences, although

[61] 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).

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., reductions in construction-related accidents and maintenance and repair cost savings due to the availability of electronic "as-built" information) between the two configurations. Quantitative measures of these differences are developed in Section 6.3.

6.3 Estimating Significant FIAPP-Related Benefits and Costs

This section develops estimates of the key benefits and costs that are the focus of the CONSiAT 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 FIAPP products and services. Similarly, considerable effort went into documenting and estimating BFRL's CONSiAT-related investments. Relatively less effort went into estimating the full range of FIAPP-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 CONSiAT-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 CONSiAT-related investments).

6.3.1 Benefits and Cost Savings

The enhanced performance of the FIAPP alternative *vis-à-vis* the base case produces five types of benefits and cost savings. These benefits and cost savings are: (1) lower first costs; (2) lower maintenance and repair costs; (3) fewer construction-related accidents; (4) reductions in delivery time; and (5) higher net income. Lower first costs are registered through a reduction in a typical industrial sector project's total installed costs (i.e., all project-related costs with the exception of land costs). Lower maintenance and repair costs are registered through reductions in future costs. Lower first costs and lower maintenance and repair costs, as measured in this study, accrue to facility owners and operators. Fewer construction-related accidents are registered through reductions in direct jobsite costs (e.g., medical costs), indirect jobsite costs (e.g., lost productivity of the crew due to the accident), and liability costs (e.g., claims costs). Reductions in delivery time are registered through increased opportunities for product sales. Higher net income is registered through the contractor's increased capability to control cost growth during the project delivery process. The first three types listed—lower first costs, lower maintenance and repair costs, and fewer construction-related accidents—are readily classified as cost savings. Reductions in delivery time are classified as a benefit, rather than as cost savings, because they create the potential for increased sales revenues due to earlier start-up of production operations. Higher net income is classified as a benefit because it increases the contractor's profit margin.

Although the FIAPP alternative is expected to result in fewer/shorter interruptions of process operations due to facility-related problems (e.g., faster turnarounds due to the availability of electronic "as-built" information), no estimates of these, potentially significant, benefits and cost savings are included in the current CONSiAT economic impact assessment. Although subject matter experts have reached consensus on the generic types of benefits and cost savings due to fewer/shorter interruptions of process operations (see Table 5-3 in Section 5.2), no such consensus emerged on how to quantify these benefits and cost savings. 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 and cost savings due to fewer/shorter interruptions of process operations are not included in this assessment, the costs of installing, operating, and maintaining the equipment and software required to achieve these benefits and cost savings are included. This decision was made to maintain the conservative approach of the CONSiAT economic impact assessment.

6.3.1.1 Reduced First Costs

Information compiled from the CII Benchmarking and Metrics database was used to establish values both for reductions in project cost growth and reductions in construction cost growth (see Table 6-1). These reductions were 1.4 % for project cost growth and 4.5 % for construction cost growth. The data used to compute both sets of reductions are from owner projects only. This is because owners bear the full cost of the project, including the contractor's profit margin. This approach ensures that any reductions in first costs are modeled independently from contractor project data.

The value used in the CONSiAT economic impact assessment is based on the 1.4 % reduction in project cost growth. There are two reasons for selecting this value. First, it is more conservative than the 4.5 % reduction in construction cost growth. Thus, it is more in keeping with the conservative approach employed in this impact assessment. Second, the definition of the project cost growth metric makes use of both actual total project cost and initial predicted project cost. Recall that actual total project cost equals the project's total installed cost at turnover to the user (excluding land costs) and initial predicted project cost equals the project's budget at the start of detailed design.

The project cost growth metric, as defined by CII, may be used as an estimator of the percent reduction in total installed cost due to the use of FIAPP products and services.[62] Therefore, the use of FIAPP products and services is estimated to reduce total installed costs for a typical industrial sector project vis-à-vis the base case by 1.4 %.

[62] Consider the case where all base case projects and FIAPP alternative projects have the same initial predicted project cost. In this case, all differences in project cost growth are due to differences in total installed cost. Thus, a 1.4 % reduction in project cost growth between the set of FIAPP alternative projects and the set of base case projects results in a 1.4 % reduction in total installed costs for the FIAPP alternative vis-à-vis the base case.

The 1.4 % reduction in total installed cost employed in this impact assessment is considered very conservative (i.e., cost reductions due to the use of the FIAPP alternative are likely to be significantly higher). The basis for the previous statement is due to a CII study on the impacts of information management in the engineer-procure-construct (EPC) process.[63] The CII study of the EPC process used an activity-based costing approach, coupled with Monte Carlo simulation, to quantify the benefits of employing traditional methods of information management on EPC projects. The study concluded "aggressive information management strategies for design related activities may yield as much as 10 percent improvement in total elapsed time (calendar time) required to fully execute a typical EPC process. These same strategies will most likely yield a reduction in overall labor costs of approximately two to three percent. Similarly, aggressive information management strategies for materials management related activities may yield as much as three percent reduction in elapsed time and seven percent reduction in execution costs. When combined, aggressive information management strategies may result in reductions as much as 14 percent for elapsed time and eight percent for execution costs."[64]

It is important to note that not all industrial sector projects will employ the FIAPP alternative. Thus, the 1.4 % reduction in first costs will only accrue to those industrial sector projects which actually employ the FIAPP alternative. Information on the annual proportion of industrial sector construction-related investments (i.e., expenditures for new construction projects and for facility renovation projects) that employ the FIAPP alternative are based on the diffusion model (see Subsection 6.4.4). Annual estimates showing how reductions in first costs contribute to cost savings nationwide are given in Section 7.2, where all key components are laid out in a spreadsheet format.

6.3.1.2 Reduced Maintenance and Repair Costs

FIAPP products and services will lower the costs of maintaining and repairing industrial facilities. How much these costs are reduced depends on a number of factors, such as, the ability to maintain electronic "as built" information in a form that will save time in troubleshooting maintenance problems, the ability to make available online information on the facility's characteristics to promote the use of fact-based maintenance programs, and the ability to use electronic data interchange to promote faster delivery of "out-of-stock" parts. The use of selected FIAPP products and services during the post "start-up" phase of the project life cycle will allow facility support systems and equipment to operate and be maintained under near optimal conditions for extended periods of time. As a result, equipment life will be extended, fewer replacements will be required, and replacement costs will decline.

To develop a range of estimates for annual maintenance and repair cost savings, industry experts and facility managers and operators were interviewed. The general consensus was that the use of selected FIAPP products and services during the post start-up phase

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[63] Construction Industry Institute. 1998. *Cost and Schedule Impacts of Information Management*. Research Summary 125-1. Austin, TX: Construction Industry Institute.
[64] *Ibid*. p. 11.

would enable both smaller crew sizes and the ability to handle more facility-related service requests with a given size of maintenance staff. To a certain extent, some potential maintenance and repair cost savings would be offset by expenditures for training for the facility's maintenance staff. However, once trained, maintenance staff can be more easily moved from one "FIAPP" location to another—a potential cost saving. Finally, the facility owner/operator would incur costs to maintain an "up-to-date" set of electronic "as built" information. Since these costs are expected to rise over time, they tend to "degrade" out year cost savings. Based on these inputs, maintenance and repair cost savings were estimated to range from 5 to 15 %. This range of values is considered very conservative (i.e., savings are likely to be greater), since a previous study focusing on a subset of the FIAPP suite of technologies produced the same range of values.[65] This range of values is used to specify the range of values for maintenance and repair cost savings in the sensitivity analysis (see Chapter 8). The baseline value for annual maintenance and repair cost savings used in the economic impact assessment is 10 %. Because these cost savings are expected to degrade over time, they are reduced by 10 % per year following their installation.

To estimate how much annual maintenance and repair costs will be reduced, we begin with Census data and information from IFMA (see Subsection 6.1.3) to derive an estimate of annual maintenance and repair expenditures for the industrial sector. The resultant figure is $10.2 billion (in 1997 dollars). In reality, only a small portion of the industrial sector total for maintenance and repair expenditures can be saved through the use of selected FIAPP products and services. This is because the $10.2 billion figure is for all facilities in the industrial sector, whereas FIAPP products and services are only employed in a fraction of each year's construction-related investments (see Subsection 6.4.4). In addition, reductions in maintenance and repair costs normally do not occur in the same year in which the capital investment is made, as is the case for reductions in first costs. To address these issues, this study assumes: (1) savings accrue only to that proportion of the industrial sector that previously employed FIAPP products and services; and (2) no FIAPP-related savings in maintenance and repair costs occur in the year in which the capital investment is made. Thus, the proportion of the industrial sector's stock of facilities that has employed FIAPP products and services will rise gradually over time, creating an opportunity for growth in savings. Similarly, for each year's set of capital investments that employ FIAPP products and services, all FIAPP-related savings in maintenance and repair costs occur in the future. Annual estimates showing how reductions in maintenance and repair costs contribute to cost savings nationwide are given in Section 7.2, where all key components are laid out in a spreadsheet format.

[65] Van Tienhoven, C. J. 1996. *The Benefits of STEP*. Report No. IS96-014. The Hague: Shell Information Services.

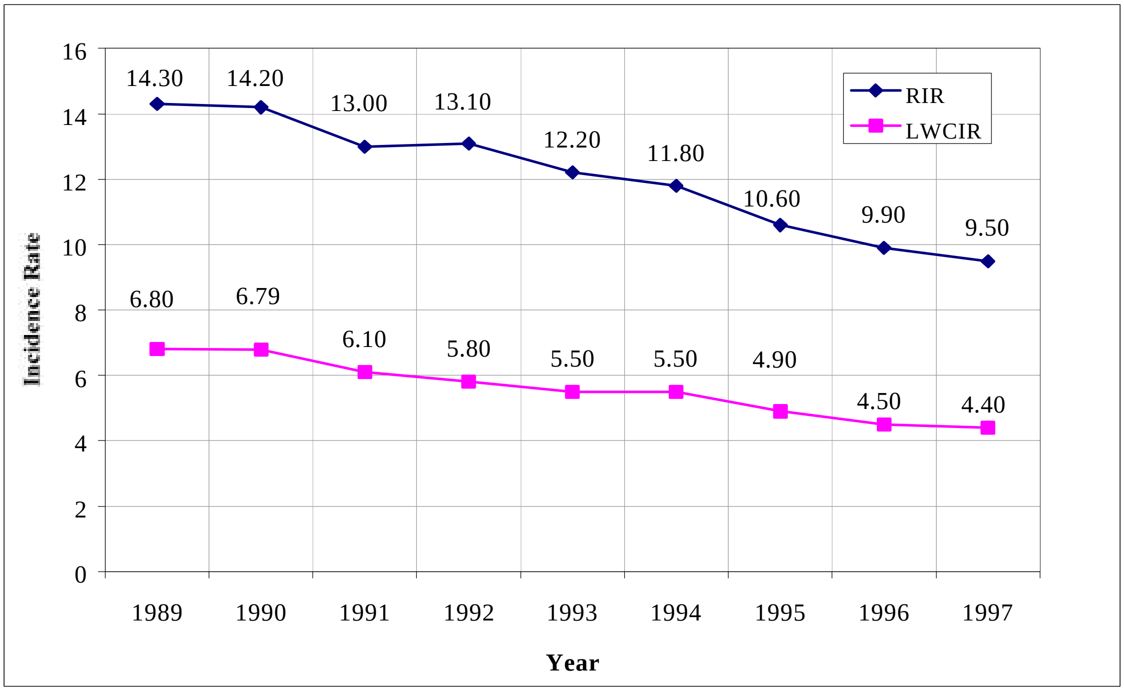
6.3.1.3 Reductions in Construction-Related Accidents

Information compiled from the CII Benchmarking and Metrics database (see Table 6-1) was used to establish the baseline values both for reductions in the recordable incidence rate (RIR) and the lost workday case incidence rate (LWCIR). These reductions were 0.745 for the RIR and 0.347 for the LWCIR. Because the RIR also includes cases which result in lost workdays (i.e., are included in the LWCIR calculation), it is necessary to "net out" the LWCIR to achieve a number which corresponds to cases without lost workdays. The resultant figure is 0.398 (i.e., 0.745 minus 0.347); it is used as the baseline value for reductions in construction-related accidents that do not result in any lost workdays. This newly defined term is referred to as the "net" RIR.

The incidence rate for construction-related accidents has been declining in recent years. Figure 6-5 shows that both the RIR and the LWCIR have declined between 1989 and 1997. During this period, the RIR has declined from 14.3 to 9.5, a compound rate of improvement of 5.25 % per annum. During the same period, the LWCIR has declined from 6.8 to 4.4, a compound rate of improvement of 5.6 %. Because these industry-wide trends are delivering improved safety performance, any measures of "improved" safety performance due to FIAPP products and services must incorporate these trends into its analysis of cost savings. The approach employed in this impact assessment (see Section 7.2) makes explicit these industry-wide trends. This is done by reducing the 0.398 figure for improvements in the "net" RIR by 5.25 % for each year beginning in 1998 and the 0.347 figure for improvements in the LWCIR by 5.6 % for each year beginning in 1998.

It is important to recognize that the reductions in construction-related accidents due to the FIAPP alternative are likely to be higher than the "absolute" measured performance improvement of the "net" RIR value of 0.398 and the LWCIR value of 0.347 resulting from the projects in the CII Benchmarking and Metrics database. This is because the "percentage" improvement in the computed value of the RIR is more than 30 % (compare Columns 3 and 1 of Table 6-1 for the RIR) and the improvement in the computed value of the LWCIR is nearly 60 % (compare Columns 3 and 1 of Table 6-1 for the LWCIR). If these improvement figures are applied to the data recorded in Figure 6-5, the reductions in the RIR and LWCIR, and hence the "net" RIR, would be much greater. The reason for the differences is due to the superior safety performance of CII member organizations. Once again, the conservative approach to estimating benefits and cost savings employed in this impact assessment caused us to choose the lower values as the basis for computing cost savings due to reductions in construction-related accidents under the FIAPP alternative.

Figure 6-5. Recordable Incidence Rate and Lost Workday Case Incidence Rate for Years 1989-1997



Information on the costs of construction-related accidents is needed to translate the baseline values for reductions in the "net" RIR and the LWCIR into dollar terms. Two studies which provide detailed information on the costs of construction-related accidents are *Design for Safety*[66] and Hinze and Applegate's survey article.[67] Data compiled from these studies and updated to 1997 dollars are summarized in Table 6-2. The table separates accident costs into three categories: (1) direct jobsite costs; (2) indirect jobsite costs; and (3) estimated liability costs. Direct jobsite costs include the medical costs for the injured worker and several incidental items. Direct jobsite costs are covered by worker's compensation insurance. Indirect jobsite costs include the lost productivity of the crew due to the accident, the additional cost of a replacement worker, time expended to complete forms related to the injury, and the cost for damage to materials and equipment. Liability costs are associated with any claims related to the injury. Claims costs can vary considerably. Hinze and Applegate calculated that claims costs are often 10 to 20 times the dollar value of direct jobsite costs for lost workday cases.[68] The figures recorded in Table 6-2 are on the low end of the recommended ratios given in Hinze and Applegate. Thus, any FIAPP-related cost savings due to improved safety performance are likely to be very conservative.

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[66] Construction Industry Institute. 1996. *Design for Safety*. Research Summary 101-1. Austin, TX: Construction Industry Institute.

[67] Hinze, J., and L. Applegate. 1991. "Costs of Construction Accidents," *Journal of Construction Engineering and Management*, Vol. 117, No. 3, pp. 537-550.

[68] *Ibid*. pp. 544-545.

Table 6-2. Average Costs of Construction Site Injuries: 1997

Type of Injury	Job Costs		Estimated Liability Costs	***Total Cost to Employer***
	Direct	Indirect		
No Lost Workdays	$650	$550	$300	$1,500
Lost Workday	$8,700	$2,000	$20,800	$31,500

Reference to Table 6-2 reveals that the total cost to the employer of a lost workday case is about 20 times higher than an accident which does not result in a lost workday (i.e., $31,500 versus $1,500). Cost savings due to reductions in construction-related accidents accrue both to industrial facility owners and to contractors engaged in the construction of those facilities. Annual estimates showing how reductions in construction-related accidents contribute to cost savings nationwide are given in Section 7.2.

6.3.1.4 Reductions in Delivery Time

Information compiled from the CII Benchmarking and Metrics database was used to establish the values for reductions in delivery time. These values were 16 weeks for total project duration and 8 weeks for construction phase duration. The data used to compute both sets of reductions are from owner projects only. This is because owners participate in all phases of the project delivery process.

The value used in the CONSiAT economic impact assessment is based on the figure for reductions in the duration of the construction phase rather than for reductions in total project duration. The decision to use the 8 week figure for reductions in delivery time was motivated by a desire to maintain a conservative approach to estimating FIAPP-related benefits.

A company’s desire to reduce delivery time is driven by the potential for increased sales of its products in the marketplace. In the case of new products, getting to the marketplace before the competition may translate into a substantial gain in market share for that company’s line of products. Because companies are assumed to be profit maximizers, reductions in delivery time offer the potential to increase profits. Therefore, to place a value on reductions in delivery time, it is necessary to employ a metric that closely approximates the profitability of the industrial sector. The “profitability” metric employed in this study is net income. This study uses net income, rather than business receipts or value added, because it best reflects profitability in the industrial sector. In addition, net income results in a more conservative estimate of the value of reductions in delivery time. The Internal Revenue Service publishes annual estimates of net income for the industrial sector (i.e., manufacturing). These estimates are used to translate reductions in delivery time into a dollar denominated value.

FIAPP-related reductions in delivery time in any one year only affect a small proportion of the industrial sector's output. This study models this outcome in two stages. First, the "maximum potential" proportion is set equal to the ratio of the total value of industrial facilities put in place in any given year and the replacement cost of the nation's stock of industrial facilities.[69] The maximum potential proportion is estimated to be 0.031; it is assumed to decline at a rate of 2.3 % throughout the study period. The decline is due to growth in the industrial sector's gross stock of fixed private capital.[70] Second, the proportion of the total value of industrial facilities put in place that employ the FIAPP alternative in any given year is estimated via the diffusion model (see Subsection 6.4.4). Because the diffusion model captures how FIAPP products and services move into the marketplace, the proportion of the industrial sector's projects employing FIAPP products and services increases over time.

To complete the calculation, an additional data item is needed, an estimate of the value of a week's reduction in delivery time to the industrial sector. Recall that the CII Benchmarking and Metrics database provides an estimate of the expected number of weeks reduction (i.e., 8 weeks) associated with the FIAPP alternative. The value of a week's reduction in delivery time is estimated by dividing the industrial sector's net income figure for 1997[71] (i.e., $288.5 billion) by 52, the number of weeks in a year. The resultant figure is $5,548 million (in 1997 dollars). Each year's net income figure, expressed in 1997 dollars, is held constant throughout the study period. This assumption is very conservative because net income has tended to increase over time. The net income figure is multiplied by each of the two proportions described above to estimate benefits nationwide due to reductions in delivery time (see Section 7.2).

6.3.1.5 Higher Net Income for Contractors

Information compiled from the CII Benchmarking and Metrics database and *Statistics of Income* from the Internal Revenue Service was used as the basis for estimating higher net income for contractors. Because higher net income serves to increase a contractor's profit margin, only data from contractor projects are used. This approach ensures that any improvements in contractor performance are modeled independently from owner project data. In this way, improvements in contractor performance, say due to better cost control stemming from process improvements and increased productivity, result in

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[69] Replacement cost is estimated as the industrial sector's gross stock of fixed private capital facilities and structures (see U.S. Bureau of Economic Analysis, *Survey of Current Business*, September 1995). Due to changes in reporting (e.g., net versus gross figures) for the industrial sector's stock of fixed private capital, the 1997 estimate was based on 1994 data rather than on later data. The data from 1994 was updated to 1997 to estimate the industrial sector's gross stock of fixed private capital facilities and structures in 1997.

[70] The annual rate of growth in the industrial sector's gross stock of fixed private capital facilities and structures is based on time-series data (expressed in 1987 dollars) between 1980 and 1994 (see U.S. Bureau of the Census, *Statistical Abstract of the United States: 1997*, p. 554).

[71] The actual net income figure for 1997 was not available at the time this study was being conducted. Consequently, the most recent figure that was available (i.e., 1995) was converted to 1997 dollars and used as an estimate for the 1997 net income figure.

improvements in profits to contractors rather than reductions in total installed cost to the owner.

Contractor data from the CII Benchmarking and Metrics database was used to construct a budget factor. The budget factor, as defined by CII, tracks deviations between the contractor's cost estimate used as the basis for the contract award for the proposed scope of work and the contractor's total cost for the final scope of work. Since changes in the scope of work sometimes occur, the CII budget metric explicitly accounts for owner-authorized changes. Because the contractor's margin enters as a multiplicative factor, resulting in the contract award amount, reductions in the calculated value of the budget factor increase the contractor's profit margin (i.e., their costs were lower than those upon which the contract award was based). Conversely, increases in the calculated value of the budget factor reduce the contractor's profit margin. Analyses of data for CII contractors performing both design and construction tasks resulted in an average improvement of 0.013 for the computed value of the budget factor metric.[72] This metric's performance improvement translates into an improvement of at least 1.3 % in the contractor's profit margin.

In order to estimate a value for higher net income, it is first necessary to factor out an estimate of the contractor's profit margin from the value of construction put in place. This is accomplished by dividing the net income figure for the construction industry by the value of construction put in place. Based on net income figures from the most recent years available from the *Statistics of Income*, an average profit margin of less than 5 % can be expected. Note that this figure encompasses the entire construction industry (e.g., it contains the residential sector where many firms are sole proprietorships or partnerships). According to industry experts, profit margins for the non-residential sectors of the construction industry (i.e., where most firms are corporations) tend to be very tight. This is borne out by the proportion of construction industry net income due to corporations (i.e., 0.3 to 0.4) versus sole proprietorships and partnerships. Thus, an assumed profit margin of 5 % can be considered to be on the high side for the average industrial sector contractor. In keeping with the conservative approach of this economic impact assessment, the base against which higher net income is computed is estimated as the value of construction put in place divided by 1.05. Annual estimates of higher net income nationwide are given in Section 7.2.

6.3.2 Cost Increases and Benefit Reductions

Two types of costs—new-technology introduction costs and increased research and development costs—are central to this economic impact assessment. The first type of costs, new-technology introduction costs, result in higher costs to industrial facility owners and managers and to contractors. Understanding the types of costs that affect industrial facility owners, managers, and contractors 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 CONSiAT-

[72] Thomas, *Impacts of Design/Information Technology on Project Outcomes*, p. 11.

related investments as well. The second type of costs, increased research and development costs, focuses only on BFRL's CONSiAT-related investments. No estimates of the investments required to develop, test, and market FIAPP products and services by the vendor tier (see Figure 3-2) 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 New-Technology Introduction Costs

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

These three costs may be classified as new-technology introduction costs. Ehlen and Marshall[73] 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, the technology enters full implementation, and its application has become routine.[74]

The establishment of the Virtual FIAPP Testbed will enable manufacturers to bring actual products and equipment that they have under development, obtain assistance in testing and evaluating their performance, and perform interoperability tests with other manufacturers. Thus, higher costs in the form of new-technology introduction costs 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 equal to 0.5 % of total installed cost is assigned when an industrial facility construction project employs the FIAPP alternative. Discussions with industry experts were used to specify a very conservative value (i.e., high value) for this additional cost. As more information becomes available, the estimated value of 0.5 % of total installed cost will be revised (see Section 9.2).

6.3.2.2 Increased Research and Development Costs

BFRL launched a multidisciplinary CONSiAT research effort in Fiscal Year (FY) 1998. This effort and the seven projects that support the overall CONSiAT effort are described in Chapter 3. Because FIAPP products and services are targeted for demonstration in

[73] 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.
[74] *Ibid.*, p. 15.

2004 and commercial availability in 2005, BFRL's highest level of investment is for FY2004 through FY2006. Beginning in FY2007, BFRL's CONSiAT-related investments will decline rapidly. Beginning in 2010, BFRL moves out of the CONSiAT major product and into a long-term basic and applied research mode. Consequently, these costs are not considered part of the CONSiAT impact assessment. By 2010, BFRL's research in this area has returned to its long-term base level of funding of $2,200,000.

It is also important to recognize that BFRL's research on the application of the ISO's Standard for the Exchange of Product (STEP) model data for the process plant industries was crucial to the establishment of its overall CONSiAT effort. Consequently, BFRL's STEP-related investments between FY1994 and FY1997 are included as part of its CONSiAT-related investments. FY1994 was chosen as the starting point, since by that time BFRL's STEP-related research had reached a high-level of maturity.

BFRL's CONSiAT-related investments are summarized in Table 6-3. The first two columns of the table record *actual investments* by Fiscal Year in thousands of dollars for Fiscal Years FY1994 through FY1999 and *estimated investments* for FY2000 and FY2001. The second two columns of the table record *estimated investments* by Fiscal Year in thousands of dollars for Fiscal Years FY2002 through FY2009. Note that all values recorded in Table 6-3 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 FY2001 investment is $2,500,000. Of the $2,500,000 total, 25 %, or $625,000, is allocated to calendar year 2000, and 75 %, or $1,875,000, is allocated to calendar year 2001.

Table 6-3. BFRL Investment Costs by Fiscal Year

Fiscal Year 1994 – 2001	BFRL Investment Costs (In $K)	Fiscal Year 2002 - 2009	BFRL Estimated Investment Costs (In $K)
1994	1,326[a]	2002	3,000
1995	1,507[a]	2003	3,500
1996	1,487[a]	2004	4,000
1997	1,733[a]	2005	4,000
1998	2,344[a]	2006	4,000
1999	2,018[a]	2007	3,500
2000	2,105[e]	2008	3,000
2001	2,500[e]	2009	2,500

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 FIAPP 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 FIAPP 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 potential cost savings (see Subsection 6.3.1) and cost savings nationwide (see Section 7.2). The model of the diffusion process presented in Subsection 6.4.4 provides the basis for calculating year-by-year savings following the introduction of FIAPP products and services. Because BFRL's CONSiAT-related research is expected to speed up the introduction of FIAPP products and services into the commercial marketplace, a process for evaluating the "value" of BFRL's contribution is needed. This process is described in Subsection 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 provide the necessary "direct" 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 Subsection 6.4.5.

6.4.1 Base Year for Computing Benefits and Costs

The base year for computing all FIAPP-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 CONSiAT project team. BFRL is working towards a prototype suite of FIAPP systems and technologies being tested and deployed in a full-scale demonstration project by 2004. 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.

6.4.2 Length of the Study Period

The study period begins in 1993 and ends in 2017. Thus, the length of the study period is 25 years. Any costs and/or savings that occur after 2017 are not included. Two factors were instrumental in determining the beginning and end of the study period.

(1) The study period begins in 1993, which is when BFRL launched its research on the application of ISO's Standard for the Exchange of Product (STEP) model data for the process plant industries. BFRL's research in this area was instrumental in the creation of PlantSTEP, Inc. in December 1994.[75] However, major investments in the overall CONSiAT effort did not begin until 1997, when BFRL formed an integrated CONSiAT project team. BFRL's CONSiAT-related investments will continue at a fairly high level until 2007, at which point they will rapidly decline.

(2) The end of the study period is 2017. By 2004, BFRL will be completing a full-scale demonstration project. By 2005, the first commercial applications of FIAPP products and services are anticipated (i.e., applications other than in demonstration projects). Thus, 2005 marks the point at which FIAPP products and services penetrate the commercial marketplace. By 2017, the use of FIAPP products and services is expected to be widespread (i.e., at least 50 % of the potential commercial marketplace will have been penetrated).

6.4.3 Discount Rate

The baseline analysis for the CONSiAT economic impact assessment uses a real rate of 7 % to convert dollar amounts to present values. This rate is specified in Section 8.b of *OMB Circular A-94*[76] as the rate for all benefit-cost analyses of public investments and regulatory programs that provide benefits or incur costs to the general public. The use of a 7 % real discount rate also facilitates comparisons of the results of the CONSiAT baseline analysis with the results of the baseline analyses of the previous economic

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[75] PlantSTEP is an industrial consortium of companies that own, design, build, operate, and maintain process plants and companies that supply equipment, materials, and information technology for the process and construction industries. The primary focus of PlantSTEP is to develop and support implementation of data exchange standards based on STEP.

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

impact assessments. For purposes of this analysis, all CONSiAT-related research costs are classified as a public investment. The benefits that accrue to the public are in the form of cost savings and increased sales revenues due to reductions in delivery time.

OMB recommends that separate analyses be used to evaluate the sensitivity of key economic measures to variations in the discount rate.[77] The sensitivity analysis presented in Chapter 8 evaluates the implications of raising the discount rate to 10 % or lowering the discount rate to 2 %. The 2 % to 10 % range of values for the real discount rate was chosen to bracket the historical values of real treasury interest rates. These rates are periodically updated by OMB and published in Appendix C of *OMB Circular A-94*; they apply to government lease-purchase and cost-effectiveness analyses. Although these rates do not apply to regulatory analyses or benefit-cost analyses of public investments, they provide a useful frame of reference for establishing minimum and maximum values for the real discount rate. All values of the discount rate used in this report are real rates, since constant dollar estimates of benefits and costs are used.

6.4.4 Diffusion Process

Facts and data are essential components in any rigorous analysis. Factual information on the industrial sector was tabulated from published sources (see Section 4.2). These data provide the basis for estimating the "potential" benefits and cost savings associated with the use of the FIAPP products and services in industrial facilities (see Subsection 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 FIAPP products and services in industrial facilities; (2) the annual proportion of industrial facilities employing FIAPP products and services for new construction activities and for additions and alterations; and (3) the cumulative proportion of industrial facilities covered by FIAPP products and services. To generate estimates of cost savings nationwide, information on potential benefits and cost savings must be coupled with a model of the diffusion process. Much of the discussion in this subsection 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 subsection 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

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[77] *Ibid*., p. 7.

diffusion process are worth noting. Readers interested in thorough treatments of this important subject, including case studies, are referred to the books by Stoneman[78] and Mansfield.[79]

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 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 CONSiAT 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,

a = the location parameter, and

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

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

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 % 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 h 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

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

h = the market saturation level,

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

a = the location parameter, and

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

An extensive review of the economics literature on the diffusion process produced candidate values for a and b. Readers interested in case studies based on the Mansfield model that are useful in specifying values for a and b are referred to Mansfield's collection of articles.[80] An additional factor used to specify the values of a and b is the length of time it takes for $P_h(t)$ to reach 50 % of its potential market. Due to the relationship between the Mansfield model and the logistics distribution, the value at which $P_h(t)$ reaches 50 % of its potential market has a closed-form relationship based solely on the values of a and b. If we assume $t = 1$ is the time at which the technology is first introduced, then a/b is the number of years it takes that technology to reach 50 % of its potential market. In order to get a meaningful value of t, it is necessary to constrain a to be positive (i.e., $a > 0$).

The values of the ratio a/b vary from 4 years to 16 years in a wide range of articles published in the economics literature (see Mansfield,[81] Mansfield *et al*,[82] and Simon[83]).

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[80] Mansfield, *Innovation, Technology and the Economy*, Vol. II, pp. 3-83.
[81] *Ibid*., pp. 63-72.
[82] 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.

Consequently, this report uses a value of *8* for the ratio a/b as its baseline value. The corresponding baseline values for a and b are *4.0* and *0.5*, respectively.

The estimated value for h was set equal to 0.5. Thus, the baseline value for h is *0.5*. This means that FIAPP products and services will eventually be employed in projects totaling 50 % of the value of construction put in place in the industrial sector. From the discussion that follows, it should be clear that this estimate is rather conservative. Thus, the estimated savings nationwide and the value of BFRL's contribution may be considered to be lower bound estimates.

Penetration of the market by FIAPP products and services for industrial sector projects will be driven by two mutually reinforcing factors. These factors are: (1) the desire of manufacturers (i.e., the owners of industrial facilities) to use information technology as a tool for reducing both costs and cycle time; and (2) the need for contractors to improve their productivity and profitability in an increasingly competitive global marketplace.

The owners of industrial facilities have a tremendous incentive to improve the delivery process for construction projects. This point is underscored by a Business Roundtable report that summarizes data on over 60 major companies' project systems.[84] When examining the relative performance of these systems, some important trends appear.

"The best company transforms a 15 % return on investment (ROI) project, based on average performance, into a 22.5 % ROI project. In contrast, the poorest performers turn that same project into a 9 % ROI.

"Most important from a business perspective, the gap between the best and the worst has widened over the past several years. Some companies have learned how to acquire consistent and significant comparative advantages from their capital project systems, while others find themselves increasingly at a disadvantage. ...

"In relative cost performance, the best company is spending 72 cents of the industry average dollar for the same functional scope. The fastest company takes only 70 % as long as the industry average to bring a project from a business idea to a facility in production. The company with the best track record in starting up and getting on-spec product from new facilities achieves 6 % more product from facilities than the industry average.

"When these three performance factors are combined, an astounding 10 % improvement in ROI can be achieved. This means that based on extraordinary project performance, a 15 % ROI project can be transformed into a 25 % ROI winner.

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[83] Simon, P. 1975. *Models of Process Diffusion and Entry in the U.S. Chemical Industry*. Ph.D. dissertation, University of Pennsylvania.
[84] The Business Roundtable. 1997. *The Business Stake in Effective Project Systems*. Washington, DC: The Business Roundtable.

"However, one company is actually achieving 75 % of that possible gain. Several others are achieving substantial boosts in ROI just by the manner in which they organize and execute their project work. Conversely, some major U.S. manufacturers are doing projects so poorly they regularly transform an average 15 % ROI project into a 9 % project.'' [85]

These same themes—reduced costs and shorter cycle times—resonate with a key subset of the industrial sector, chemical manufacturers. The American Chemical Society's *Technology Vision 2020* [86] identifies two distinct areas that are targeted for significant performance improvement—areas that will benefit from FIAPP products and services. These areas are: (1) supply chain management; and (2) engineering design and construction. It is important to note that the goals set forth in *Technology Vision 2020* have been endorsed by a broad cross section of the U.S. chemical industry. For example, key organizational players involved in the production of *Technology Vision 2020* were the American Chemical Society, the American Institute of Chemical Engineers, the Chemical Manufacturers Association, the Council for Chemical Research, and the Synthetic Organic Chemical Manufacturers Association. Thus, one can conclude that chemical manufacturers represent a focused and motivated market for FIAPP products and services.

While the chemical industry has concentrated on science and production, an area that has received less attention than it merits is that of the supply chain. The supply chain is defined as the critical linkages between the supplier and the producer, and the producer and the customer. Thus, the delivery process for construction projects is a key component of the supply chain. As the chemical industry becomes increasingly global, issues related to the supply chain are increasingly critical to industrial competitiveness.

Today, many estimate that the costs associated with supply chain issues represent about 10 % of the sales value of delivered products domestically and as much as 40 % internationally.[87] Clearly, this represents an area of opportunity for increasing competitiveness.

The American Chemical Society's *Technology Vision 2020* has a goal that "the supply chain functions will operate in an environment of seamless coordination of orders, production, and distribution across countries and continents." [88] To achieve this vision, the chemical industry plans to sponsor an effort to drive information systems toward harmonized communications, data transmission, and information processing in support of global supply chain activities.

The revenue-generating capability of the chemical industry is derived from its ability to deliver chemicals and materials that satisfy customers' needs in a timely and cost-

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[85] *Ibid*. pp. 2-3.
[86] American Chemical Society. 1996. *Technology Vision 2020*. Washington, DC: American Chemical Society.
[87] *Ibid*. p. 39.
[88] *Ibid*. p.41.

effective manner. Consequently, maintaining and improving the competitiveness of the U.S. chemical industry will require advances in engineering design and construction.

"The building of new plants continues to be in a state of change. Improvements will result from both innovations and the better application of old technologies. Future conditions will cause this change to continue. (1) Owners will often partner with the engineering firms, construction companies, and major equipment suppliers when building new plants. (2) Standard, prefabricated modular components designed for industry-wide requirements will be increasingly used. (3) Pressure to shorten the time needed to design and build a plant will force significant change in the way this process is carried out. (4) The design of a plant will be done globally to minimize the cost. (5) The use of electronic footprints of existing plants will enable plant designs to be done more quickly.

"Plants will need to be designed and built in a much shorter time. Technology is needed to automate the design process through modular concepts in easy-to-use software. In addition, compatible communications systems between major equipment suppliers and their design firms will allow for rapid translation of concepts into innovative plant structures. Partnering is required to get adequate response from the supplier to cut the building time. Dynamic simulation will allow for integrated design with verification of structural integrity. This will shorten start-up time and eliminate overdesign."[89]

Contractors who wish to survive and prosper will be pushed to employ design and information (i.e., FIAPP-like) technologies from two sources. First, industrial facility owners will increasingly demand the use of these technologies as a requirement for partnering (i.e., owners are committed to the use of these technologies both in their manufacturing processes and in their supply chain management process). This point was discussed previously from the owner's perspective and will not be explored further here. Second, contractors have experienced a significant, sustained decline in productivity vis-à-vis the rest of the economy.[90] This decline in productivity has adversely affected profitability, causing profit margins to shrink. Thus, contractors see the use of FIAPP products and services as a competitive edge for their business, enabling them to both increase net income and reduce project duration. The former directly impacts profitability, whereas the latter creates the opportunity for a greater volume of work.

Because large contractors dominate the markets for engineering design and construction of industrial facilities, their adoption and use of FIAPP products and services are likely to be both rapid and extensive. The basis for the previous statement may be seen by noting that the top 10 contractors in 1997 installed $23.7 billion worth of industrial sector projects.[91] Although these figures represent global revenues, a significant share of these industrial sector projects was domestic.

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

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[89] *Ibid*. p.60.
[90] Teicholz, Paul M. "Reverse Productivity Declines," *ENR*, Vol. 243, No. 23, December 13, 1999, p. 59.
[91] Tulacz, Gary J. "Top 400 Contractors," *ENR Sourcebook*, November 1998, pp. 4-10.

value at which $t = 1$. The baseline value for the time of first use is based on the assumption that the demonstration project will be completed in 2004. Once the demonstration project has been completed, FIAPP products and services will become available commercially. Thus, the baseline value for the *time of first use* is *2005*.

The values of a and b specify the rate of adoption of FIAPP products and services in industrial facilities, whereas the value of h 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 annual proportion of construction-related expenditures in the industrial sector covered by FIAPP products and services. For any given year, this amount is equal to the product of $P_h(t)$ for that year and the total value of construction-related expenditures in the industrial sector (i.e., $47.0 billion). Table 6-4 records the value of $P_h(t)$ for values of t from 0 to 16 (i.e., from 2004 to 2020). Note that the years shown on the table extend past the end of the study period.

A secondary diffusion process specifies how FIAPP products and services penetrate the stock of industrial facilities. The secondary diffusion process is used only in the estimation of reductions in maintenance and repair costs. The need for a secondary diffusion process is driven by the way in which additions and alterations affect the industrial base. For example, a $50 million modernization project could reduce future maintenance and repair costs for a $250 million industrial facility. Thus, a given dollar amount for additions and alterations has a greater impact on the industrial base (i.e., it affects a greater dollar value) than does the same dollar amount for new construction. However, because the value of the industrial base is so much greater than the value of construction put in place in any given year, it will take longer for FIAPP products and services to reach saturation (i.e., 50 % of the value of the industrial base, which is assumed to be equal to its replacement cost).

The secondary diffusion model, $B_h(t)$, where *"B"* is used to indicate that this diffusion model applies to the industrial base, uses the same values for b and h as does $P_h(t)$ but a different value for the location parameter. The new location parameter, a', is set equal to 6. This means that it will take 12 years for FIAPP products and services to penetrate 25 % of the industrial base. Table 6-4 records the value of $B_h(t)$ for values of t from 0 to 16. Comparisons between $P_h(t)$ and $B_h(t)$ reveal that $B_h(t+4)$ equals $P_h(t)$. This is because the only difference between $P_h(t)$ and $B_h(t)$ is the value of the location parameter.

The diffusion model, as specified above and used in the baseline analysis, is plotted in a graphical form in Figure 6-6. The trace of $P_h(t)$ is shown as a solid line in Figure 6-6. The trace of $B_h(t)$ is shown as a dashed line in Figure 6-5. The figure includes both a left and a right vertical axis. The left vertical axis of Figure 6-6 records the values of $P_h(t)$. The right vertical axis of Figure 6-6 records the values of $B_h(t)$. The values on both vertical axes range from 0 to h. The horizontal axis of Figure 6-6 records the values of t and the years for which the values of $P_h(t)$ and $B_h(t)$ are calculated. Recall that in the baseline analysis $t = 1$ corresponds to the year 2005. Note that the years shown on the horizontal axis extend past the end of the study period. This is done to show that $P_h(t)$

and $B_h(t)$ do not approach the market saturation level, h, until well after the study period is over. Thus, substantial cost savings due to the use of FIAPP 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.

Much of the sensitivity analysis is concerned with the diffusion model (see Chapter 8). As such, ranges of values were specified for a, b, h, and the *time of first use*. The ranges for a and b were selected based on values of a and b published in the economics literature ***and*** their implications for the values of the ratio a/b also published in the economics literature. The range of values for a used in the sensitivity analysis is a low of 3 and a high of 5 (i.e., $3 \leq a \leq 5$). The range of values for a' is tied to the range of values of a. In particular a' is equal to $a + 2$. The range of values for b used in the sensitivity analysis is a low of 0.4 and a high of 0.6 (i.e., $0.4 \leq b \leq 0.6$). These ranges of values for a and b and a' and b result in ranges for the ratios a/b and a'/b which are consistent with the values published in the economics literature (i.e., $5.0 \leq a/b \leq 12.5$) and (i.e., $8.33 \leq a'/b \leq 17.5$).

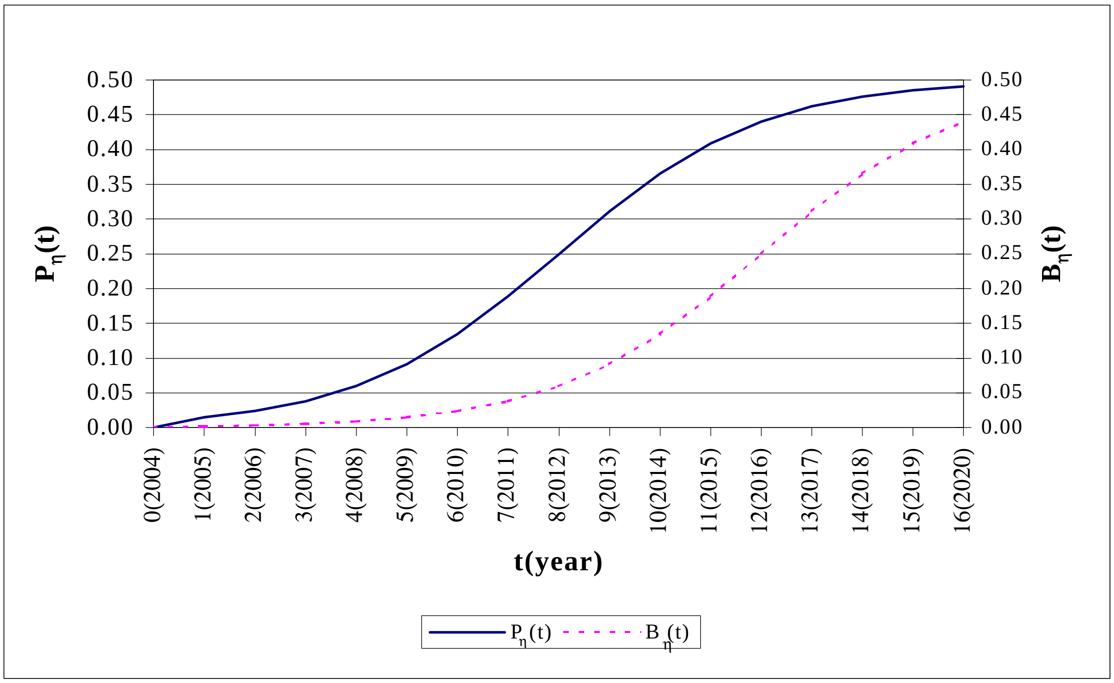
Table 6-4. Baseline Case of $P_\eta(t)$ ($\alpha = 4.0$, $\beta = 0.5$, $\eta = 0.5$) and $B_\eta(t)$ ($\alpha' = 6.0$, $\beta = 0.5$, $\eta = 0.5$)

Year	t	$P_\eta(t)$	$B_\eta(t)$
2004	0	0.0000	0.0000
2005	1	0.0147	0.0020
2006	2	0.0237	0.0033
2007	3	0.0379	0.0055
2008	4	0.0596	0.0090
2009	5	0.0912	0.0147
2010	6	0.1345	0.0237
2011	7	0.1888	0.0379
2012	8	0.2500	0.0596
2013	9	0.3112	0.0912
2014	10	0.3655	0.1345
2015	11	0.4088	0.1888
2016	12	0.4404	0.2500
2017	13	0.4621	0.3112
2018	14	0.4763	0.3655
2019	15	0.4853	0.4088
2020	16	0.4910	0.4404

The range of values for h is based on information provided by industrial sector experts. These values range from a low of 30 % to a high of 70 % (i.e., $0.3 \leq h \leq 0.7$).

The range of values for the *time of first use* are based on "targeted" times (i.e., years) at which FIAPP products and services will be available commercially. These times range from a low of 2004 to a high of 2007. That is, the earliest date at which FIAPP products and services are commercially available is in the year 2004 and the latest date is 2007. 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: 2004, 0.125; 2005, 0.5; 2006, 0.25; and 2007, 0.125.

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



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.[92] 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 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 to the development of FIAPP products and services for use in industrial facilities. It begins with a review of the nature of BFRL's contribution.

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[92] 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.

BFRL's contribution serves two vital roles. One is that of a facilitator, and the other is that of a developer of key FIAPP 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 is participating in a consortium of facility owners, contractors, construction product and equipment manufacturers, and service providers interested in producing, testing, demonstrating, and buying and selling FIAPP products and services. Second, BFRL is participating in the Virtual FIAPP Testbed to facilitate the development and evaluation of new products and systems by manufacturers and external service providers. Third, BFRL is working towards an operational prototype FIAPP being tested and deployed in a full-scale demonstration project by 2004.

BFRL's role as developer of key FIAPP enabling technologies is extensive and pervasive; it spans all seven projects in the integrated CONSiAT project team (see Section 3.2). However, three 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 interoperability testing procedures to facilitate the development and introduction of FIAPP 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 FIAPP products and services. Does this mean that FIAPP products and services would not be developed without BFRL's participation? The answer to that question is an unequivocal "No." Eventually, FIAPP 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 FIAPP 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 FIAPP products and services.

Because BFRL's research effort is expected to result in a faster introduction of FIAPP 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[93, 94] was used to develop an

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

estimate of how much the commercial introduction of FIAPP products and services would have been delayed, were it not for BFRL's dual role as a facilitator and developer of key FIAPP enabling technologies. Without BFRL's involvement, the commercial introduction of FIAPP products and services is estimated to occur in 2009, a delay of four years (i.e., commercial introduction in 2009 rather than in 2005). Therefore, any savings prior to the "delayed" introduction of FIAPP products and services in 2009 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 FIAPP products and services in 2009, 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 BFRL's efforts to speed up the commercial introduction of FIAPP products and services. These efforts vary in their funding requirements, depending on whether commercial introduction is targeted for 2004, 2005, 2006, or 2007. The estimated BFRL investment costs, as a function of the year targeted for first commercial use, are summarized in Table 6-5. Reference to the table shows that a very aggressive level of funding is required if FIAPP products and services are to become available in 2004. However, if these products become available in 2004, then the BFRL weighting factor takes on a value of 1 for 2004 through 2008 (i.e., a "delay" of five years is avoided) and a value of 0 from 2009 until the end of the study period. On the other hand, if funding were held constant, then commercial introduction is not expected to occur until 2007. In this scenario, the BFRL weighting factor would take on a value of 1 for 2007 and 2008 (i.e., a "delay" of two years is avoided) and a value of 0 from 2009 until the end of the study period.

Table 6-5. Estimated Investment Costs as a Function of the Year of First Commercial Use

Fiscal Year	BFRL Estimated Investment Costs (In $K) as a Function of the Year of First Commercial Use			
	2004	**2005**	**2006**	**2007**
2001	4,000	2,500	2,200	2,200
2002	5,000	3,000	2,500	2,200
2003	6,000	3,500	3,000	2,200
2004	6,000	4,000	3,500	2,200
2005	6,000	4,000	4,000	3,000
2006	5,000	4,000	4,000	4,000
2007	3,500	3,500	4,000	4,000
2008	3,000	3,000	3,500	4,000
2009	2,500	2,500	3,000	3,000

[94] Chapman, Robert E. 1999. *Benefits and Costs of Research: A Case Study of Cybernetic Building Systems*. NISTIR 6303. Gaithersburg, MD: National Institute of Standards and Technology.

Each of the four scenarios (i.e., year targeted for first commercial use) is examined in Chapter 8. A two-stage analysis is employed. The first stage analysis focuses on measuring the return to the public from each scenario, assuming that the first commercial use of FIAPP products and services occurs in the year targeted. The second stage evaluates the consequences of targeting commercial introduction for one year but not achieving it until later. This analysis examines the critical relationship between risk and return for each scenario. The second stage analysis employs both deterministic and Monte Carlo techniques to measure the expected outcomes associated with no lag, a one year lag, and a two year lag between the year targeted for commercial introduction and year in which commercial introduction was achieved. The alternative lags are specified by a discrete distribution. The discrete probabilities for each lag are: no lag, 0.6; a one year lag, 0.25; and a two year lag, 0.15.

7 Baseline Analysis of Economic Impacts

The baseline analysis presented in this chapter is the reference point for the CONSiAT economic 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 CONSiAT economic impact assessment are presented for two basic cases (see Exhibit 7-1). First, are the cost savings nationwide achievable through the use of FIAPP products and services in industrial facilities. Second, are the cost savings attributable to BFRL and the return on BFRL's CONSiAT-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 CONSiAT-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 FIAPP products and services (see Section 6.4.6).

The results of the baseline analysis demonstrate that the use of FIAPP products and services will generate substantial cost savings to industrial facility owners and managers and to contractors engaged in the construction of those facilities. The present value of savings nationwide expected from the use of FIAPP products and services is in excess of $2.0 billion (measured in 1997 dollars). Furthermore, because of BFRL's involvement, FIAPP products and services are expected to be commercially available in 2005. If BFRL had not participated in the development of FIAPP products and services, the commercial introduction of FIAPP products and services is expected to be delayed until 2009. Consequently, potential cost savings accruing to industrial facility owners and managers and to contractors over the period 2005 through 2008 would have been foregone. The present value of these cost savings is approximately $150 million. These cost savings measure the value of BFRL's contribution for its CONSiAT-related investment costs of approximately $30.1 million. Stated in present value terms, every public dollar invested in BFRL's CONSiAT-related research, development, and deployment efforts is expected to generate $4.95 in cost savings to the public (i.e., an SIR of 4.95). The annual percentage yield (AIRR) from BFRL's CONSiAT-related investments over the study period is 14.1 %.

Exhibit 7-1. Summary of Economic Impacts of BFRL Research on Construction Systems Integration and Automation Technologies in Industrial Facilities

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1.a Significance of Research Effort:

Owners of industrial facilities and contractors engaged in the construction of those facilities are pressing for reductions in delivery time as a means of improving their competitive positions. Owner concerns over both the first costs and life-cycle costs of industrial facilities and tightening profit margins for contractors are also affecting the competitive positions of each stakeholder. One means of improving the competitive positions of each industrial sector stakeholder is through the development, adoption, and use of fully-integrated and automated project process (FIAPP) products and services. Characteristics of FIAPP products and services include one-time data entry; interoperability with design, construction, and operation processes; and user-friendly input/output techniques. BFRL's focused research efforts, its collaboration with the Construction Industry Institute (CII), and its participation in the FIATECH Consortium are designed to deliver FIAPP products and services to CII members and the rest of the construction industry.

BFRL's focused research on Plant STEP, construction metrology, and economic analysis led BFRL to form an integrated CONSiAT project team in 1997. In addition, BFRL is uniquely positioned to collaborate with industry on the development of FIAPP products and services and to provide a forum for conducting interoperability testing. BFRL is working towards a prototype FIAPP being tested and deployed by 2004. To achieve this goal, BFRL is working with facility owners, contractors, equipment and systems manufacturers and service providers, software developers, facility operators, trade associations, professional societies, standards organizations, university researchers, and other government agencies. Without BFRL's participation, it is likely that the introduction of FIAPP products and services will be delayed for at least four years.

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1.b Key Points:

- Pressure to reduce delivery time and life-cycle costs has created a potential market for FIAPP products and services.

- BFRL is uniquely positioned to collaborate with industry on the development of FIAPP products and services and to provide a forum for conducting interoperability testing.

- Without BFRL's participation, it is likely that the introduction of FIAPP products and services will be delayed for at least four years.

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2. Analysis Strategy: How Key Measures are Estimated

The objective of the study is to (1) evaluate, for the period 1993 through 2017, the net cost savings due to the adoption and use of FIAPP products and services in industrial facilities, 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 industrial facilities that employ FIAPP products and services. PV cost savings nationwide are estimated for each year from 1993 to 2017 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., 1993 to 2008).

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.

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Exhibit 7-1. Summary of Economic Impacts of BFRL Research on Construction Systems Integration and Automation Technologies in Industrial Facilities (continued)

2. Analysis Strategy: Data and Assumptions

- The period over which costs and savings are measured begins in 1993 and ends in 2017. 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 % (real).
- Estimates of cost savings associated with the adoption and use of FIAPP products and services are based on construction industry data and information provided by industry experts.
- Without BFRL's participation, the introduction of FIAPP products and services will be delayed by four years.

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

Savings and Costs

Present Value Cost Savings Nationwide:
Sum from 1993 to 2017 of present value of cost savings nationwide by year
= $2,043.2 million

Present Value Savings (PVS) Attributable to BFRL:
Sum from 1993 to 2008 of present value of cost savings nationwide by year
= $149.0 million

Present Value Investment Costs (PV Costs) to BFRL:
Sum from 1993 to 2017 of present value of investment cost to BFRL by year
= $30.096 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

= $149.0 - $30.096 = $118.9 million

Additional Measures

SIR of BFRL Contribution:
Savings-to-Investment Ratio on BFRL investment
= $149.9/$30.096 = 4.95

AIRR of BFRL Contribution:
Adjusted Internal Rate of Return on BFRL investment
$= (1+ 0.07) * 4.95^{1/25} – 1 = 0.141$

3.b Key Results:

1997 Dollars
($ amounts in millions)

Cost Savings Nationwide:

$2,043.2

Savings Attributable to BFRL:

PVS	**$149.0**
PV Costs	**$30.096**
PVNS	**$118.9**
SIR	**4.95**
AIRR	**14.1%**

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).

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 primary and secondary diffusion models developed in Section 6.4.4; (2) the cost savings due to reductions in first costs, maintenance and repair costs, and construction-related accidents *and* the increases in net income for owners and contractors due to reductions in delivery time and higher contractor profit margins; and (3) new-technology introduction costs. These three types of information are combined via three sets of calculations to estimate "annual" cost savings to the nation. Estimates are produced for each year from 1993 to 2017. 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 employing FIAPP products and services in industrial facilities. The results of the baseline analysis show that cost savings nationwide exceed $2.0 billion ($2,043 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.

Table 7-1 summarizes information derived from the diffusion models. Column 1 of the table lists each year of the study period from 1993 through 2017. Columns 2 and 3 of Table 7-1 record information on the calculated values of the primary diffusion model, $P_h(t)$, and the secondary diffusion model, $B_h(t)$, for each year. Recall that $t = 1$ corresponds to the year in which FIAPP products and services are expected to become commercially available (i.e., $t = 1$ corresponds to the year 2005). Thus, $P_h(t) = 0$ and $B_h(t) = 0$ for all values of t less than 1. Next, the primary diffusion model is combined with information on the 1997 value of construction put in place for the industrial sector as a whole to generate annual estimates of the value of construction put in place for that proportion of the industrial sector which employs FIAPP products and services. Estimates are given for each year from 1993 to 2017. To get the annual value of construction put in place which employs FIAPP products and services, the value of $P_h(t)$ in Column 2 is multiplied by the 1997 value of construction put in place for the industrial sector as a whole. This value, expressed in 1997 dollars, is held constant at $47.0 billion throughout the period during which FIAPP products and services diffuse into the marketplace (i.e., 2004 through 2017). The secondary diffusion model specifies how FIAPP products and services penetrate the stock of industrial facilities. The secondary diffusion process is used only in the estimation of reductions in maintenance and repair costs. Recall that the need for a secondary diffusion process is driven by the way additions and alterations affect the industrial base (see Section 6.4.4).

Table 7-1. Baseline Values for the Diffusion Models and of FIAPP-Related Investments by Year: 1993 - 2017

Year	Proportion of Industrial Sector Investments Covered by FIAPP Products and Services $P_\eta(t)$	Proportion of Industrial Base Covered by FIAPP Products and Services $B_\eta(t)$	Value of FIAPP-Related Investments (In Millions of 1997 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4)
1993	0	0	0
1994	0	0	0
1995	0	0	0
1996	0	0	0
1997	0	0	0
1998	0	0	0
1999	0	0	0
2000	0	0	0
2001	0	0	0
2002	0	0	0
2003	0	0	0
2004	0	0	0
2005	0.0147	0.0020	688.8
2006	0.0237	0.0033	1,114.5
2007	0.0379	0.0055	1,782.7
2008	0.0596	0.0090	2,801.3
2009	0.0912	0.0147	4,287.0
2010	0.1345	0.0237	6,320.1
2011	0.1888	0.0379	8,872.2
2012	0.2500	0.0596	11,750.0
2013	0.3112	0.0912	14,627.8
2014	0.3655	0.1345	17,179.9
2015	0.4088	0.1888	19,213.0
2016	0.4404	0.2500	20,698.7
2017	0.4621	0.3112	21,717.3

Table 7-2 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 7-2. The years run from 1993 until 2017 (i.e., the entire study period). The table records information on five categories of cost savings: (1) first cost savings; (2) maintenance and repair cost savings; (3) savings due to reductions in two types of construction-related accidents; (4) reductions in delivery time; and (5) higher net income for contractors. Annual values for each category of cost savings are recorded in Column 2 for first costs, Column 3 for maintenance and repair costs, Column 4 for accidents avoided which do not result in any lost workdays, Column 5 for accidents avoided which do result in lost workdays, Column 6 for reductions in delivery time, and Column 7 for higher net income for contractors. Note that no cost savings for any category occur until 2005, the year in which FIAPP products and services first become commercially available.

To help readers reproduce the values recorded in Table 7-2, the formula used to estimate the annual cost saving for each category of cost savings is given (see Equations 7.1 through 7.6). In each formula, t corresponds to the *Year* (see Column 1 of Table 7-2) for which savings are calculated (i.e., $t = 1$ corresponds to *Year* = 2005). The nature of the anticipated cost savings for each category is designated with a subscript, depending on whether they result in cost avoidance (i.e., savings) or in higher net income (i.e., benefits). The subscript, S, is used to denote savings; these values appear in Columns 2 through 5. They are calculated through application of Equations 7.1 through 7.4. The subscript, B, is used to denote benefits; these values appear in Columns 6 and 7. They are calculated through application of Equations 7.5 and 7.6.

To facilitate cross-referencing between Table 7-2 and Equations 7.1 through 7.6, a short hand notation for each column heading is used. Specifically, the year-by-year savings(benefits) for each category are: $RFC_S(t)$ for Column 2; $RMRC_S(t)$ for Column 3; $NETRIR_S(t)$ for Column 4; $LWCIR_S(t)$ for Column 5; $RDT_B(t)$ for Column 6; and $HCNI_B(t)$ for Column 7. Terms used in each formula which have not already been defined are defined the first time they appear (e.g., $VIP_{IS}(t)$ in Equation 7.1). Note that several equations use the same term (e.g., $P_h(t)$ appears in every equation and $VIP_{IS}(t)$ appears in both Equations 7.1 and 7.6).

Reductions in First Costs

$$RFC_S(t) = \left[P_h(t) * VIP_{IS}(t)\right] * (0.014) \qquad 7.1$$

where $VIP_{IS}(t)$ = the value of construction put in place in the industrial sector in year t (in millions of 1997 dollars); and

0.014 = the expected reduction in first costs expressed as a decimal.

Table 7-2. Baseline Cost Savings by Category and in Total in Millions of 1997 Dollars by Year: 1993-2017

Year	Annual Cost Savings By Category						Total Cost Savings by Year (In Millions of 1997 Dollars)
	Savings Due to Reductions in First Costs (In Millions of 1997 Dollars)	Savings Due to Reductions in Maintenance and Repair Costs (In Millions of 1997 Dollars)	Savings Due to Reductions in Construction-Related Accidents (In Millions of 1997 Dollars)		Benefits Due to Reductions in Delivery Time (In Millions of 1997 Dollars)	Benefits From Higher Net Income for Contractors (In Millions of 1997 Dollars)	
			Cases With No Lost Workdays	Lost Workday Cases			
Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (5)	Col. (6)	Col. (7)	Col. (8) (2)+(3)+(4)+(5)+(6)+(7)
1993	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0
2005	9.644	0	.025	.440	16.974	8.528	35.611
2006	15.603	.268	.038	.675	26.846	13.799	57.229
2007	24.957	.703	.058	1.022	41.975	22.071	90.785
2008	39.218	1.450	.086	1.520	64.476	34.682	141.432
2009	60.018	2.807	.125	2.204	96.454	53.077	214.684
2010	88.482	5.381	.175	3.076	139.000	78.249	314.363
2011	124.211	10.392	.234	4.089	190.742	109.846	439.514
2012	164.500	20.169	.294	5.129	246.931	145.476	582.499
2013	204.789	38.736	.348	6.046	300.498	181.106	731.523
2014	240.518	72.078	.389	6.725	344.991	212.703	877.403
2015	268.982	127.214	.413	7.122	377.144	237.875	1,018.750
2016	289.782	209.299	.423	7.265	397.173	256.270	1,160.212
2017	304.043	317.509	.421	7.219	407.349	268.881	1,305.422

Reductions in Maintenance and Repair Costs

$$RMRC_S(t) = \{[MRC_{IS}(t) * (0.02 + B_h(t-1)) * (1.023)^{-Y}] * \left[\sum_{j=1}^{t} P_h(t-j) * (1.1)^{-(j-1)}\right]\} * (0.1) \quad 7.2$$

where $MRC_{IS}(t)$ = the value of maintenance and repair costs in the industrial sector in year t (in millions of 1997 dollars);

0.02 = net additions to the industrial base due to the value of new construction put in place expressed as a decimal;

Y = *Year* – 1997;

1.023 = deflator used to adjust for the long-term growth in the industrial base of 2.3 %;

1.1 = deflator used to adjust for "degraded" performance over time of 10 % per year beginning the year after construction; and

0.1 = the expected reduction in maintenance and repair costs expressed as a decimal.

Reductions in Construction-Related Accidents Resulting in No Lost Workdays: NETRIR

$$NETRIR_S(t) = [(0.398) * (1.0525)^{-Y} * P_h(t) * CWH_{IS}(t) * (200{,}000)^{-1}] * (0.0015) \quad 7.3$$

where 0.398 = the expected reduction in "NETRIR" expressed as a decimal;

1.0525 = deflator used to adjust for improved RIR-related safety performance of 5.25 % per year;

$CWH_{IS}(t)$ = the number of craft workhours in the industrial sector in year t;

200,000 = the base for computing safety-related measures (100 full-time workers working 40 hours per week, 50 weeks per year); and

0.0015 = the value of avoiding an accident which results in no lost workdays (in millions of 1997 dollars).

Reductions in Construction-Related Accidents Resulting in One or More Lost Workdays: LWCIR

$$LWCIR_S(t) = \left[(0.347) * (1.056)^{-Y} * P_h(t) * CWH_{IS}(t) * (200{,}000)^{-1}\right] * (0.0315) \qquad 7.4$$

where 0.347 = the expected reduction in LWCIR expressed as a decimal;

1.056 = deflator used to adjust for improved LWCIR–related safety performance of 5.6 % per year; and

0.0315 = the value of avoiding an accident which results in one or more lost workdays (in millions of 1997 dollars).

Reductions in Delivery Time

$$RDT_B(t) = \left[(0.0313) * (1.023)^{-Y} * P_h(t) * WNI_{IS}(t)\right] * 8 \qquad 7.5$$

where 0.0313 = net additions to the industrial base due to the combined value of new construction and additions and alterations expressed as a decimal;

$WNI_{IS}(t)$ = weekly net income in the industrial sector in year *t* (in millions of 1997 dollars); and

8 = the expected reduction in delivery time expressed in weeks.

Higher Contractor Net Income

$$HCNI_B(t) = \left[P_h(t) * VIP_{IS}(t) * (1.05)^{-1}\right] * (0.013) \qquad 7.6$$

where 1.05 = deflator used to translate total installed cost to contractor cost; and

0.013 = the expected increase in contractor net income expressed as a decimal.

In addition to annual cost savings by category, Table 7-2 also contains total cost savings by year. These cost savings are recorded in Column 8. 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 2005 and 2017.

Table 7-3 summarizes how the present values of net cost savings nationwide by year and in total are calculated. The table also includes information on total cost savings, additional FIAPP-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 7-3. The years run from 1993 until 2017 (i.e., the entire study period). Column 2 of Table 7-3 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 8 of Table 7-2. The additional cost to install FIAPP products and services for each year is recorded in Column 3 of Table 7-3. This cost equals the product of the additional cost to building owners and contractors of 0.5 % of total installed cost and the value of construction put in place which employ FIAPP products and services. The value of construction put in place which employ FIAPP products and services is contained in Column 4 of Table 7-1 for each year of the specific calculation. The difference between total cost savings and the additional costs to employ FIAPP products and services equals net cost savings. Column 4 of Table 7-3 records net cost savings for each year in millions of 1997 dollars. Note that net cost savings increase steadily. The calculated value of the single compound amount factor for each year is recorded in Column 5 of Table 7-3. All entries are calculated using a real discount rate of 7 % (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, *Year*, equals $(1.07)^{1997\text{-}Year}$ where $1993 \leq Year \leq 2017$. The present value of net cost savings nationwide by year is recorded in Column 6 of Table 7-3. 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 net cost savings nationwide 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 three sets of baseline analysis calculations exceed \$2.0 billion (\$2,043 million in present value 1997 dollars); see the bottom of Column 6 in Table 7-3.

Reference to Table 7-3 demonstrates the magnitude of the savings to the nation from using FIAPP products and services in the industrial sector. These cost savings nationwide also provide a basis for measuring the value of BFRL's contribution.

Table 7-3. Baseline Computation of Present Value Cost Savings Nationwide in Millions of 1997 Dollars: 1993-2017

Year	Total Cost Savings by Year	New Technology Introduction Costs	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)**
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	0	0	0	0.666	0
2004	0	0	0	0.623	0
2005	35.611	3.444	32.167	0.582	18.721
2006	57.229	5.573	51.656	0.544	28.097
2007	90.785	8.913	81.872	0.508	41.619
2008	141.432	14.006	127.426	0.475	60.539
2009	214.684	21.435	193.249	0.444	85.805
2010	314.363	31.601	282.763	0.415	117.336
2011	439.514	44.361	395.153	0.388	153.247
2012	582.499	58.750	523.749	0.362	189.831
2013	731.523	73.139	658.384	0.339	223.018
2014	877.403	85.899	791.504	0.317	250.570
2015	1,018.750	96.065	922.685	0.296	272.989
2016	1,160.212	103.494	1,056.718	0.277	292.191
2017	1,305.422	108.587	1,196.836	0.258	309.285
				TOTAL	**2,043.250**

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

Measuring the value of BFRL's contribution to the development of FIAPP products and services and the return on its CONSiAT-related investments is the focus of this section. Information on BFRL's CONSiAT-related research, development, and deployment effort—in terms of its dollar investments—over the 25-year period from 1993 to 2017 are first presented. These figures demonstrate not only a significant, up-front research commitment by BFRL, but also a continued effort as FIAPP products and services move into the commercial marketplace. Next, the likely delay in the commercial availability of FIAPP products and services is addressed. Finally, a full array of economic measures summarizes the importance of BFRL's contribution to the development of FIAPP products and services for use in industrial facilities.

Table 7-4 summarizes information on BFRL's CONSiAT-related investments. Column 1 of the table records the year in which CONSiAT-related investments were made. Column 2 records the value (in millions of current dollars) by year of investment for each year between 1993 and 1999. For example, in 1993 the investment was $332,000 (in 1993 dollars), in 1994 the investment was $1,371,000 (in 1994 dollars), and in 1995 the investment was $1,502,000 (in 1995 dollars). For 2000 through 2017, the entries in Column 2 are in millions of 1999 dollars. Investments over the 1993 to 1996 time period cover STEP-related and construction metrology-related research. Investments beginning in 1997 include research, development, and deployment efforts aimed at producing FIAPP products and services. Because the values for 1993 through 1999 in Column 2 are in current dollars by year and the values for 2000 through 2017 are in 1999 dollars, 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 7-4. 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 value terms through the use of a single compound amount factor, based on a real discount rate of 7 %. 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 CONSiAT-related investments. The present value of BFRL's CONSiAT-related investments, PV Costs, totals $30.096 million; this value is recorded at the bottom of Column 6.

Table 7-4. Summary of BFRL Research Investments: 1993-2017

Year	Annual Dollar Amount (In Millions of Current Dollars)	Conversion Factor by Year (Current Dollars to 1997 Dollars)	Investment Costs by Year (In Millions of 1997 Dollars)	Single Compound Amount Factor by Year	Present Value of Investment Costs 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)
1993	.332	1.111	.369	1.311	.483
1994	1.371	1.083	1.485	1.225	1.819
1995	1.502	1.053	1.582	1.145	1.811
1996	1.548	1.023	1.584	1.070	1.694
1997	1.886	1.000	1.886	1.000	1.886
1998	2.263	0.985	2.228	0.935	2.083
1999	2.039	0.965	1.967	0.873	1.718
2000	2.204	0.965	2.126	0.816	1.735
2001	2.625	0.965	2.532	0.763	1.932
2002	3.125	0.965	3.014	0.713	2.149
2003	3.625	0.965	3.496	0.666	2.330
2004	4.000	0.965	3.858	0.623	2.403
2005	4.000	0.965	3.858	0.582	2.245
2006	3.875	0.965	3.738	0.544	2.033
2007	3.375	0.965	3.255	0.508	1.655
2008	2.875	0.965	2.773	0.475	1.317
2009	1.875	0.965	1.809	0.444	.803
2010	0	0.965	0	0.415	0
2011	0	0.965	0	0.388	0
2012	0	0.965	0	0.362	0
2013	0	0.965	0	0.339	0
2014	0	0.965	0	0.317	0
2015	0	0.965	0	0.296	0
2016	0	0.965	0	0.277	0
2017	0	0.965	0	0.258	0
				TOTAL	**30.096**

Note: The dollar amounts for 1993 through 1999 are in millions of current dollars. The dollar amounts for 2000 through 2017 are in millions of 1999 dollars.

Table 7-5 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 7-5. The years run from 1993 until 2017 (i.e., the entire study period). The present value of cost savings nationwide by year is recorded in Column 2 of Table 7-5. The present value of cost savings nationwide for each year is transferred from the respective row of Column 6 of Table 7-3. BFRL's dual role as a facilitator and developer of key FIAPP enabling technologies is expected to speed up the introduction of FIAPP products and services into the commercial marketplace. Without BFRL's participation, the introduction of FIAPP 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 two to five years for the likely delay. The selected baseline value for the delay is four years (see Section 6.4.6). Because BFRL's research, development, and deployment efforts are expected to result in faster introduction of FIAPP 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 four years (starting with 2005), prior to the "delayed" introduction of FIAPP products and services in 2009, 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 7-5. 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 7-5.

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 $148.997 million; this value is recorded at the bottom of Column 4.

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 CONSiAT-related investments; and (3) the adjusted internal rate of return (AIRR) on BFRL's CONSiAT-related investments.

The PVNS attributable to BFRL, expressed in millions of present value 1997 dollars and based on the approach outlined in Section 2.2.1, is equal to:

$$
\begin{aligned}
\text{PVNS} &= \text{PVS} - \text{PV Costs} \\
&= \$148.977 - \$30.096 \\
&= \$118.881 \text{ million}
\end{aligned}
$$

Table 7-5. Estimated Cost Savings in Millions of 1997 Dollars Attributable to BFRL

Year	Present Value of Cost Savings Nationwide by Year	BFRL Baseline Weighting Factor (4-Year Delay)	Present Value of Cost Savings by Year Attributable to BFRL
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2) x (3)
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	0	1	0
2004	0	1	0
2005	18.721	1	18.721
2006	28.097	1	28.097
2007	41.619	1	41.619
2008	60.539	1	60.539
2009	85.805	0	0
2010	117.336	0	0
2011	153.247	0	0
2012	189.831	0	0
2013	223.018	0	0
2014	250.570	0	0
2015	272.989	0	0
2016	292.191	0	0
2017	309.285	0	0
		TOTAL	**148.977**

Utilizing the approach outlined in Section 2.2.2, the SIR on BFRL's CONSiAT-related investments is equal to:

$$SIR = PVS / (PV\ Costs)$$

$$= \$148.977 / \$30.096$$

$$= 4.95$$

Utilizing the approach outlined in Section 2.2.3, the AIRR on BFRL's CONSiAT-related investments is equal to:

$$AIRR = (1 + 0.07) * 4.95^{1/25} - 1$$

$$= 0.141$$

$$= 14.1\%$$

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 CONSiAT 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, eleven 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 eleven 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 eleven input variables, both singly and in combination, translates into changes in each of the 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 CONSiAT-related investment costs; (4) the present value of net savings due to BFRL; (5) the savings-to-investment ratio on BFRL's CONSiAT-related investments; and (6) the adjusted internal rate of return on BFRL's CONSiAT-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 shows a net dollar value to the public net of BFRL's CONSiAT-related investments. The second, the savings-to-investment ratio on BFRL's CONSiAT-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 CONSiAT-related investments is a rate of return; it shows the return on the public monies going into the development of CONSiAT products and services throughout the 25-year study period.

8.1 Methodology

Because the values of many variables that enter into the CONSiAT 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 two of the previous economic impact assessments.[95]

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[96] and by Harris;[97] 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. This approach was used in one of the previous economic impact assessments.[98]

The method of model sampling was implemented through application of the *@RISK* software product.[99] 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 eleven 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.

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[95] See Chapman and Fuller, *Two Case Studies in Building Technology*, and Chapman and Weber, *A Case Study of the Fire Safety Evaluation System*.
[96] 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.
[97] 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.
[98] See Chapman, *A Case Study of Cybernetic Building Systems*.
[99] 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.

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 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 CONSiAT 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.[100]

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 eight input variables for which clustering about a central value was to be expected. Once the triangular distribution was selected for these eight 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 eleven input variables that are the focus of the sensitivity analysis is presented in this section. The eleven variables are: (1) alpha, a, the location parameter in the diffusion model; (2) beta, b, the shape parameter in the diffusion model; (3) eta, h,

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

the market saturation level in the diffusion model; (4) the discount rate; (5) first cost savings; (6) maintenance and repair cost savings; (7) reductions in delivery time; (8) higher contractor net income; (9) new-technology introduction costs; (10) the time of first use; and (11) the length of the delay.

Table 8-1 summarizes information on each of the eleven 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.

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

Variable Name	Probability Distribution	Setting and Value		
		Baseline	Minimum	Maximum
(1) Alpha	Uniform	4	3	5
(2) Beta	Triangular	0.5	0.4	0.6
(3) Eta	Triangular	0.5	0.3	0.7
(4) Discount Rate	Triangular	0.07	0.02	0.10
(5) First Cost Savings	Triangular	0.014	0	0.045
(6) Maintenance and Repair Cost Savings	Triangular	0.10	0.05	0.15
(7) Reductions in Delivery Time	Triangular	8	0	16
(8) Higher Contractor Net Income	Triangular	0.013	0	0.031
(9) New-Technology Introduction Costs	Triangular	0.005	0	0.010
(10) Time of First Use	Discrete	2005	2004	2007
(11) Delay	Discrete	0	0	2

Reference to the entries under the heading Probability Distribution shows that all but three of the eleven input variables use the triangular distribution to model variations about the baseline value for that variable. One of these variables, a, employs the uniform distribution. The input variable, a, 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 4.0. The economics literature was, however, useful in specifying the range about the baseline value of a. 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 CONSiAT products and services first become available commercially) either occurs in 2005 (i.e., the year corresponding to the baseline value) or in some other year. It does not occur in year 2005.5. Thus, the discrete distribution is the most meaningful

way to model when CONSiAT products and services first become available commercially.

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 % (real); it is recorded in decimal form as 0.07. Two other values for the discount rate, 2 % and 10 %, are selected to bracket the baseline value. These values are recorded in decimal form as 0.02 and 0.10, respectively.

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 eleven 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 ten input variables at their baseline values. These results are summarized in Tables 8-2 through 8-12. Table 8-13 summarizes the results of a deterministic sensitivity analysis for the combined effects of the time of first use and the length of delay. Table 8-13 has three parts: (1) Part A, where each time of first use is evaluated assuming no delay; (2) Part B, where each time of first use is evaluated assuming a one-year delay; and (3) Part C, where each time of first use is evaluated assuming a two-year delay. The second set covers the case where all eleven 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 8-14 and 8-15 and in Figures 8-1 through 8-6. To facilitate comparisons among each of the Monte Carlo simulations, Tables 8-2 through 8-12 and Table 8-14 use the same presentation format. Table 8-15 summarizes in tabular form the results plotted in Figures 8-1 through 8-6.

8.3.1 Changing One Input

Tables 8-2 through 8-12 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 CONSiAT-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 CONSiAT-related investments is designated by SIR_{BFRL}. The adjusted internal rate of return on BFRL's CONSiAT-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 % 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, a, b, and h is analyzed in turn.

Table 8-2 shows how variations about the baseline value for a (i.e., a = 4.0) affect each economic measure. The parameter, a, was selected for evaluation because it is the location parameter for the diffusion model. The effect of a is as follows: lower values of a produce a thicker tail immediately following the introduction of CONSiAT products and services into the marketplace (i.e., higher values of $P_h(t)$, whenever t is small), whereas higher values of a produce a thinner tail (i.e., lower values of $P_h(t)$, whenever t is small). Reference to Table 8-2 reveals that a exerts a strong effect on five of the six 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 a, 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 four years are attributable to BFRL, higher values of a reduce these savings and lower values of a increase these savings over the value calculated in the baseline analysis. For example, the minimum value of SIR_{BFRL} is one-sixth the highest value, and $PVNS_{BFRL}$ varies by more than a factor of 10. Note that PVC_{BFRL} is unaffected by changes in the value of a. 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., $84.5 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}	1,248.776	1,624.427	2,032.286	2,485.172	3,112.868	2,077.268	535.216
PVS_{BFRL}	57.880	94.643	147.367	222.565	356.658	166.290	84.466
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	27.783	64.547	117.271	192.469	326.561	136.193	84.466
SIR_{BFRL}	1.923	3.145	4.897	7.395	11.851	5.525	2.807
$AIRR_{BFRL}$	0.098	0.120	0.140	0.159	0.181	0.140	0.024

Table 8-3 shows how variations about the baseline value for *b* (i.e., *b* = 0.6) affect each economic measure. The parameter, *b*, was selected for evaluation because it specifies the rate of change for the diffusion model. The effect of *b* is as follows: higher values of *b* produce a higher rate of adoption of CONSiAT products and services in the marketplace immediately following the introduction of these products and services (i.e., higher values of $P_h(t)$, whenever *t* is small), whereas lower values of *b* produce a lower rate of adoption (i.e., lower values of $P_h(t)$, whenever *t* is small). Reference to Table 8-3 reveals that *b* exerts a moderate to strong effect on five of the six economic measures. For example, the range of values for PVS_{ALL} is slightly in excess of $1.3 billion in 1997 dollars. Although the present value of savings nationwide is strongly affected by changes in the value of *b*, the measures of BFRL's influence are affected to a lesser degree than for changes in *a*. The reason is due to the way in which BFRL's influence is measured. Because those savings occurring in the first four years are attributable to BFRL, lower values of *b* reduce these savings and higher values of *b* increase these savings over the value calculated in the baseline analysis. However, these differences are less than those associated with *a*, because *a* affects the thickness of the lower tail of $P_h(t)$, whereas *b* only affects the rate of change of the slope of the tail in the period immediately following the introduction of CONSiAT products and services. For example, the minimum value of SIR_{BFRL} is slightly more than half the highest value, and $PVNS_{BFRL}$ varies by a factor of slightly less than two. Note that PVC_{BFRL} is unaffected by changes in the value of *b*. 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., $16.8 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}	1,404.935	1,834.252	2,041.845	2,251.657	2,723.587	2,041.902	291.497
PVS_{BFRL}	115.920	137.473	148.898	161.257	192.840	149.699	16.773
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	85.824	107.376	118.801	131.161	162.743	119.602	16.773
SIR_{BFRL}	3.852	4.568	4.947	5.358	6.407	4.974	0.557
$AIRR_{BFRL}$	0.129	0.137	0.141	0.144	0.153	0.141	0.005

Table 8-4 shows how variations about the baseline value for *h* (i.e., *h* = 0.5) affect each economic measure. The parameter, *h*, was selected for evaluation because it specifies the level at which the market for CONSiAT products and services saturates. The effect of *h* is as follows: higher values of *h* produce a higher level of adoption of CONSiAT products and services in the marketplace towards the latter part of the study period (i.e., higher values of $P_h(t)$, for all values of *t*, especially whenever *t* is large), whereas lower values of *h* produce a lower level of adoption (i.e., lower values of $P_h(t)$). Reference to Table 8-4 reveals that *h* exerts a moderate to strong effect on five of the six economic measures. For example, the range of values for PVS_{ALL} (i.e., Maximum – Minimum)

exceeds $1.7 billion in 1997 dollars. Although the present value of savings nationwide is strongly affected by changes in the value of h, the measures of BFRL's influence are affected to a lesser degree than for changes in a. The reason, once again, is due to the way in which BFRL's influence is measured. Because those savings occurring in the first four years are attributable to BFRL, lower values of h reduce these savings and higher values of h increase these savings over the value calculated in the baseline analysis. However, these differences are less than those associated with a, because a affects the thickness of the lower tail of $P_h(t)$, whereas h affects the level at which the market saturates. Thus, the influence of h on the years immediately following the introduction of CONSiAT 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 h tend to be wider than for b, but narrower than for a.

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$_{ALL}$	1,219.790	1,770.095	2,026.181	2,310.484	2,959.476	2,038.923	367.166
PVS$_{BFRL}$	92.291	130.599	147.841	166.585	207.939	148.342	24.437
PVC$_{BFRL}$	30.096	30.096	30.096	30.096	30.096	30.096	0.0
PVNS$_{BFRL}$	62.195	100.502	117.744	136.488	177.843	118.245	24.437
SIR$_{BFRL}$	3.067	4.339	4.912	5.535	6.909	4.929	0.812
AIRR$_{BFRL}$	0.119	0.135	0.140	0.146	0.156	0.140	0.008

Table 8-5 shows how variations about the baseline value of the discount rate (7 % (real)) affect each economic measure. The discount rate affects calculations in a number of ways. For example, BFRL's CONSiAT-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 8-5 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 2005, whereas the base year is 1997. Thus, savings occurring in the out years (e.g., 2009 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 $3.1 billion in 1997 dollars. On the other hand, BFRL's CONSiAT-related investments are largely clustered around 1997, and BFRL's savings occur between 2005 and 2008 (i.e., much earlier than the bulk of the savings used to calculate PVS$_{ALL}$). This explains why the key measures of BFRL's influence are less sensitive to changes in the discount rate than is PVS$_{ALL}$.

The results presented in Tables 8-6, 8-7, 8-8, and 8-9 address the "savings/benefits" side of the analysis. Tables 8-6 and 8-7 are related to the values of percent cost savings. Tables 8-8 and 8-9 are related to increases in benefits, which in both cases are due to increases in net income.

Table 8-5. 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}	1,321.505	1,887.285	2,230.423	2,759.449	4,508.559	2,367.167	636.863
PVS_{BFRL}	114.148	141.953	157.118	178.703	239.911	161.466	25.884
PVC_{BFRL}	27.136	29.507	30.775	32.553	37.447	31.114	2.133
$PVNS_{BFRL}$	87.012	112.446	126.343	146.150	202.464	130.352	23.752
SIR_{BFRL}	4.207	4.811	5.105	5.490	6.407	5.158	0.465
$AIRR_{BFRL}$	0.099	0.125	0.136	0.145	0.164	0.135	0.014

Table 8-6 summarizes the results of the Monte Carlo simulation of variations about the baseline value of first cost savings. Reference to Table 8-6 reveals considerable variation about the values calculated in the baseline analysis for five of the six economic measures. For example, the range of values for PVS_{ALL} (i.e., Maximum – Minimum) exceeds $1.7 billion in 1997 dollars. Four of the five measures of BFRL's influence are strongly affected by changes in the input variable first cost savings. For example, the value calculated in the baseline analysis for the SIR_{BFRL} is 4.95. In Table 8-6, the minimum value for the SIR_{BFRL} is 3.542, and the maximum value is 8.219. The value of PVC_{BFRL} is not affected by the input variable first cost savings.

Table 8-6. Summary Statistics Due to Changes in the Input Variable First Cost Savings

Economic Measure	Statistical Measure						
	Minimum	25 %	50 %	75 %	Maximum	Mean	Standard Deviation
PVS_{ALL}	1,482.988	1,988.166	2,235.039	2,582.936	3,343.625	2,290.636	410.975
PVS_{BFRL}	106.593	144.810	163.487	189.806	247.353	167.693	31.091
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	76.496	114.714	133.390	159.709	217.257	137.596	31.091
SIR_{BFRL}	3.542	4.812	5.432	6.307	8.219	5.572	1.033
$AIRR_{BFRL}$	0.126	0.139	0.145	0.152	0.164	0.145	0.008

Table 8-7 summarizes the results of the Monte Carlo simulation of variations about the baseline value of maintenance and repair cost savings. Table 8-7 reveals only minimal variations about the values calculated in the baseline analysis for five of the six economic measures. For example, the minimum value for the PVS_{ALL} is $1,937.927 million, and the maximum is $2,156.953 million, a range of slightly less than $220 million (measured in 1997 dollars). Whereas, the minimum value for the PVS_{BFRL} is $148.431 million, and the maximum is $149.568 million, a range of only $1.1 million (measured in 1997 dollars). The value of PVC_{BFRL} is not affected by the input variable maintenance and repair cost savings.

Table 8-7. Summary Statistics Due to Changes in the Input Variable Maintenance and Repair Cost Savings

Economic Measure	Statistical Measure						
	Minimum	25 %	50 %	75 %	Maximum	Mean	Standard Deviation
PVS_{ALL}	1,937.927	2,009.539	2,041.028	2,074.552	2,156.953	2,042.315	46.381
PVS_{BFRL}	148.431	148.802	148.966	149.140	149.568	148.973	0.241
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	118.334	118.706	118.870	119.044	119.472	118.876	0.241
SIR_{BFRL}	4.932	4.944	4.950	4.955	4.970	4.950	0.008
$AIRR_{BFRL}$	0.141	0.141	0.141	0.141	0.141	0.141	0.0

Table 8-8 summarizes the results of the Monte Carlo simulation of variations about the baseline value of reductions in delivery time. Reference to Table 8-6 reveals considerable variation about the values calculated in the baseline analysis for five of the six economic measures. The pattern of results presented in Table 8-8 is similar to the one resulting from first cost savings (see Table 8-6). For example, the range of values for PVS_{ALL} (i.e., Maximum – Minimum) exceeds $1.7 billion in 1997 dollars. As was the case for first cost savings, four of the five measures of BFRL's influence are strongly affected by changes in the input variable reductions in delivery time. For example, the value calculated in the baseline analysis for the SIR_{BFRL} is 4.95. In Table 8-8, the minimum value for the SIR_{BFRL} is 2.452, and the maximum value is 7.433, a relative difference of a factor of three-to-one. The value of PVC_{BFRL} is not affected by the input variable reductions in delivery time.

Table 8-8. Summary Statistics Due to Changes in the Input Variable Reductions in Delivery Time

Economic Measure	Statistical Measure						
	Minimum	25 %	50 %	75 %	Maximum	Mean	Standard Deviation
PVS_{ALL}	1,179.578	1,770.534	2,016.121	2,271.635	2,901.429	2,021.755	353.400
PVS_{BFRL}	73.783	125.234	146.616	168.862	223.694	147.106	30.768
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	43.687	95.137	116.519	138.765	193.597	117.010	30.768
SIR_{BFRL}	2.452	4.161	4.872	5.611	7.433	4.888	1.022
$AIRR_{BFRL}$	0.109	0.133	0.140	0.146	0.159	0.139	0.010

Table 8-9 summarizes the results of the Monte Carlo simulation of variations about the baseline value of higher contractor net income. Table 8-9 reveals moderate to strong variations about the values calculated in the baseline analysis for five of the six economic measures. The value of PVC_{BFRL} is not affected by the input variable higher contractor net income. Reference to Table 8-9 reveals that the range of values for PVS_{ALL} (i.e., Maximum – Minimum) exceeds $1.2 billion in 1997 dollars. Note that the ranges of values and the standard deviations for the five economic measures for which variations

do occur for this input variable are less than those for first cost savings and reductions in delivery time (see Tables 8-6 and 8-8).

Table 8-9. Summary Statistics Due to Changes in the Input Variable Higher Contractor Net Income

Economic Measure	Statistical Measure						
	Minimum	25 %	50 %	75 %	Maximum	Mean	Standard Deviation
PVS_{ALL}	1,543.990	1,913.755	2,092.345	2,313.189	2,761.761	2,107.822	266.124
PVS_{BFRL}	111.208	139.181	152.692	169.399	203.334	153.862	20.133
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	81.111	109.085	122.595	139.303	173.238	123.766	20.133
SIR_{BFRL}	3.695	4.625	5.073	5.629	6.756	5.112	0.669
$AIRR_{BFRL}$	0.127	0.138	0.142	0.147	0.155	0.142	0.006

The results presented in Table 8-10 address the "costs" side of the analysis. Table 8-10 summarizes the results of the Monte Carlo simulation of variations about the baseline value of new technology introduction costs. Table 8-10 reveals moderate variations about the values calculated in the baseline analysis for five of the six economic measures. The value of PVC_{BFRL} is not affected by the input variable new technology introduction costs. Reference to Table 8-10 reveals that the range of values for PVS_{ALL} (i.e., Maximum – Minimum) exceeds $400 million in 1997 dollars. One of the economic measures of BFRL's influence is the SIR. For this economic measure, the value calculated in the baseline analysis is 4.95. In Table 8-10, the minimum value for the SIR_{BFRL} is 4.446, and the maximum value is 5.454 (i.e., the baseline value of the SIR_{BFRL} $\pm$ 0.5). Note that the ranges of values and the standard deviations for the five economic measures for which variations do occur for the "costs" side of the analysis are less than those for three of the four input variables associated with the "savings/benefits" side of the analysis (i.e., first cost savings, reductions in delivery time, and higher contractor net income (see Tables 8-6, 8-8, and 8-9)). Thus, the economic measures are "less sensitive" to variations in the "costs" side of the analysis than they are to the "savings/benefits" side of the analysis.

Table 8-10. Summary Statistics Due to Changes in the Input Variable New-Technology Introduction Costs

Economic Measure	Statistical Measure						
	Minimum	25 %	50 %	75 %	Maximum	Mean	Standard Deviation
PVS_{ALL}	1,842.763	1,980.217	2,039.650	2,099.005	2,243.845	2,038.547	82.690
PVS_{BFRL}	133.810	144.209	148.705	153.195	164.153	148.622	6.256
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	103.714	114.113	118.609	123.099	134.057	118.525	6.256
SIR_{BFRL}	4.446	4.792	4.941	5.090	5.454	4.938	0.208
$AIRR_{BFRL}$	0.136	0.139	0.141	0.142	0.145	0.141	0.002

Table 8-11 shows how variations about the baseline value for the time of first use (i.e., t = 1 in the year 2005) 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: 2004, 0.125; 2005, 0.5; 2006, 0.25; and 2007, 0.125. The time of first use affects all six economic measures. It exerts a strong influence on 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 2017. Thus, if the year of first use is 2007, there are fewer years over which savings can accrue than for the baseline value (i.e., 2005). Notice that the measures of BFRL's influence are strongly affected. This is because BFRL's contribution is measured in terms of the savings occurring in those years before CONSiAT products and services would become available commercially *were it not for BFRL's influence* (i.e., 2009). The year of first use defines when savings begin. Also, because BFRL is targeting the introduction of CONSiAT products and services for a particular year, BFRL's investment cost stream, $PVC_{BFRL,}$ varies as a function of the target date. Thus, the differences from the value calculated in the baseline analysis are due to the timing of the savings and BFRL's investment cost stream, which, through the discount rate, affects the values of PVS_{BFRL} and PVC_{BFRL}. Variations in the value of PVS_{BFRL} and PVC_{BFRL} are responsible for variations in the values of $PVNS_{BFRL}$, SIR_{BFRL}, and $AIRR_{BFRL}$.

Table 8-11. 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}	1,228.759	1,600.363	2,043.250	2,043.250	2,565.989	1,895.803	377.778
PVS_{BFRL}	39.878	81.620	148.978	148.978	254.392	131.538	60.316
PVC_{BFRL}	27.724	29.590	30.096	30.096	37.152	30.520	2.565
$PVNS_{BFRL}$	12.154	52.030	118.881	118.881	217.240	101.019	58.042
SIR_{BFRL}	1.438	2.758	4.950	4.950	6.847	4.204	1.613
$AIRR_{BFRL}$	0.086	0.114	0.141	0.141	0.156	0.129	0.021

Table 8-12 shows how variations about the baseline value for the length of the delay 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: 0 years, 0.6; 1 year, 0.25; and 2 years, 0.15. The length of delay affects five of the six economic measures. The value of PVC_{BFRL} is not affected by the input variable length of delay. Because the baseline analysis assumed no delay, the computed value for each economic measure equals the value calculated in the baseline analysis for three of the six statistical measures (i.e., the 50th percentile, the 75th percentile, and the maximum). By virtue of the way the discrete distribution is specified for the length of the delay, the 25th percentile is associated with a one-year delay and the minimum is associated with a two-year delay. Reference to Table 8-12 reveals that the minimum value for three of the five measures of BFRL's influence—$PVNS_{BFRL}$, SIR_{BFRL}, and $AIRR_{BFRL}$—is lower than the corresponding minimum value for each of

these variables examined previously. Although the minimum values for these three measures of BFRL's influence are smaller for this input variable than for the other ten, in every case BFRL's contribution is positive (i.e., $PVNS_{BFRL} > 0.0$, $SIR_{BFRL} > 1.0$, and $AIRR_{BFRL} > 0.07$). The length of delay affects the calculated values of the economic measures in a way that is similar to the year of first use. This is because BFRL's contribution is measured in terms of the savings occurring in those years before CONSiAT products and services would become available commercially *were it not for BFRL's influence* (i.e., 2009). Thus, a two-year delay, measured against the baseline year of first use of 2005, delays the commencement of the savings/benefits stream until 2007. Reference to Table 8-11 reveals that the minimum values for PVS_{ALL} and PVS_{BFRL} are the same as in Table 8-12. In the case of Table 8-11, these values correspond to a "no delay" (i.e., the baseline value for the length of delay) and a year of first use of 2007.

Table 8-12. 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}	1,228.759	1,600.363	2,043.250	2,043.250	2,043.250	1,809.484	304.240
PVS_{BFRL}	39.878	81.620	148.977	148.977	148.977	115.552	42.329
PVC_{BFRL}	30.096	30.096	30.096	30.096	30.096	30.096	0.0
$PVNS_{BFRL}$	9.782	51.523	118.881	118.881	118.881	85.456	42.329
SIR_{BFRL}	1.325	2.712	4.950	4.950	4.950	3.839	1.406
$AIRR_{BFRL}$	0.082	0.114	0.141	0.141	0.141	0.125	0.021

Table 8-13 summarizes the results of a deterministic sensitivity analysis for the combined effects of the "targeted" time of first use and the length of delay. Table 8-13 has three parts: (1) Part A, where each targeted time of first use is evaluated assuming no delay; (2) Part B, where each targeted time of first use is evaluated assuming a one-year delay; and (3) Part C, where each targeted time of first use is evaluated assuming a two-year delay. The results presented in Table 8-13 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 $650 million to nearly $2.6 billion in 1997 dollars. Thus, the combined effects of the targeted time of first use and the length of the delay are a key driver in estimating PVS_{ALL}. Second, the minimum values of four of the key measures of BFRL's influence (i.e., PVS_{BFRL}, $PVNS_{BFRL}$, SIR_{BFRL}, and $AIRR_{BFRL}$[101]) indicate that BFRL's CONSiAT-related investments may not be cost effective. To place the previous remark in context, it is important to recognize that this outcome corresponds to situations where a non-zero delay is present. For example, reference to Part A of Table 8-13 reveals that for all targeted times of first use all economic measures indicate that BFRL's CONSiAT-related investments are cost effective. Reference to Parts B and C

[101] 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. Similarly, if the computed value of SIR_{BFRL} is zero or positive but after taking the $1/L^{th}$ root (see Equation 2.5) the imputed value of $AIRR_{BFRL}$ is negative, then the value of $AIRR_{BFRL}$ is listed as n.a.

reveals that a delay of one year for the 2007 targeted time of first use and of two years for the 2006 targeted time of first use will result in a negative $PVNS_{BFRL}$. What Table 8-13 does not show is the probability that BFRL's CONSiAT-related investment will not be cost effective. To estimate the probability that BFRL's CONSiAT-related investment will not be cost effective requires a more comprehensive analysis. Specifically, Table 8-13 demonstrates that the combined effects of the targeted year of first use and the length of the delay are sufficient to lead to "undesirable" outcomes. However, what about other combinations of input variables? Could combinations of all eleven inputs lead to more extreme outcomes or will they offset the "undesirable" outcomes illustrated in Table 8-13? This analysis "topic" is the subject of Subsection 8.3.2

Table 8-13. Results of the Deterministic Sensitivity Analysis for the Combined Effects Due to Changes of the Input Variables "Targeted" Time of First Use and the Length of the Delay

Part A: No Delay

Economic Measure	Year of First Commercial Use			
	2004	**2005**	**2006**	**2007**
PVS_{ALL}	2,565.989	2,043.250	1,600.362	1,228.758
PVS_{BFRL}	254.392	148.977	81.620	39.878
PVC_{BFRL}	37.152	30.096	29.590	27.724
$PVNS_{BFRL}$	217.240	118.881	52.030	12.154
SIR_{BFRL}	6.847	4.950	2.758	1.438
$AIRR_{BFRL}$	0.156	0.141	0.114	0.086

Part B: One-Year Delay

Economic Measure	Year of First Commercial Use			
	2004	**2005**	**2006**	**2007**
PVS_{ALL}	2,043.250	1,600.362	1,228.758	920.073
PVS_{BFRL}	148.977	81.620	39.878	14.717
PVC_{BFRL}	37.152	30.096	29.590	27.724
$PVNS_{BFRL}$	111.825	51.523	10.288	-13.007
SIR_{BFRL}	4.010	2.712	1.348	0.531
$AIRR_{BFRL}$	0.131	0.114	0.083	0.043

Part C: Two-Year Delay

Economic Measure	Year of First Commercial Use			
	2004	**2005**	**2006**	**2007**
PVS_{ALL}	1,600.362	1,228.758	920.073	667.724
PVS_{BFRL}	81.620	39.878	14.717	0.0
PVC_{BFRL}	37.152	30.096	29.590	27.724
$PVNS_{BFRL}$	44.467	9.782	-14.872	-27.724
SIR_{BFRL}	2.197	1.325	0.497	0.0
$AIRR_{BFRL}$	0.104	0.082	0.041	n.a.

8.3.2 Changing All Eleven Inputs in Combination

Table 8-14 summarizes the results of the Monte Carlo simulation in which all eleven of the input variables were varied in combination. Reference to Table 8-14 reveals 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 CONSiAT-related investments are not cost effective. However, on the opposite extreme, $PVNS_{BFRL}$ may exceed \$975 million in 1997 dollars, and SIR_{BFRL} reaches 26.1.

A closer examination of Table 8-14 reveals several interesting outcomes. First, the range of values—the difference between the minimum and maximum—is very wide. For example, the minimum value of PVS_{ALL} is approximately \$175 million, whereas the maximum is over \$9.0 billion. Second, the computed value of the mean equals or exceeds the computed value of the median for each of the six economic measures. This is because a small number of very large observations are pulling up the computed value of the mean. Third, the computed value of the standard deviation for each of the six economic measures is higher than the corresponding value for variations in a single input variable. This is also due to a small number of very large observations. Finally, the computed value of the median for five of the six economic measures is lower than the corresponding baseline value. This is due to the way the length of the delay enters into the calculations. In the baseline analysis, no delay was assumed. Thus, if CONSiAT products and services were targeted for commercialization in 2005, they were assumed to enter the market in 2005. In the sensitivity analysis, CONSiAT products and services enter the market in the year targeted 60 % of the time, one year after the year targeted 25 % of the time, and two years after the year targeted 15 % of the time. As was seen in Part C of Table 8-13, a delay of two years may lead to commercialization in 2009, the year in which commercialization is assumed to take place without BFRL's participation. Thus, although the nation reaps substantial cost savings associated with the use of CONSiAT products and services, none of these savings are attributed to BFRL. This is due to our conservative approach to measuring BFRL's impact, in which zero weight is assigned to any savings accruing in 2009 or thereafter.

Table 8-14. 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}	175.344	1,281.868	2,021.767	2,880.348	9,458.448	2,241.291	1,264.779
PVS_{BFRL}	0.0	49.370	102.290	197.981	965.197	144.963	137.569
PVC_{BFRL}	25.332	29.082	30.563	32.969	43.914	31.519	3.573
$PVNS_{BFRL}$	-31.500	19.083	71.917	166.170	921.690	113.444	136.092
SIR_{BFRL}	0.0	1.634	3.275	6.151	22.185	4.465	3.963
$AIRR_{BFRL}$	n.a.	0.083	0.115	0.144	0.224	0.115	0.043

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.

The graphical results of the sensitivity analysis where all eleven 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 8-15. 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 8-15 and the values used to plot each figure.

Table 8-15 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.[102]

Figure 8-1 shows how present value cost savings nationwide, PVS_{ALL}, varies when all eleven 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 \$2,043.2 million. As was seen in Table 8-14, the median value of the 1,000 observations was \$2,021.8 million, more than \$20 million less than 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 8-15. First, the lower limit shown on Figure 8-1 is \$175.3 million. However, the 1st percentile for PVS_{ALL} is \$434.9 million. Thus, only 10 observations out of 1,000 are clustered between \$175.3 and the 1st percentile (\$434.9 million). Second, the CDF increases at a steady, almost linear rate between the 5th percentile (\$722.5 million) and the 65th percentile (\$2,482.9 million). Third, above the 65th 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 more than \$9.0 billion. However, the 99th percentile is \$6,159.9 million. Thus, only 10 observations out of 1,000 account for

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

approximately \$3.3 billion in the total range of values for PVS_{ALL}. This implies that the trace of the CDF for PVS_{ALL} is positively skewed.

Figure 8-2 shows how present value savings due to BFRL, PVS_{BFRL}, varies when all eleven 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 \$149.0 million. As was seen in Table 8-14, the median value of the 1,000 observations was more than \$45 million less than 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 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 8-15. First, note that the lower limit shown on Figure 8-2 extends to \$0.0. Reference to Table 8-15 reveals that the 1st percentile for PVS_{BFRL} is still \$0.0. However, by the 2nd percentile, the computed value of PVS_{BFRL} becomes positive (\$6.8 million). Thus, less than 20 observations out of 1,000 result in no savings attributable to BFRL. Stated another way, there is at least a 98 percent probability that BFRL's CONSiAT-related efforts will produce positive and measurable cost savings to building owners, managers, and contractors. Second, the CDF increases at a steady, almost linear rate between the 5th percentile (\$14.0 million) and the 55th percentile (\$114.2 million). Third, above the 55th 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 \$1.0 billion. However, the 99th percentile is \$643.6 million. Thus, only 10 observations out of 1,000 account for more than \$300 million in the total range of values for PVS_{BFRL}.

Figure 8-3 shows how the present value of BFRL's CONSiAT-related investment costs, PVC_{BFRL}, varies when all eleven input variables are varied in combination. Because the only variables that produce variations in PVC_{BFRL} are the discount rate and the "targeted" time of first use, 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 8-14 and 8-15 reveals that the CDF for PVC_{BFRL} exhibits not only a long tail on the upper end but a significant lower tail as well. From Table 8-14 we see that the mean and median are relatively close in value, and are nearly equal to the baseline value. An examination of Figure 8-3 reveals that the trace of the CDF for PVC_{BFRL} is nearly linear between the 15th percentile (\$28.388 million) and the 55th percentile (\$30.927 million). Below the 15th percentile and above the 55th percentile the traces exhibit similar patterns of non-linearity.

Table 8-15. 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	434.878	0.000	26.036	-26.850	0.000	n.a.
2ND	535.190	6.845	26.591	-21.885	0.247	0.004
3RD	611.309	9.062	26.905	-20.003	0.322	0.018
4TH	659.043	12.307	27.200	-17.723	0.392	0.023
5TH	722.468	14.047	27.337	-15.570	0.478	0.029
6TH	756.238	16.313	27.501	-12.919	0.541	0.035
7TH	780.614	19.329	27.604	-9.873	0.670	0.039
8TH	808.963	20.901	27.715	-8.470	0.725	0.043
9TH	851.209	22.900	27.819	-6.664	0.781	0.047
10TH	881.443	24.145	27.926	-5.273	0.806	0.051
11TH	922.071	25.263	28.044	-3.841	0.872	0.053
12TH	943.764	27.136	28.128	-2.985	0.905	0.056
13TH	972.305	28.713	28.227	-1.651	0.947	0.059
14TH	988.239	30.432	28.315	-0.610	0.983	0.063
15TH	1,025.116	32.704	28.388	1.039	1.035	0.065
16TH	1,060.482	34.788	28.464	3.175	1.114	0.067
17TH	1,091.651	37.324	28.569	6.427	1.212	0.069
18TH	1,119.391	38.655	28.644	7.784	1.247	0.070
19TH	1,151.653	40.161	28.747	9.374	1.293	0.072
20TH	1,182.443	41.665	28.798	10.834	1.343	0.074
21ST	1,213.660	42.734	28.834	12.097	1.402	0.076
22ND	1,228.623	44.129	28.895	13.797	1.479	0.079
23RD	1,248.936	45.506	28.947	15.758	1.542	0.081
24TH	1,271.603	47.711	28.992	17.948	1.588	0.082
25TH	1,281.868	49.370	29.082	19.083	1.634	0.083
26TH	1,307.276	50.509	29.107	20.613	1.672	0.086
27TH	1,333.089	52.804	29.193	22.568	1.708	0.087
28TH	1,356.584	54.515	29.236	23.617	1.763	0.088
29TH	1,398.697	56.196	29.288	25.335	1.822	0.090
30TH	1,421.671	57.908	29.348	26.796	1.875	0.091
31ST	1,443.509	59.648	29.425	29.352	1.970	0.092
32ND	1,472.499	61.347	29.494	31.135	2.009	0.093
33RD	1,485.861	63.396	29.538	32.216	2.051	0.095

Table 8-15. 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	1,513.295	64.937	29.597	33.512	2.082	0.097
35TH	1,544.215	68.040	29.675	36.785	2.151	0.098
36TH	1,563.046	71.734	29.726	39.019	2.247	0.099
37TH	1,626.350	73.356	29.773	41.736	2.320	0.100
38TH	1,646.932	74.381	29.825	43.514	2.410	0.102
39TH	1,676.115	76.058	29.878	45.381	2.478	0.103
40TH	1,723.824	78.632	29.934	47.709	2.557	0.104
41ST	1,756.417	80.998	30.005	50.170	2.623	0.105
42ND	1,790.737	82.459	30.093	52.795	2.721	0.107
43RD	1,821.645	85.515	30.144	54.932	2.800	0.108
44TH	1,840.118	87.200	30.184	56.528	2.848	0.109
45TH	1,887.268	89.643	30.261	59.088	2.919	0.110
46TH	1,906.372	92.488	30.329	61.974	3.002	0.111
47TH	1,922.767	95.384	30.401	63.911	3.070	0.112
48TH	1,950.238	97.624	30.463	66.466	3.104	0.113
49TH	1,991.902	100.021	30.507	68.780	3.196	0.114
50TH	2,021.767	102.289	30.563	71.917	3.275	0.115
51ST	2,040.600	104.153	30.613	72.883	3.345	0.116
52ND	2,061.042	107.092	30.708	75.335	3.466	0.118
53RD	2,094.349	109.727	30.817	78.448	3.557	0.120
54TH	2,118.994	111.740	30.862	80.298	3.630	0.122
55TH	2,147.880	114.233	30.927	83.571	3.722	0.123
56TH	2,175.044	116.571	31.017	85.307	3.771	0.124
57TH	2,204.782	118.358	31.111	87.573	3.820	0.125
58TH	2,238.217	120.712	31.220	90.327	3.947	0.125
59TH	2,274.449	124.728	31.278	92.708	4.034	0.127
60TH	2,291.294	129.318	31.353	97.929	4.131	0.128
61ST	2,318.604	132.214	31.473	101.426	4.224	0.129
62ND	2,355.183	137.925	31.528	105.731	4.337	0.130
63RD	2,369.167	143.833	31.654	111.489	4.484	0.131
64TH	2,439.813	148.742	31.749	116.733	4.576	0.133
65TH	2,482.908	151.108	31.831	119.040	4.684	0.133
66TH	2,524.340	155.513	31.946	122.814	4.765	0.134

Table 8-15. 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	2,569.283	159.333	32.018	126.568	4.909	0.135
68TH	2,600.039	160.924	32.099	130.421	5.036	0.136
69TH	2,641.754	166.157	32.181	133.533	5.161	0.138
70TH	2,684.697	173.168	32.258	139.907	5.324	0.139
71ST	2,715.175	175.196	32.427	143.015	5.461	0.140
72ND	2,742.537	180.309	32.554	148.406	5.604	0.142
73RD	2,784.116	186.752	32.718	152.843	5.760	0.143
74TH	2,840.822	191.332	32.822	160.434	5.982	0.144
75TH	2,880.348	197.981	32.969	166.170	6.151	0.144
76TH	2,911.200	203.773	33.166	170.681	6.283	0.145
77TH	2,969.542	207.453	33.382	173.426	6.417	0.147
78TH	3,041.057	213.672	33.563	179.975	6.722	0.148
79TH	3,091.839	220.699	33.698	186.540	6.795	0.150
80TH	3,142.960	225.004	34.006	191.383	6.885	0.151
81ST	3,191.522	231.086	34.182	199.983	7.031	0.153
82ND	3,284.231	239.803	34.372	205.397	7.246	0.155
83RD	3,322.662	246.877	34.607	215.811	7.414	0.156
84TH	3,406.120	255.861	34.854	221.688	7.760	0.158
85TH	3,464.851	262.125	35.057	232.176	8.118	0.160
86TH	3,574.719	277.741	35.437	244.341	8.555	0.161
87TH	3,631.953	284.927	35.836	251.437	8.917	0.163
88TH	3,748.802	293.996	36.150	262.652	9.099	0.165
89TH	3,872.849	303.034	36.414	270.953	9.339	0.168
90TH	4,004.900	323.771	36.728	292.232	9.897	0.170
91ST	4,066.758	336.964	37.161	305.919	10.315	0.172
92ND	4,165.854	354.956	37.752	321.525	11.013	0.173
93RD	4,279.951	370.381	38.231	332.924	11.563	0.176
94TH	4,497.911	388.787	38.949	352.795	12.399	0.180
95TH	4,689.204	418.273	39.510	387.700	12.803	0.181
96TH	4,903.826	472.659	40.079	442.733	13.458	0.184
97TH	5,260.735	522.145	40.946	481.645	14.610	0.189
98TH	5,501.136	556.376	41.625	521.035	15.959	0.197
99TH	6,159.887	643.572	42.021	611.532	18.018	0.205

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

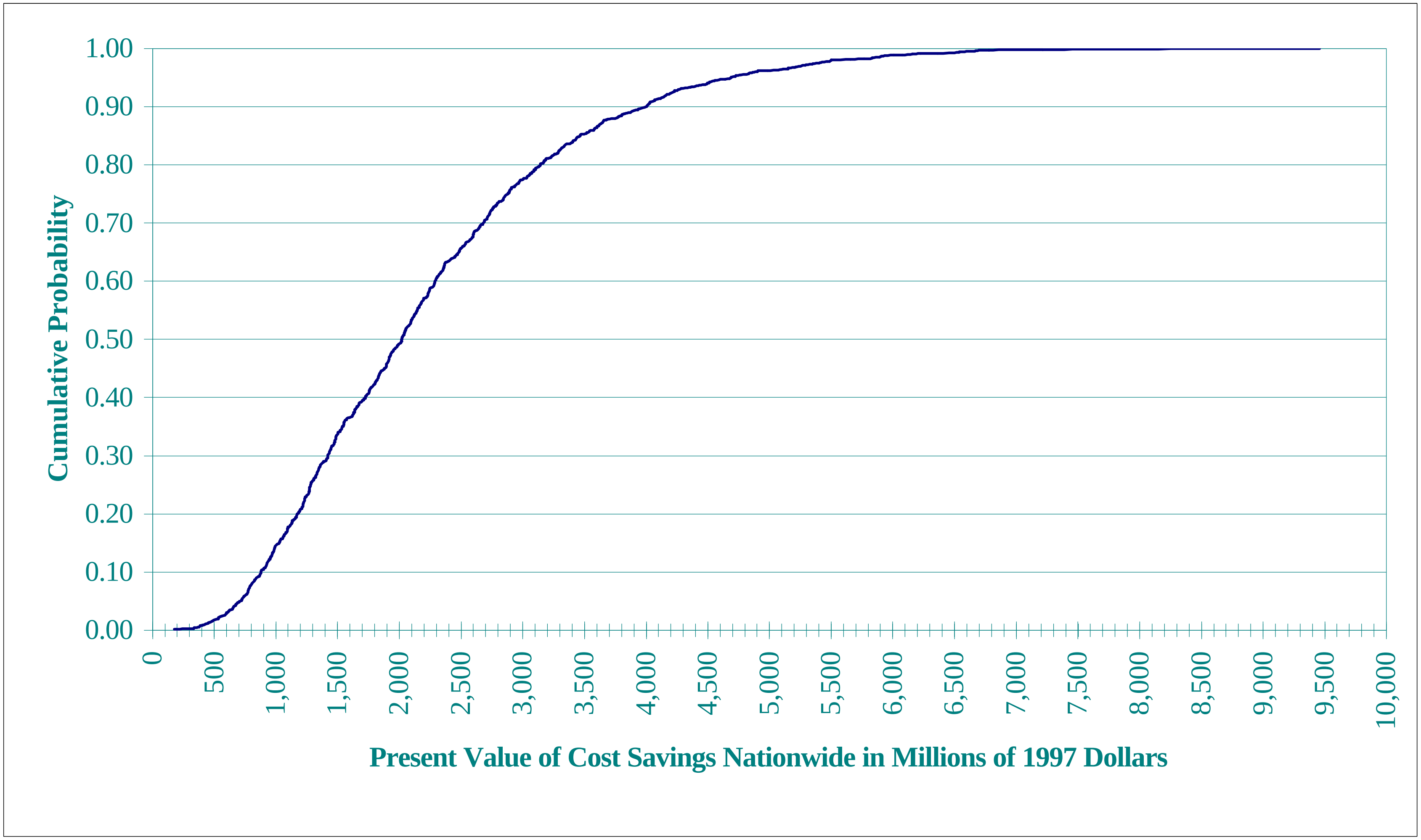


Figure 8-2. Present Value of Cost Savings Attributable to BFRL in Millions of 1997 Dollars

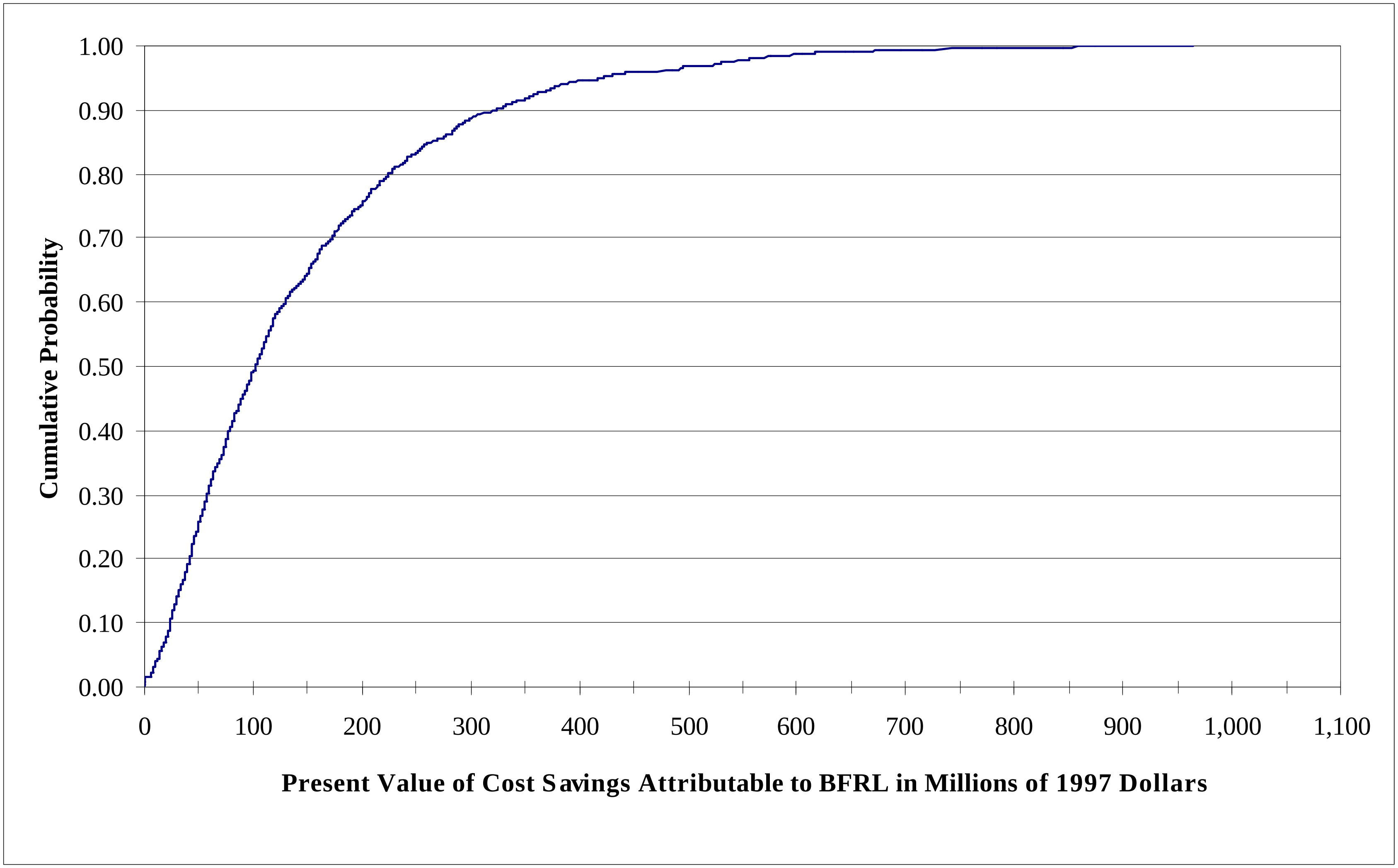


Figure 8-3. Present Value of BFRL's Investment Costs in Millions of 1997 Dollars

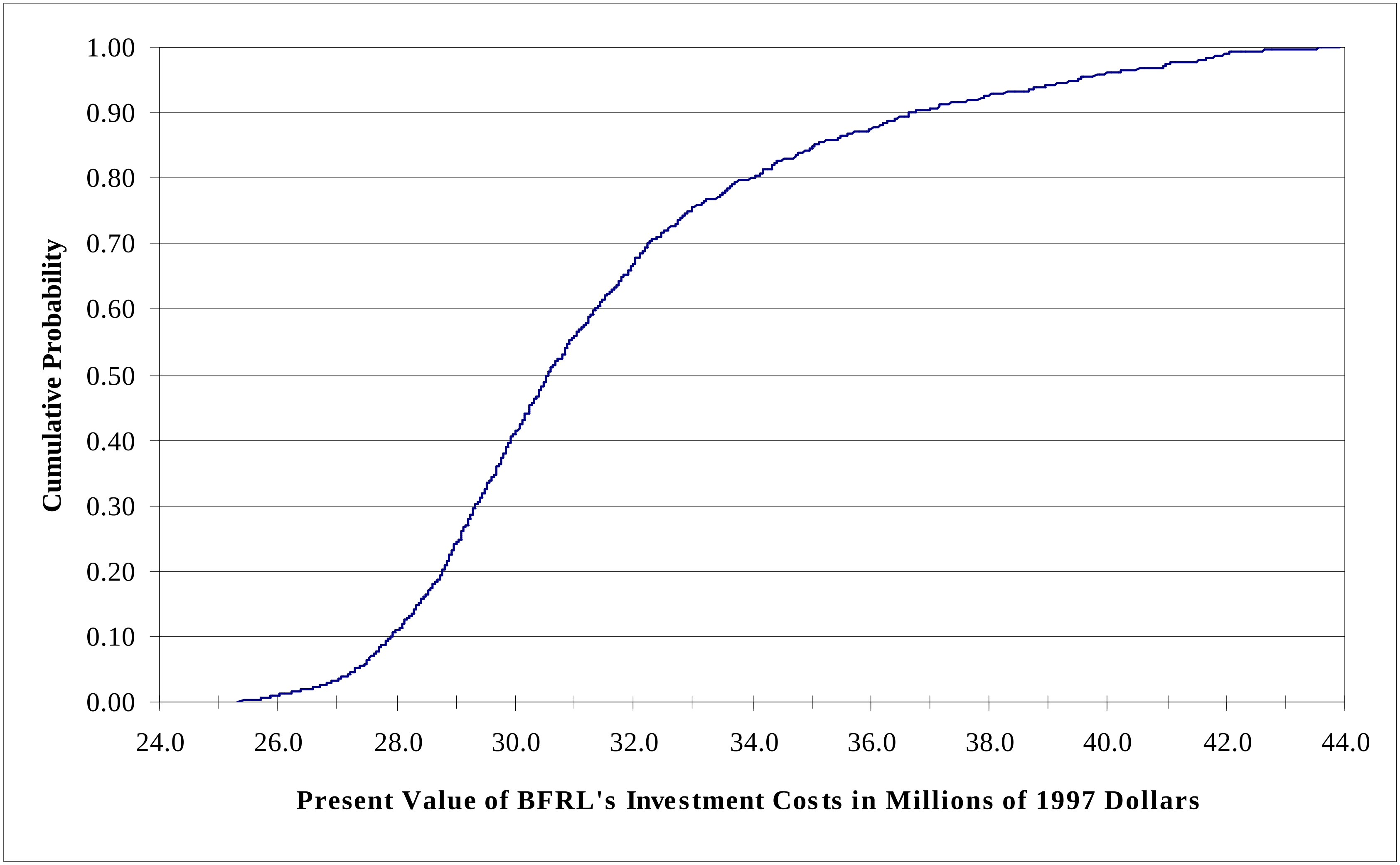


Figure 8-4 shows how present value net savings due to BFRL, $PVNS_{BFRL}$, varies when all eleven input variables are varied in combination. In analyzing Figure 8-4, it is useful to keep in mind that the value of $PVNS_{BFRL}$ resulting from the baseline analysis was $118.9 million. As was seen in Table 8-14, the median value of the 1,000 observations was nearly $50 million less than 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 relatively narrow range of values. Thus, throughout the range of values over which PVS_{BFRL} and $PVNS_{BFRL}$ are defined, the value of PVC_{BFRL} acts 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 8-15. First, note that the lower limit shown on Figure 8-4 extends below $0.0. Reference to Table 8-15 reveals that the 1st percentile for $PVNS_{BFRL}$ is still negative (-$26.8 million). However, by the 15th percentile, the computed value of $PVNS_{BFRL}$ becomes positive ($1.0 million). Thus, less than 150 observations out of 1,000 are negative. Stated another way, there is at least an 85 percent probability that BFRL's CONSiAT-related investments are cost effective. Second, the CDF increases at a steady, almost linear rate between the 5th percentile (-$15.6 million) and the 55th percentile ($83.6 million). Third, above the 55th 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 $1.0 billion. However, the 99th percentile is $611.5 million. Thus, only 10 observations out of 1,000 account for more than $300 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 $PVNS_{BFRL}$ (i.e., the 50 lowest values). Two factors, operating in combination, contribute to very low values of PVS_{BFRL} and $PVNS_{BFRL}$. These factors are "later" values for the "targeted" time of first use and the length of the delay. For example, of the 50 lowest values, only two had no delay, whereas 35 had a two-year delay. Four other factors had a strong influence: (1) reductions in delivery time, if its value is less than the 10th percentile of its parent CDF;

(2) reductions in first cost, if its value is less than the 10th percentile of its parent CDF; (3) h, the level at which the market for FIAPP products and services saturates, if its value is less than the 10th percentile of its parent CDF; and (4) a, the location parameter in the diffusion model, if its value is greater than the 90th percentile of its parent CDF. Very high values (i.e., the 50 highest values) were associated with two factors operating in combination—"earlier" values for the "targeted" time of first use and the length of the delay. For example, 48 of the 50 highest values had no delay and a "targeted" time of first use of 2004 or 2005. Five other factors had a strong influence: (1) reductions in first cost, if its value is greater than the 90th percentile of its parent CDF; (2) higher net income, if its value is greater than the 90th percentile of its parent CDF; (3) a, if its value is less than the 10th percentile of its parent CDF; (4) h, the level at which the market for FIAPP products and services saturates, if its value is greater than the 90th percentile of its parent CDF; and (5) the discount rate, if its value is less than the 10th percentile of its parent CDF.

Figure 8-5 shows how the savings-to-investment ratio on BFRL's CONSiAT-related investments, SIR_{BFRL}, varies when all eleven 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 4.95. As was seen in Table 8-14, the median value of the 1,000 observations was 3.275. 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 relatively narrow range of values. 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 8-15. First, note that the lower limit shown on Figure 8-5 extends to 0.0. Reference to Table 8-15 reveals that the 1st percentile for SIR_{BFRL} is still zero. However, by the 15th percentile, the computed value of SIR_{BFRL} exceeds 1.0 (1.035). Thus, less than 150 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 an 85 % probability that BFRL's CONSiAT-related investments are cost effective. Second, the CDF increases at a steady, almost linear rate between the 10th percentile (0.806) and the 50th percentile (3.275). 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 22.2. However, the 99th percentile is 18.018. Thus, only 10 observations out of 1,000 account for approximately 4 units in the total range of values for SIR_{BFRL}.

Figure 8-6 shows how the adjusted internal rate of return on BFRL's CONSiAT-related investments, $AIRR_{BFRL}$, varies when all eleven 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 0.141. As was seen in Table 8-14, both the mean and median values of the 1,000 observations were 0.115. 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 8-15. 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. Such cases are designated by the term n.a. in Tables 8-14 and 8-15. Reference to Table 8-15 reveals that the 1st percentile for $AIRR_{BFRL}$ is n.a. This entry is reflected by the "step-up" in the CDF at 0.0. By the 15th percentile, the computed value of $AIRR_{BFRL}$ exceeds the average value for the 1,000 "draws" from the parent CDF for the real discount rate of 0.0644. Thus, less than 150 observations out of 1,000 produce a value for the $AIRR_{BFRL}$ less than the average value of the discount rate.[103] Stated another way, based on the calculated value of $AIRR_{BFRL}$, there is at least an 85 percent probability that BFRL's CONSiAT-related investments are cost effective. Second, the CDF increases at a steady, almost linear rate between the 15th percentile (0.065) and the 85th percentile (0.160). 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 CONSiAT-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 15th 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.

[103] Note that the 18th percentile had a value of 0.07 (i.e., a value that equals the baseline value for the discount rate).

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

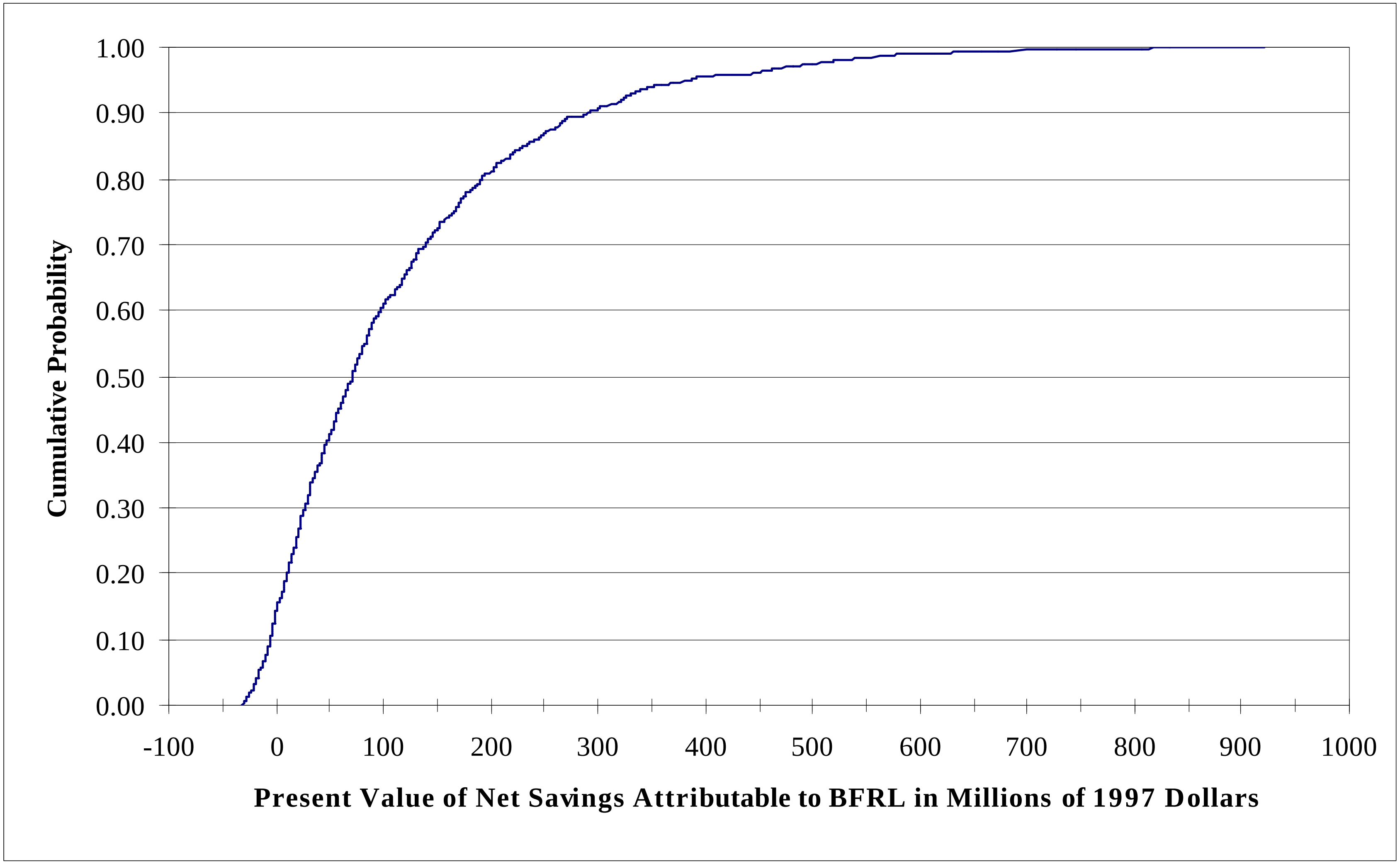


Figure 8-5. Savings to Investment Ratio on BFRL's Research and Development Investment

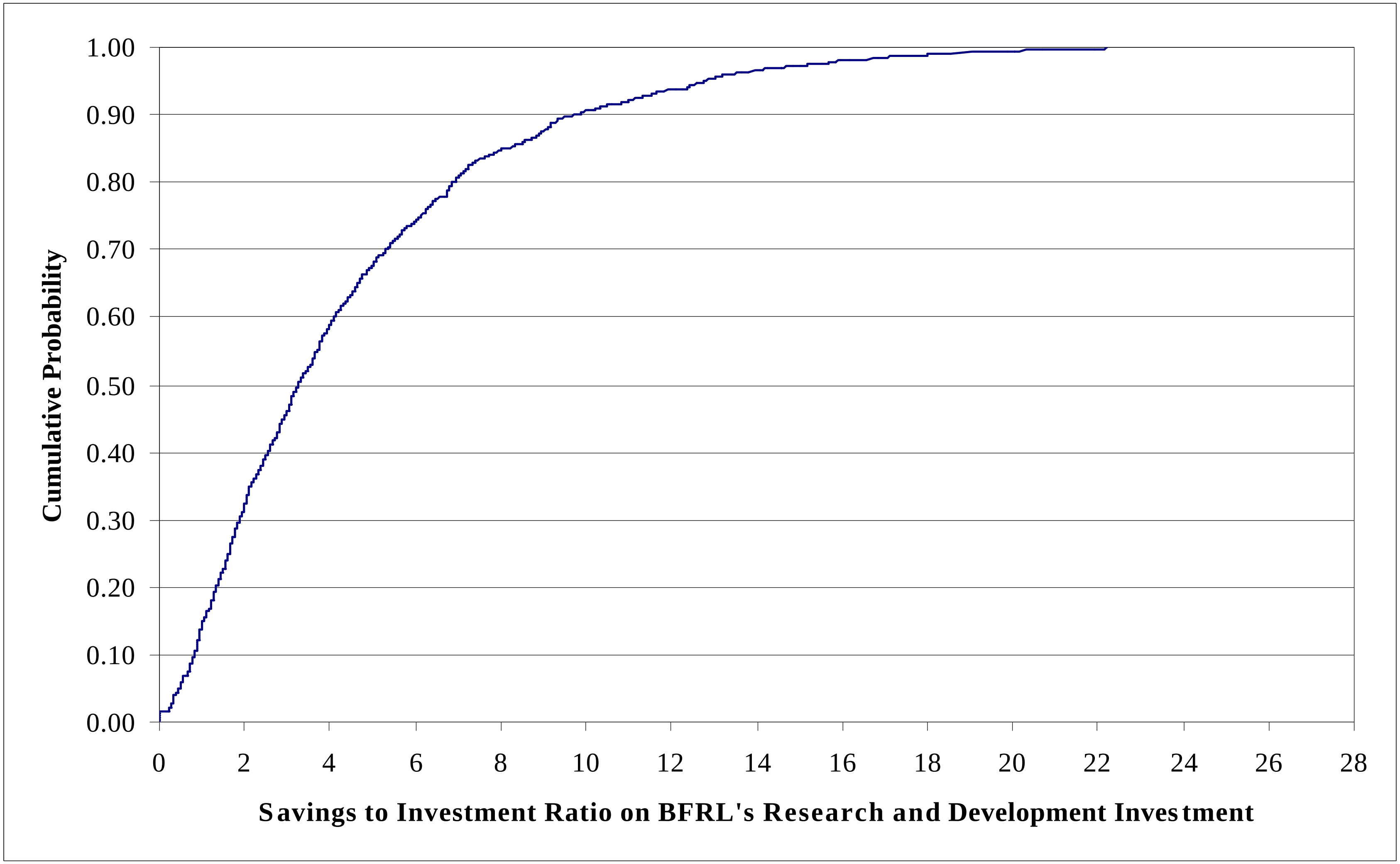
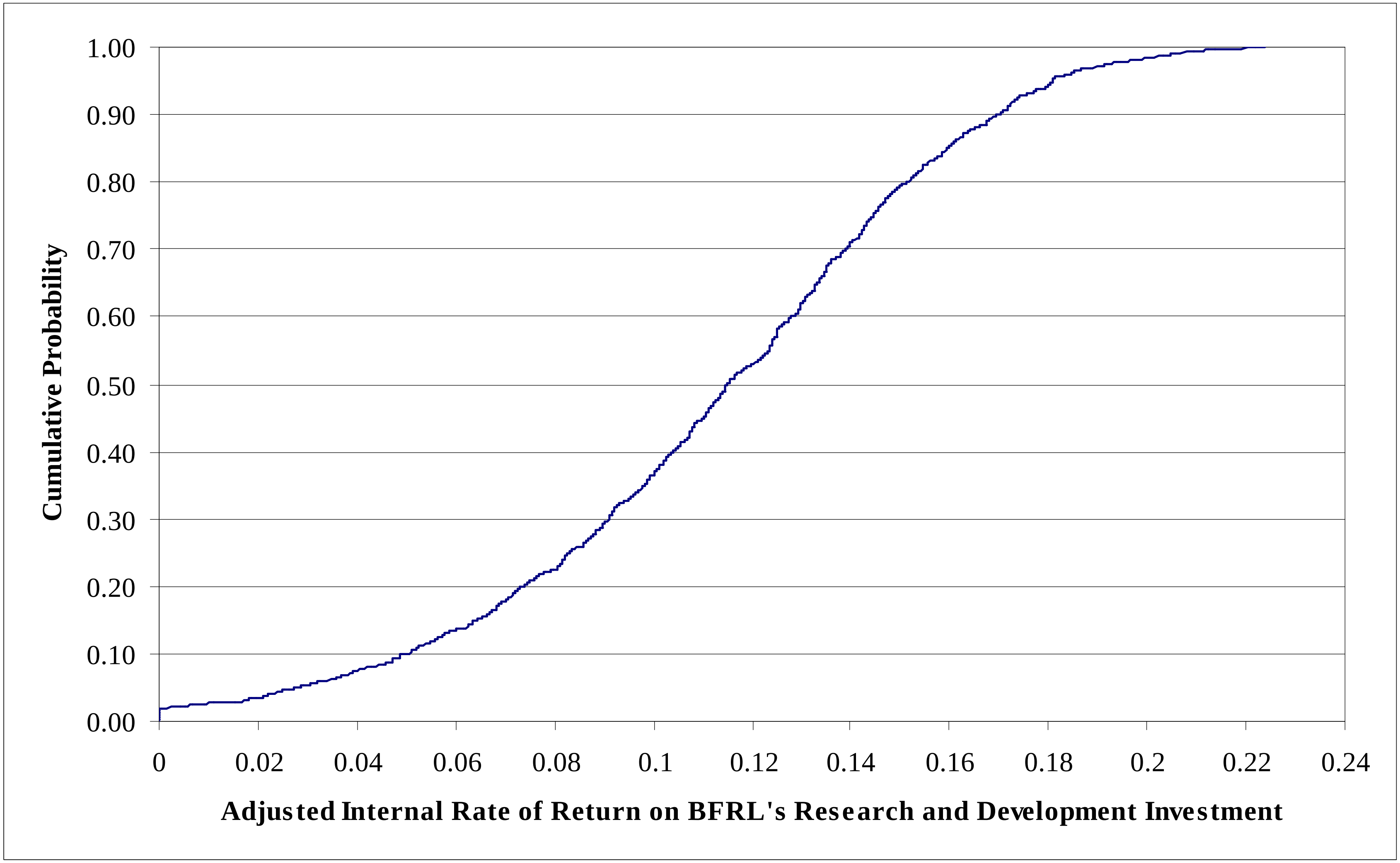


Figure 8-6. Adjusted Internal Rate of Return on BFRL's Research and Development Investment



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 fourth in a series of impact studies prepared by BFRL.[104] It focuses on BFRL's construction systems integration and automation technologies (CONSiAT) major product. The CONSiAT major product is an interdisciplinary research effort within BFRL—in collaboration with the Construction Industry Institute, the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies, standard communication protocols, and advanced measurement technologies needed to deliver fully-integrated and automated project process (FIAPP) products and services to the construction industry.

BFRL's CONSiAT major product is aimed at producing a suite of products and services that integrate a wide variety of planning, design, and construction activities. The goal of BFRL's

[104]The first report in the series 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). 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*. NISTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology). The third report focuses on the research, development, deployment, and adoption and use of cybernetic building systems in office buildings (see Chapman, Robert E. 1999. *Benefits and Costs of Research: A Case Study of Cybernetic Building Systems*. NISTIR 6303. Gaithersburg, MD: National Institute of Standards and Technology).

CONSiAT major product is to produce FIAPP products and services that will result in significant reductions in ***both*** the delivery time of constructed facilities ***and*** the life-cycle costs of those facilities. These products and services are being developed for use by building owners and operators, construction contractors, architects, engineers, and other providers of professional services.

This case study of BFRL's CONSiAT-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 CONSiAT-related investment costs that have already occurred along with estimates of future investment costs and cost savings due to the use of FIAPP products and services.

The CONSiAT 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, eleven 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 FIAPP products and services will generate substantial cost savings to industrial facility owners and managers and to contractors engaged in the construction of those facilities. The present value of savings nationwide expected from the use of FIAPP products and services is in excess of $2.0 billion (measured in 1997 dollars). Furthermore, because of BFRL's involvement, FIAPP products and services are expected to be commercially available in 2005. If BFRL had not participated in the development of FIAPP products and services, the commercial introduction of FIAPP products and services is expected to be delayed until 2009. Consequently, potential cost savings accruing to industrial facility owners and managers and to contractors over the period 2005 through 2008 would have been foregone. The present value of these cost savings is approximately $150 million. These cost savings measure the value of BFRL's contribution for its CONSiAT-related investment costs of approximately $30.1 million. Stated in present value terms, every public dollar invested in BFRL's CONSiAT-related research, development, and deployment effort is expected to generate $4.95 in cost savings to the public (i.e., an SIR of 4.95). The annual percentage yield (AIRR) from BFRL's CONSiAT-related investments over the study period is 14.1 %.

The objective of the sensitivity analysis was to evaluate how uncertainty in the values of each of the eleven 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 CONSiAT-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 CONSiAT-related investments, SIR_{BFRL}; and (6) the adjusted internal rate of return on BFRL's CONSiAT-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 CONSiAT-related investments were cost effective).

The results of the sensitivity analysis serve to validate the results of the baseline analysis. For example, each Monte Carlo simulation in which a single input variable was varied produced 1,000 observations for each of the six economic measures. Ten of the 11 such simulations produced values for the median and mean that were nearly identical to the corresponding value calculated in the baseline analysis for that measure. The final Monte Carlo simulation, in which all eleven of the input variables were varied in combination, also produced 1,000 observations for each of the six economic measures. In this case, the median value for each economic measure was less than the corresponding value calculated in the baseline analysis for that measure. In addition, the 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 CONSiAT-related investments are not cost effective. However, on the opposite extreme, $PVNS_{BFRL}$ may reach nearly $1.0 billion in 1997 dollars.

The range of values for an economic measure is so wide that it 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 CONSiAT-related investments. The second, the savings-to-investment ratio on BFRL's CONSiAT-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 CONSiAT-related investments, is a rate of return; it shows the annual return on the public monies going into the development of FIAPP products and services throughout the 25-year study period.

For each of the three economic measures, less than 150 observations out of 1,000 were responsible for the observed "uneconomical" outcome. Stated another way, there is at least an 85 % probability that BFRL's CONSiAT-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.[105] 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.[106] 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

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

[106]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.

the sole vehicle for communication is being eclipsed by other means of information dissemination. This 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 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 fewer/ shorter interruptions of process operations due to facility-related problems (e.g., faster turnarounds due to electronic "as-built" information) are not included. Similarly, estimates of the investments required to develop, test, and market FIAPP products and services by the vendor tier (see Figure 3-2) are not included. These challenges and others (e.g., improved estimates of new-technology introduction costs) are being addressed through the design and creation of a

database for compiling information on CONSiAT-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 CONSiAT-related impacts in preparation for the follow-up CONSiAT 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.[107]

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.[108]

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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[107]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.

[108]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. West Conshohoken, PA: American Society for Testing and Materials.

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