**Advanced Energy Design and
Operation Technologies Research
Recommendations for a
U.S. Department of Energy
Multiyear Program Plan**

**M. R. Brambley
D. B. Crawley
D. D. Hostetler
R. C. Stratton**

**M. S. Addison
J. J. Deringer
J. D. Hall
S. E. Selkowitz**

December 1988

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A10
226-250	A11
251-275	A12
276-300	A13

ADVANCED ENERGY DESIGN
AND OPERATION TECHNOLOGIES RESEARCH

RECOMMENDATIONS FOR A
U.S. DEPARTMENT OF ENERGY
MULTIYEAR PROGRAM PLAN

M. R. Brambley
D. B. Crawley
D. D. Hostetler
R. C. Stratton
M. S. Addison(a)
J. J. Deringer(b)
J. D. Hall(b)
S. E. Selkowitz(c)

December 1988

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

-
- (a) Arizona State University, Tempe, Arizona
(b) The Deringer Group, Riva, Maryland
(c) Lawrence Berkeley Laboratory, Berkeley, California

FOREWORD

This report is one in a series of reports describing research activities in support of the Commercial Building System Integration Research Program. The goal of the program is to develop the scientific and technical basis for improving integrated decision making during design and construction. Improved decision making could significantly reduce energy use in commercial buildings by the year 2010.

The objectives of the Commercial Building System Integration Research Program are:

- to identify and quantify the most significant energy-related interactions among building subsystems (for example, walls, roofs, windows, HVAC systems and equipment, lighting, power)
- to develop the scientific and technical basis for improving energy-related interactions in building subsystems
- to provide guidance to designers, owners and builders for improving the integration of building subsystems for energy efficiency.

This report describes the proposed multiyear program plan for one element of the Building System Integration Research program--advanced energy design and operation technologies. The objective of the advanced energy design and operation technologies research is to develop computer-based energy design and operation systems that can be integrated with proprietary systems.

The Pacific Northwest Laboratory leads this program, incorporating expertise and resources from industry, academia, other government entities, and other U.S. Department of Energy laboratories in planning, reviewing, and conducting research activities. Cooperative and complementary research, development, and technology transfer activities with other interested organizations are actively pursued.

Comments about the work described in this report will be appreciated by the authors and program managers. Program research reports prepared to date are listed on page xxiii of this report.

Drury B. Crawley
Program Manager
Building System Integration
Pacific Northwest Laboratory

Jean Boulin
Group Leader
Architectural and Engineering
Systems
Building Systems Division
U.S. Department of Energy

ABSTRACT

This document describes recommendations for a multiyear plan developed for the U.S. Department of Energy (DOE) as part of the Advanced Energy Design and Operation Technologies (AEDOT) research project. The plan is an outgrowth of earlier planning activities conducted for DOE as part of design process research under the Building System Integration Program (BSIP). The proposed research will produce intelligent computer-based design and operation technologies for commercial buildings. In this document, the concept is explained, the need for these new computer-based environments is discussed, the benefits are described, and a plan for developing the AEDOT technologies is presented for the 9-year period beginning FY 1989.

EXECUTIVE SUMMARY

This document recommends a basis for the U.S. Department of Energy (DOE) Advanced Energy Design and Operations Technologies (AEDOT) research project. The long-term goal of the project, supported by the DOE Office of Buildings and Community Systems (OBCS), is to increase the energy efficiency of the U.S. building stock. Most commercial buildings are uniquely designed and constructed one at a time. They are not generally produced in quantity from a single design as are cars, appliances, and many building components. Therefore, the building designer or design team is critical to increasing the energy efficiency of our new buildings. The project has two primary objectives:

- to develop technologies for building designers to use in making informed energy-related design decisions
- to provide computer-based aids for use in operating and managing buildings more energy efficiently.

The project is targeted at the nation's commercial buildings. Most public and private commercial buildings designed today will use more energy and cost more to operate than is necessary. Conservative estimates, based on recent research on building energy performance standards, indicate that with no additional first costs, at least 15% of the energy now used in new buildings could be saved using readily available energy-efficient building design knowledge. If additional measures requiring modest additional first cost (with payback periods less than 3 years) are considered, this estimate increases to approximately 30%. Early building system integration research suggests that by using building subsystem integration techniques, savings of 60% could be achieved.

Despite abundant opportunities for energy conservation in this sector, the buildings industry has made only limited progress toward improvements, for two principal reasons:

- Designing energy-efficient buildings is a complex task, involving many different design disciplines and requiring specialized expertise that takes years of study and practice to acquire.

- Currently available design tools do not provide sufficient information in a readily usable form at appropriate times in the design process, particularly in the early stages, to compensate for each individual designer's lack of knowledge about energy-efficient design.

The technologies produced by the AEDOT project will alleviate these obstacles during design and will help maintain energy performance throughout the building life cycle by providing automated assistance for

- identifying, at appropriate times in the process, design opportunities for reducing energy use
- identifying non-energy design decisions that could adversely impact building energy efficiency
- identifying good design strategies for implementing the most cost-effective energy conservation opportunities suitable for each specific building
- developing detailed design solutions for the design strategies that are selected
- operating and maintaining buildings to ensure energy-efficient performance.

The proposed research will use several rapidly developing computer technologies to make better use of existing and emerging energy-efficient building design and operation expertise and analysis tools. These technologies include computer-aided design (CAD), artificial intelligence (AI), random access databases, and advanced graphics and visualization systems. Emphasis will be placed on assisting design teams in the early phases of building design, which have the most significant impacts on a building's ultimate energy consumption.

The technologies developed during the AEDOT project will enable designers to consider many more design alternatives and evaluate each of them in greater depth than now possible. The AEDOT design tools are intended to be integrated with advanced CAD environments developed by the private sector. User-friendly graphic interfaces specifically designed for building designers will be intended to provide easy and efficient access to knowledge on energy-efficient building design and operation at any time and in any order desired by the designer. Advanced imaging capabilities will allow the user to directly investigate, in addition to quantitative criteria, the critical qualitative aspects of design

(e.g., view and glare) that strongly influence energy-related decisions and that currently are beyond the scope of simulation models.

A plan for the AEDOT research project is presented in this report. It provides background on the need for this research, describes the AEDOT concept, and details the tasks and activities needed for the 9-year project lifetime beginning in FY 1989.

Efforts during the first 4 years of the project should focus on developing energy-efficient building design technologies. The design effort comprises three primary activities:

- Requirements Analysis
- System Development
- Component Development

During the first 1.5 years of the project, efforts should focus on the Requirements Analysis. As results of this activity are produced, they should be used to guide the development of a demonstration system as part of the System Development task. Once the requirements are clearly specified, the Component Development task should begin. At that time, the focus should shift to developing components, integrating them into systems, and analyzing the individual components and the resulting systems. Obstacles associated with system integration should be addressed at the outset of the project through development and use of a testbed for System Development.

At the beginning of the project's fifth year, work on operation technologies should begin. This work should use technological advances resulting from earlier efforts on design technologies. Because this part of the project would depend on accomplishments earlier in the project, these recommendations for the multiyear plan currently provide fewer specific details on timelines and subtasks for the operation technologies effort. However, this information should be provided in annual planning documents as the project unfolds.

Research throughout the project should rely on established energy and computer technology bases developed in both the public and private sectors. By closely cooperating with industry, the AEDOT project would produce state-

of-the-art, integrated, building design and operation technologies that provide assistance throughout the building life cycle. The application of these technologies in the U.S. buildings industry presents an opportunity for major increases in productivity, significantly lower costs of owning and operating buildings, and improved decision making. The end result would be better, less expensive, more energy-efficient buildings.

The potential impact of the AEDOT technologies is unprecedented. These technologies are projected to provide annual savings from 2.3 to 4.6 quads of primary energy, or about 15% to 30% of the projected total commercial building sector consumption. The estimated savings of \$50 billion to \$200 billion (1986 \$) resulting from these technologies over the first 15 years of use alone greatly overshadow the \$27 million cost for research and development. As a result, these technologies have the potential for a major, lasting impact on the nation's energy consumption.

ACKNOWLEDGMENTS

Many people and organizations were involved in the development and review of this proposed multiyear program plan for Advanced Energy Design and Operation Technologies research. The authors acknowledge the contributions of

T. A. Armstrong, IBM Corporation
J. J. Boulin, U.S. Department of Energy
C. Bovill, University of Tennessee
G. Z. Brown, University of Oregon
R. S. Crowder, III, Pacific Northwest Laboratory
C. Gardner, U.S. Department of Energy
J. Haberl, Princeton University
R. E. Johnson, University of Michigan
Y. E. Kalay, State University of New York, Buffalo
J. J. Kim, Lawrence Berkeley Laboratory
L. Lawrie, U.S. Army Construction Engineering Research Laboratory
R. B. Melton, Pacific Northwest Laboratory
L. Norford, Massachusetts Institute of Technology
B. J. Novell, Intergraph Corporation
K. Papamichael, Lawrence Berkeley Laboratory
M. S. Rees, Kaiser Engineers Hanford Company
F. Rubinstein, Lawrence Berkeley Laboratory
K. Ruberg, National Research Council Canada
G. Schmitt, Carnegie-Mellon University
P. H. Smeallie, National Research Council
R. Sullivan, Lawrence Berkeley Laboratory
G. Ward, Lawrence Berkeley Laboratory
G. M. Wilde, Lawrence Berkeley Laboratory
J. E. Woods, Honeywell Inc.

ACRONYMS

AEDOT	Advanced Energy Design and Operation Technologies
AE	architecture/engineering
AI	artificial intelligence
AIA	American Institute of Architects
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
BOMA	Building Owners and Managers Association International
BPA	Bonneville Power Administration
BSIP	Building System Integration Research Program
CABD	computer-aided building design
CAD	computer-aided design
CADD	computer-aided design and drafting
DOE	U.S. Department of Energy
EDA	Energy Design Advisor
ELCAP	End-Use Load and Consumer Assessment Program
EMCS	energy management and control systems
ERAB	Energy Research Advisory Board
ICADD	intelligent computer-aided building design and drafting system
GNP	gross national product
HVAC	heating, ventilation, and air conditioning
IES	Illuminating Engineering Society of North America
KBS	knowledge-based systems
LBL	Lawrence Berkeley Laboratory
NAHB	National Association of Home Builders

OBCS	DOE Office of Buildings and Community Systems
PNL	Pacific Northwest Laboratory
R&D	research and development
VLSI	very large scale integration

CONTENTS

FOREWORD	iii
ABSTRACT	v
EXECUTIVE SUMMARY	vii
ACKNOWLEDGMENTS	xi
ACRONYMS	xiii
BUILDING SYSTEM INTEGRATION RESEARCH REPORTS	xxiii
1.0 INTRODUCTION	1.1
1.1 BACKGROUND	1.1
1.2 PROJECT OBJECTIVES	1.4
1.3 REPORT CONTENTS	1.7
2.0 OPPORTUNITIES FOR ENERGY-EFFICIENT BUILDING DESIGN	2.1
2.1 COMPLEXITY AND COST OF ENERGY-EFFICIENT BUILDING DESIGN	2.3
2.1.1 Complex Energy Interactions	2.3
2.1.2 Multiple Design Criteria	2.4
2.1.3 Use of Design Teams	2.4
2.1.4 Current Cost of Designing Energy-Efficient Buildings	2.8
2.2 THE NEED FOR NEW TECHNOLOGIES TO SUPPORT ENERGY-EFFICIENT BUILDING DESIGN	2.8
2.2.1 Inadequacies of Current Design Support	2.9
2.2.2 Current and Emerging Methods	2.12
2.2.3 Software	2.13
2.2.4 Computer Hardware	2.15

3.0	CONCEPTUAL DESCRIPTION OF AEDOT CAPABILITIES AND CHARACTERISTICS	3.1
3.1	GENERAL CAPABILITIES	3.1
3.2	CHARACTERISTICS	3.2
3.3	USE SCENARIO	3.3
4.0	BENEFITS OF THE AEDOT RESEARCH PROJECT	4.1
4.1	BENEFITS TO THE NATION	4.1
4.2	BENEFITS TO BUILDING OWNERS	4.5
4.3	BENEFITS TO BUILDING USERS	4.8
5.0	RESEARCH AND DEVELOPMENT PLAN	5.1
5.1	APPROACH	5.1
5.2	OVERVIEW	5.2
5.3	ELEMENTS OF THE PLAN	5.5
5.3.1	Requirements Analysis	5.5
5.3.2	System Development	5.12
5.3.3	Other Elements	5.24
5.4	MANAGEMENT AND COORDINATION	5.26
5.4.1	Management	5.26
5.4.2	Industry Coordination	5.28
5.5	ESTIMATED COSTS AND LEVEL OF EFFORT	5.29
6.0	REFERENCES	6.1
APPENDIX A	- DIMINISHING DEMAND FOR DESIGNING ENERGY-EFFICIENT BUILDINGS	A.1
APPENDIX B	- CHARACTERISTICS OF THE BUILDING DESIGN AND CONSTRUCTION INDUSTRY	B.1
APPENDIX C	- EMERGING TECHNOLOGY AND RESEARCH BASE	C.1

APPENDIX D - CURRENT RESEARCH ON KNOWLEDGE-BASED BUILDING DESIGN SYSTEMS AND KNOWLEDGE-BASED OPERATION MANAGEMENT SYSTEMS	D.1
APPENDIX E - POTENTIAL APPLICATIONS FOR INTELLIGENT COMPUTER-BASED DESIGN AND OPERATION TECHNOLOGIES	E.1
APPENDIX F - PRINCIPAL AREAS FOR KNOWLEDGE ACQUISITION	F.1

FIGURES

1.1	Computer and CADD Use by Building Design Professionals	1.3
1.2	Sample Conceptual Structure for the Advanced Building Design System	1.6
2.1	Average Commercial-Sector Building Primary Energy-Use Intensity	2.1
2.2	Median Share of Operating Costs by Major Categories for Commercial Office Buildings	2.2
2.3	Relative Impact of Design Team Members on Life-Cycle Costs . . .	2.7
2.4	Computer Automation by Task for Building Design Practices	2.10
2.5	Impact of Major Decision Makers on Building Life-Cycle Costs	2.11
2.6	Impact of Design Phases on Building Life-Cycle Costs	2.11
2.7	Distribution of Costs for CADD Systems Currently Owned by Architectural and Engineering Offices	2.15
4.1	Contributions of Energy Resources, Including Improved End-Use Efficiency, to U.S. Energy Supply in 1984	4.1
4.2	Relative Energy Consumption and Savings by Economic Sector for 1973 and 1984	4.2
4.3	Relative Energy-Use Intensities (EUIs) by Economic Sector	4.3
4.4	Cumulative Projected Dollar Savings from Improved Energy Efficiency in New and Retrofitted Commercial Buildings	4.4
4.5	Relative Magnitude of Typical Office Building Life-Cycle Costs	4.6
4.6	Analysis of Life-Cycle Cost Components Based on Prototypical Building	4.7
5.1	Domain of AEDOT Research	5.2
5.2	Schedule of Elements Comprising the AEDOT Research Project . . .	5.3
5.3	Sequence and Timing of Requirements Analysis Tasks	5.9

5.4	Relationships Between the Three Components of System Development	5.14
5.5	Preliminary AEDOT Components and Their Relationships to the Testbed	5.15
5.6	Testbed Software by Function	5.16
5.7	System Development Life Cycle	5.17
5.8	Stages of Analysis	5.18
5.9	Sequence and Timing of System Development Tasks	5.20
5.10	Sequence and Timing of System Development Tasks Over the First 1.5 Years of the Project	5.21
5.11	Example of the Testbed Hardware Environment	5.22
5.12	Organizational Structure for the AEDOT Project	5.27
A.1	Commercial-Sector Energy Prices by Source	A.2
A.2	Average Operating Costs by Component for Commercial Office Buildings	A.3
A.3	Average Fraction of Total Operating Costs by Component for Commercial Office Buildings	A.4
A.4	Commercial Sector Energy Consumption Share by Source	A.5
A.5	Nonresidential Building Energy Expenditures by Source for 1983	A.6
A.6	Fuel Expense as a Component of Average U.S. Retail Price of Electricity (in constant 1985 \$) for 1980-1985	A.6
B.1	Relative Frequency Distribution of Architecture Design Firms by Size	B.2
B.2	Relative Frequency Distribution of Engineering Design Firms by Size	B.3
E.1	Application Areas for the Proposed Design and Operation Technologies	E.2
E.2	Whole Building Framework	E.6

TABLES

2.1	Categories of Building Design Decisions	2.5
2.2	Predicted Microcomputer Features Available Within 5 Years	2.16
5.1	Principal Areas Addressed in the Requirements Analysis	5.8
5.2	Funding Requirements for the DOE Advanced Energy Design and Operation Technologies Project	5.31
5.3	Funding Requirements During the First 1.5 Years by Project Element	5.31
5.4	Funding Requirements for Years 1.5 through 7.5 by Major Activity	5.32
D.1	Research and Development Organizations Surveyed	D.7
D.2	Current Developmental Status of KBS Activities	D.8
E.1	Building Subsystems: Areas for Design Process Research with Priorities Assigned by Heidel and Deringer	E.5

BUILDING SYSTEM INTEGRATION RESEARCH REPORTS

- PNL-4358 Pacific Northwest Laboratory, Project Plan, Development of Recommendations to Upgrade ASHRAE/IES Standard 90A-1980 "Energy Conservation in New Building Design, Pacific Northwest Laboratory, Richland, WA. June 1982.
- PNL-4435 W. M. Bowen, S. Moreno, A. R. Olsen, Climate Selection and Development of Climate Indicators, Pacific Northwest Laboratory, Richland, WA. September 1982.
- PNL-5123 J. L. Stoops, J. J. Deringer, S. Moreno, H. P. Misuriello, Summary Report: The BEPS Redesign of 168 Commercial Buildings, Pacific Northwest Laboratory, Richland, WA. May 1984.
- PNL-5143 Vol.I A. R. Olsen, S. Moreno, J. J. Deringer, C. R. Watson, Weather Data for Simplified Energy Calculation, Volume I. Eastern United States: TRY Data, Pacific Northwest Laboratory, Richland, WA. August 1984.
- PNL-5143 Vol.II A. R. Olsen, S. Moreno, J. J. Deringer, C. R. Watson, Weather Data for Simplified Energy Calculation, Volume II. Middle United States: TRY Data, Pacific Northwest Laboratory, Richland, WA. August 1984.
- PNL-5143 Vol.III A. R. Olsen, S. Moreno, J. J. Deringer, C. R. Watson, Weather Data for Simplified Energy Calculation, Volume III. Western United States: TRY Data, Pacific Northwest Laboratory, Richland, WA. August 1984.
- PNL-5143 Vol.IV A. R. Olsen, S. Moreno, J. J. Deringer, C. R. Watson, Weather Data for Simplified Energy Calculation, Volume IV. United States: WYEC Data, Pacific Northwest Laboratory, Richland, WA. August 1984.
- PNL-4870-1 through 40 R. W. Reilly, Recommendations for Energy Conservations Standards and Guidelines for New Commercial Buildings, Pacific Northwest Laboratory, Richland, WA. October 1984.
- * Burt Hill Kosar Rittelmann Associates, Small Office Building Handbook: Design for Reducing First Costs & Utility Costs, Van Nostrand Reinhold, New York, NY. January 1985.
- PNL-5027 J. A. Heidell, R. P. Mazzucchi, R. W. Reilly, Commercial Building End-Use Energy Metering Inventory, Pacific Northwest Laboratory, Richland, WA. April 1985.

- PNL-5462 C. Claar, R. P. Mazzucchi, J. A. Heidell, Project on Restaurant Energy Performance End-Use Monitoring, Pacific Northwest Laboratory, Richland, WA. June 1985.
- PNL-5462 Appendices C. Claar, R. P. Mazzucchi, J. A. Heidell, Project on Restaurant Energy Performance End-Use Monitoring, Pacific Northwest Laboratory, Richland, WA. June 1985.
- PNL-5696 R. W. Reilly, Recommendations for a Multi-Year Plan for Building Systems Integration Research, Pacific Northwest Laboratory, Richland, WA. January 1986.
- PNL-5709 J. A. Heidell, J. J. Deringer, Developing an Energy Design Tool -- Phase I Report, Pacific Northwest Laboratory, Richland, WA. February 1987.
- ** National Association of Home Builders, Cutting Costs in Multifamily Housing: Case Studies in Energy Savings, National Association of Home Builders, Washington, DC. August 1986.
- DOE/CE-0166 Vol.1 G. L. Wilfert, J. W. Callaway, Environmental Assessment: Proposed Interim Energy Conservation Standards for New Commercial and Multifamily High Rise Buildings. U.S. Department of Energy, Washington, DC. November 1986.
- DOE/CE-0166 Vol.2 J. M. Roop, Economic Analysis: Proposed Interim Energy Conservation Standards for New Commercial and Multifamily High Rise Buildings. U.S. Department of Energy, Washington, DC. November 1986.
- DOE/CE-0166 Vol.3 Volume 3 of 4. D. B. Crawley, P. D. Gilbride, Envelope System Performance Compliance Calculation Program Documentation - Version 1.0. U.S. Department of Energy, Washington, DC. November 1986.
- DOE/CE-0166 Vol.4 Volume 4 of 4. D. B. Crawley, E. G. Stephan, Lighting Prescription and System Performance Compliance Calculation Program Documentation - Version 1.0. U.S. Department of Energy, Washington, DC. November 1986.
- PNL-5854 Vol.1 D. B. Crawley, R. S. Briggs, J. W. Jones, W. W. Seaton, J. E. Kaufman, J. J. Deringer, E. W. Kennett, Development of Whole-Building Energy Design Targets for Commercial Buildings -- Phase I Planning, Volume 1: Final Report, Pacific Northwest Laboratory, Richland, WA. April 1987.

PNL-5854 Vol.2

D. B. Crawley, R. S. Briggs, J. W. Jones, W. W. Seaton, J. E. Kaufman, J. J. Deringer, E. W. Kennett, Development of Whole-Building Energy Design Targets for Commercial Buildings -- Phase 1 Planning, Volume 2: Technical Report, Pacific Northwest Laboratory, Richland, WA. September 1987.

PNL-6255

M. R. Brambley, D. B. Crawley, D. D. Hostetler, R. C. Stratton, M. S. Addison, J. J. Deringer, J. D. Hall, S. E. Selkowitz, Advanced Energy Design and Operation Technologies Research, Pacific Northwest Laboratory, Richland, WA. December 1988.

- * Available directly from the publisher: Van Nostrand Reinhold, New York, NY.
- ** Available directly from the publisher: National Association of Home Builders, Washington, DC.

All Other Research Reports are Available from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

1.0 INTRODUCTION

The goal of the U.S. Department of Energy (DOE) Advanced Energy Design and Operation Technologies (AEDOT) research project is to increase the energy efficiency of the nation's building stock by developing technologies that assist building designers in making informed energy-related design decisions and to provide intelligent computer-based aids for building management and operation. Most commercial buildings are uniquely designed and constructed one at a time. They are not generally produced in quantity from a single design as are cars, appliances, and many building components. Therefore, the building designer or design team is critical to increasing the energy efficiency of our new buildings. The primary product of this research will be an integrated set of software packages that can be incorporated into advanced commercial computer-aided building design (CABD) systems. Widespread use of these systems would significantly reduce energy consumption by the buildings sector.

This section contains an overview of ongoing development activities in the area of computer-aided design (CAD), a brief discussion of CAD developments related to energy design of buildings, the objectives of the project, and an outline of this report.

1.1 BACKGROUND

Recent developments in computer technology provide new opportunities for incorporating design experience and expertise into computer software, promising significant improvements in decision making during building design. However, the capability of computers to manipulate knowledge has not yet been sufficiently utilized for this purpose. How well this promise to improve the quality and energy efficiency of the nation's building stock is realized will depend on several developing computer technologies critical to the future capabilities of CAD.

The most significant of these technologies include artificial intelligence, graphics/imaging technologies, parallel processing, microprocessing, and data storage/retrieval technologies. The potential benefits of these technologies

and CAD are so widely recognized that virtually all industrialized nations are investing heavily in their rapid development. Examples include Japan's Fifth Generation Project, the European Economic Community's ESPRIT, and CAD developments in various foreign electronics, aerospace, and automotive industries. The United States has also committed heavily to developing these new technologies, seeing them as important opportunities for improving the nation's productivity (White House Conference on Productivity 1984; Morse 1976, p. 20; Dryden 1985, p. 57; Dorfman 1985a, p. 171).

In the United States, significant early developments in CAD resulted from government-sponsored research on flight simulation and radar detection. More recent advances have occurred in capital-intensive industries such as the electronics, aerospace, and automotive industries. These developments provide the technological base for integrating CAD into the buildings industry. Although still relatively immature, CABD has become the third largest component of the CAD industry (Filey 1985). Most existing CABD systems simply automate the drafting phase of building design. These systems, generally referred to as computer-aided design and drafting (CADD), are widely used in the building design industry, as shown in Figure 1.1.

The current trend in CABD systems development is toward integrated systems that provide support throughout the entire building life cycle, from preliminary design through facilities management and operation. Many functions, such as space planning, engineering analysis, and database management, have been proposed for development as part of integrated CABD systems.

Significant progress on efforts of similar scope is being made in the aerospace industry, and some foreign countries are exploring integrated CABD. The application of integrated CABD technologies in the U.S. building design industry presents an opportunity for major increases in productivity, significantly lower costs, and improved decision making. The end result will be better buildings that are less expensive and more energy-efficient.

Although incomplete use of scientific and technological advances occurs in many disciplines, it is especially a problem in the field of energy-efficient building design. Despite significant advances in the scientific

FIGURE 1.1. Computer and CADD Use by Building Design Professionals [General Accounting Office (GAO) 1980; Architectural Record 1985; Practice Management Associates, Ltd. 1986]

understanding of how buildings use energy and in tools that simulate energy use, only modest improvements in energy efficiency have typically been attained in commercial building practice. Energy design technologies that are integrated as part of advanced CABD systems have an enormous potential for changing this.

The U.S. building design industry is recognized as being fragmented, undercapitalized, labor-intensive, and composed of a large number of relatively small firms [Energy Research Advisory Board (ERAB) 1985]. Building design, construction, and operation is not the responsibility of a single group but

of a wide variety of professionals with different expertise: owners, financiers, architects, engineers, and facility managers. Despite substantial financial benefits of CAD that have been demonstrated in other industries with similar requirements, the CABD market lags well behind in maturity. Moreover, despite the continued increases in utility-related operating costs for buildings, lower world energy prices have temporarily diminished the perceived financial benefit of energy-efficient building design. Consequently, realizing the potential of CABD to affect energy efficiency in buildings will require a concerted effort that is not likely to be expended for many years without federal assistance in its development.

Without a carefully planned and coordinated development effort, the building research community is likely to produce a collection of independently developed design tools with very specific, narrow areas of application, which are more appropriate for use by researchers than designers. Previous experience has shown that the general acceptance of nonintegrated energy-related design tools is very low. Building designers will not be willing or able to expend the effort to adopt additional, uncoordinated energy-related design tools into the design process. It is important that research begin now to permit active coordination and integration of emerging design tools.

1.2 PROJECT OBJECTIVES

The principal objectives of this project are to make energy performance a primary design criterion and to integrate design knowledge with building use requirements to provide the capability for energy-efficient building management and operation throughout the building life cycle. To accomplish these objectives, new design and operation technologies should be developed and incorporated into an intelligent computer-based environment. After first specifying requirements resulting from the relationships among the stages of the building life cycle, early work would focus on development of the design technologies; development of the operation technologies would begin later in the project. As a consequence, the design concepts are currently better developed and greater emphasis is placed on them in this document.

One possible conceptual description of this integrated building design environment is shown in Figure 1.2. The user communicates with the system through a highly graphical user interface. The Design Executive manages and controls interactions between the user and various elements of the system in response to user requests. It accesses and controls several design advisors, one of which is the Energy Design Advisor (EDA). The EDA functions in coordination with the other design advisors, with control of the process provided by the Design Executive.

The EDA would be developed as a series of computer programs and databases that include knowledge-based systems (KBS), decision support systems, and integrated database management. Incorporating knowledge-based design advisors within existing CAD environments in other industries has had dramatic results. For example, RCA Corporation has reported a reduction of up to 50% in very large scale integration design costs using a recently developed expert system that has been added to its existing CAD system (Naegele 1986, p. 25).

The user interface would provide user-friendly, graphics-oriented communications for easy and efficient access to the EDA, facilitating the use of the tool and enhancing the user's ability to understand the output. Advanced computer visualization capabilities would allow the user to visually investigate many of the critical qualitative aspects of design, such as view and glare, in addition to quantitative ones. These issues strongly interact with energy-related decisions and are beyond the scope of simulation models currently available.

The structure shown in Figure 1.2 is given as an example only. The exact structure should be determined during the project, once requirements of the system are determined in detail. The focus of this project is the development of technologies that provide the capabilities of the EDA and Design Executive (as necessary to provide access to and control of the EDA) in Figure 1.2. The CABD industry and academic researchers are already investigating other design advisors in parallel efforts. Interaction with industry is an important part of planned activities. In addition to providing valuable guidance for

FIGURE 1.2. Sample Conceptual Structure for the Advanced Building Design System. The other (nonenergy) design advisors shown are outside the domain of AEDOT research.

the project, interaction may also encourage industry to develop intelligent building design systems sooner. Whenever possible, the AEDOT project should incorporate developments by industry.

Through both federal and private participation, this research should ultimately result in CABD systems that integrate state-of-the-art energy design expertise throughout the building design and operation process. The critical early stages of building design have historically proved to be the most difficult to support with adequate energy design expertise. The most promising aspect of the proposed tools is the ability to support architects and their clients as they make decisions in these early stages of design, which have the most dramatic influences on energy consumption.

This research should begin now, because the CABD industry is rapidly moving toward integrated systems and protocols to support this integration are being established. Energy design tools do not appear within the scope of these industry activities; therefore, this project is essential to ensure adequate treatment of energy considerations. A state-of-the-art energy design module that can be integrated with other design software has the potential to significantly affect energy consumption in new buildings. Even though industry does not plan to develop energy design tools independently, through close cooperation with industry early in its work on integrated (nonenergy) building design tools, this project is much more likely to succeed.

1.3 REPORT CONTENTS

Opportunities for improving building energy efficiency through better design are discussed in greater detail in Section 2. Descriptions of the proposed capabilities of the advanced energy design and operation technologies to take advantage of these opportunities are presented in Section 3. Section 4 addresses the benefits of developing these technologies, and Section 5 presents the proposed research and development plan. Additional supporting material is included in the appendixes.

the project, interaction may also encourage industry to develop intelligent building design systems sooner. Whenever possible, the AEDU project should incorporate developments by industry.

Through both federal and private participation, this research should ultimately result in CAD systems that integrate state-of-the-art energy design expertise throughout the building design and construction process. The critical early stages of building design have historically proved to be the most difficult to support with adequate energy design expertise. The most promising aspect of the proposed tools is the ability to support architects and their clients as they make decisions in these early stages of design, which have the most dramatic influences on energy consumption.

This research should begin now, because the CAD industry is rapidly moving toward integrated systems and protocols to support this integration are being established. Energy design tools do not appear within the scope of these industry activities; therefore, this project is essential to ensure adequate treatment of energy considerations. A state-of-the-art energy design model that can be integrated with other design software has the potential to significantly affect energy consumption in new buildings. Even though industry does not plan to develop energy design tools independently, through close cooperation with industry early in its work on integrated (low-energy) building design tools, this project is much more likely to succeed.

4.3. REPORT COMMENTS

Opportunities for improving building energy efficiency through better design are discussed in greater detail in Section 2. Descriptions of the proposed capabilities of the advanced energy design and operation technologies to take advantage of these opportunities are presented in Section 3. Section 4 addresses the benefits of developing these technologies, and Section 5 presents the proposed research and development plan. Additional supporting material is included in the appendixes.

2.0 OPPORTUNITIES FOR ENERGY-EFFICIENT BUILDING DESIGN

Most commercial buildings designed today will use more energy and cost more to operate than if designed to incorporate economically optimal levels of energy efficiency. After increases between 1960 and 1973, the average energy intensity of commercial buildings improved somewhat during the last decade, as shown in Figure 2.1 (Adams et al. 1985). However, various estimates place the current energy use of most new buildings well above the level that could be attained with little or no increase in first cost (Piette, Wall, and Gardiner 1986; Burt Hill Kosar Rittelmann Associates 1985). Case studies involving redesign of buildings have shown that in some cases energy consumption can be cost-effectively reduced by more than 50% [National Association of Home Builders (NAHB) 1987; Stoops et al. 1984].

Utility costs represent the largest component of building operating costs, as shown in Figure 2.2 [Building Owners and Managers Association International

FIGURE 2.1. Average Commercial-Sector Building Primary Energy-Use Intensity (Adams et al. 1985)

FIGURE 2.2. Median Share of Operating Costs by Major Categories for Commercial Office Buildings (BOMA 1986)

(BOMA) 1986]. When energy efficiency is not adequately considered during design, higher operating costs result and accrue over the life of a building (which averages 50 to 75 years). These costs also affect national productivity and the nation's ability to compete in world markets (White House Conference on Productivity 1984). Savings that could have been achieved through cost-effective levels of conservation in new commercial buildings over the 1974 to 1982 period alone are estimated at \$50 billion (1986 \$) and 8.0 quads (Stoops et al. 1984).

Major reasons for this lagging performance in energy-efficient building design include

- inadequate transfer of buildings research findings to the building design, construction, and operation industries
- inadequate support for design decisions in the critical early design stages where decisions typically have the most dramatic influence on ultimate energy consumption and costs

- high incremental costs currently associated with properly considering energy efficiency during building design
- depressed world oil prices that diminish the perceived benefits and demand for energy-efficient building design (see Appendix A)
- a fragmented and undercapitalized building design and construction industry, which, if unaided, is unable to overcome these limitations (see Appendix B).

The products of the AEDOT research project would address all these issues and facilitate the design of buildings that cost no more to construct but use less energy to operate and at the same time provide enhanced amenities.

A large body of knowledge concerning building energy use and conservation has accumulated over the past decade. However, the building design industry cannot apply this knowledge in building design because

- designing energy-efficient buildings is technically complex, costly, and involves many different design disciplines
- current energy-design tools do not provide sufficient information in a readily usable form throughout the design process, particularly in the early design stages.

These problems and the opportunities they present for the use of AEDOT technologies are discussed in the sections that follow.

2.1 COMPLEXITY AND COST OF ENERGY-EFFICIENT BUILDING DESIGN

Factors contributing to the complexity of energy-efficient building design include interactions among building components, the need to satisfy many design criteria simultaneously, and the multiplicity of specialists that make up a design team. This complexity results in the current high cost of energy-efficient building design. These factors and the resulting cost are discussed below.

2.1.1 Complex Energy Interactions

Very few building components consume energy directly. Virtually all, however, influence the energy use of those few that do, and many have significant influence. For example, the impact of building glazing on energy use depends in part on

- interior and exterior shading device design
- building orientation and siting
- glazing type (solar, optical, and conductive properties)
- local climate.

Such interactions among building components make energy-efficient building design an extremely complex task.

2.1.2 Multiple Design Criteria

Design decisions must ultimately satisfy a number of criteria. For example, the designer of an energy-efficient building must consider the impact of windows and their orientations on energy consumption, but must also satisfy other design criteria associated with factors such as

- cost
- aesthetic appeal
- access to views and the related marketability of the spaces
- visual and thermal comfort
- security requirements
- ultraviolet damage to interior finishes
- exterior shading by trees, shrubs, and adjacent buildings
- reflections from exterior window surfaces affecting adjacent objects or activities.

Each decision in building design involves a similarly large set of criteria, which are both interactive and recursive. Many decisions ultimately impact energy performance, either directly or indirectly. The breadth of building design decisions is illustrated by the list in Table 2.1.

2.1.3 Use of Design Teams

Building design is a process of integrating separate components into a complete interactive system. For commercial buildings, this process is generally too complex for a single designer to accomplish and usually involves

TABLE 2.1. Categories of Building Design Decisions [from Palmer (1981, p. 19) reproduced with permission of McGraw-Hill Book Company]

HUMAN FACTORS	PHYSICAL FACTORS	EXTERNAL FACTORS
Activities	Location	Legal Restrictions (Codes / Standards / Regulations)
Behavior	— Region	— Building
Objectives / Goals	— Locality	— Land use
Organization	— Community	— Systems
— Hierarchy	— Vicinity	— Energy
— Groups	Site Conditions	— Environment
— Positions	Building / Facility	— Materials
— Classifications	Envelope	— Safety
— Leadership	Structure	— Solar access
Characteristics (Demographics)	Systems	Topography
Social Forces	— Engineering	Climate
Political Forces	— Communications	Ecology
Interactions	— Lighting	Resource Availability
— Communication	— Security	Energy Supplies / Prices
— Relationships	Space	— Conventional
— Transfer of materials, etc.	— Types	— Solar
Policies / Codes	— Dimensions	— Alternatives
Attitudes / Values	— Relationships	Economy
Customs / Beliefs	Equipment / Furnishings	Financing
Perceptions	Materials / Finishes	Time
Preferences	Support Services	— Schedule
Qualities	— Storage	— Deadlines
— Comfort	— Parking	— Operations
— Productivity	— Access	Costs / Budget
— Efficiency	— Waste removal	— Construction
— Security	— Utilities (water, sewage, telephone)	— Materials
— Safety	Uses	— Services
— Access	Functions	— Operations
— Privacy	Behavior / Activity Settings	Costs / Benefits
— Territory	Operations	
— Control	Circulation	
— Convenience	Environment	
	— Comfort	
	— Visual	
	— Acoustical	
	Energy Use / Conservation	
	Durability / Flexibility	

the coordinated effort of a team of specialists, each responsible for distinct building subsystems.

The boundaries between the design disciplines, or subsystems, were historically drawn on the basis of function (e.g., spatial functions, structure, environmental control, and lighting). Many traditional design criteria for buildings (such as aesthetic appeal, privacy, structural economy, thermal comfort, fire and life safety, and visual comfort) still fit well in these functional categories. As a result, the various design disciplines tend to develop their design solutions independently of each other.

Building energy use, however, involves interactions among all major building subsystems, crossing virtually all functional boundaries. An example is the influence other factors have on the relationship between the amount of glass (primarily an architectural decision) and the total energy use of the building. These factors include

- thermal capacitance of the building structure
- potential for passive solar heating
- interior finishes selected
- lighting levels, sources, equipment, and controls, and the potential for natural lighting
- ventilation requirements and the potential for ventilative cooling
- heating, ventilating, and air conditioning (HVAC) system design and control type and efficiency (including the potential for free cooling)
- occupancy patterns and HVAC scheduling
- fuels selected
- utility rate structures.

Just as the energy impact of one building component depends on the configuration of other components, the impact any one design professional has on the overall energy efficiency of a building depends on decisions made by other design team members, especially those whose decisions are made early in the design process. The relative effects of the various members of the design

team on life-cycle costs are shown in Figure 2.3. Each design team member is represented by a circle. The area of each circle represents that team member's relative impact on life-cycle costs. Overlapping areas represent impacts that depend on two or more team members; nonoverlapping areas are affected by only one member (i.e., profession) (Dell'Isola 1982). As shown, many professions must interact, crossing several disciplinary boundaries, to produce an energy-efficient building design. As a result, energy-efficient design

FIGURE 2.3. Relative Impact of Design Team Members on Life-Cycle Costs (after Dell'Isola 1982)

requires a level of communication between design disciplines to which most building designers are not accustomed.

2.1.4 Current Cost of Designing Energy-Efficient Buildings

The preceding sections have described limitations preventing the more complete use of existing energy design expertise. These limitations currently result in relatively high costs for energy-efficient building design. Fee structures in the traditionally competitive building design market do not generally include the current substantial cost of energy design. Building owners expect the cost of energy design services to be included in standard design fees. Most owners do not know what energy performance levels can reasonably be attained. Thus, they do not correctly perceive the benefits available to them when energy considerations are properly assessed during design, and they are unable to evaluate the quality of the energy design services they receive. In the absence of a major change in attitudes of building owners toward energy efficiency, another oil crisis, or the development of tools that reduce the cost of energy-efficient design like those proposed in the AEDOT research plan, energy will likely retain its low priority in building design.

2.2 THE NEED FOR NEW TECHNOLOGIES TO SUPPORT ENERGY-EFFICIENT BUILDING DESIGN

Most technically oriented industries (e.g., automotive, electronics, and aerospace) are dominated by relatively few companies that design products for a mass market. Therefore, in these industries, only a few design teams are responsible for relatively few product designs that are then produced in great numbers.

Unfortunately for energy conservation practice, the building design and construction industry is quite different. Although mass-produced components are often used, most buildings are individually designed and constructed as unique objects. Therefore, there are many design teams, and each team is responsible for the design of a relatively small number of products each year.

In the U.S., about 72,000 registered architects and about 90,000 professional engineers are involved in commercial building design and construction (New York Times 1986; Edmunds 1986). Each year, about 120,000 new buildings are designed and constructed, and about 80,000 buildings are retrofitted (about 2.5% and 2% of existing stock, respectively). These numbers show that energy-efficient building design expertise must be widely distributed to a large number of building design professionals before an energy-efficient building stock can be produced.

The complexity of designing a building that is both cost-effective and energy-efficient is beyond the capabilities of most building designers today. Most building design teams do not have the expertise to adequately consider energy during design; neither can they devote the requisite 5 to 10 years to develop such expertise. The complexity of energy-efficient building design, coupled with the large number of designers, makes dissemination of energy expertise difficult. Practice of energy-efficient design is necessary to develop this expertise; courses and training sessions have proved ineffective except as introductions and supplements to experience. Another method of dissemination must be found.

Computer-based energy design advisors using artificial intelligence methods have the potential to transfer and provide convenient access to the expertise that is now held by a relatively small number of specialists. Designers using these advisors would acquire experience in energy-efficient design while actually engaged in designing buildings. This is the same way (i.e., by experience) much of the valuable expertise that already exists was acquired. Ultimately, knowledge-based technologies may allow the unique insights of individual designers to be captured in automated environments for immediate access in the future.

2.2.1 Inadequacies of Current Design Support

Building design encompasses a diverse range of activities, including design synthesis, design analysis, production, and management. Except for design synthesis, these activities are receiving significant assistance from

computer technologies. The current contributions of computers to these building design activities are shown in Figure 2.4.

Design synthesis is that part of the design sequence that generates new ideas and alternatives. Once conceived, a new idea must be evaluated against design objectives. This second step, the evaluation, is design analysis. Synthesis and analysis, applied in iterative and recursive sequences, constitute design. Analyzing individual quantifiable aspects of design is well supported. The lack of computer-based support for the critical step of design synthesis is a significant failing of current design tools.

Building owners and architects typically have the greatest influence of the design team members (see Figure 2.3), largely because of the place they occupy in the design sequence--generating the initial concept and providing constraints. Their decisions early in design have a dramatic influence on life-cycle costs, as illustrated in Figures 2.5 and 2.6. Historically,

FIGURE 2.4. Computer Automation by Task for Building Design Practices (Practice Management Associates 1986)

FIGURE 2.5. Impact of Major Decision Makers on Building Life-Cycle Costs (Dell'Isola 1982)

FIGURE 2.6. Impact of Design Phases on Building Life-Cycle Costs (GAO 1978)

however, these two design team members have received the least benefit from energy-efficient buildings research, primarily because of the technological difficulty in supporting their unique needs. The early conceptual design process, carried out by architects working in conjunction with building owners, is difficult to support because it is convoluted, relies heavily on heuristics, and utilizes many visually-oriented, qualitative design criteria.

2.2.2 Current and Emerging Methods

Recent developments provide the potential to significantly improve support throughout the design process, including design synthesis. Emerging technologies for imaging systems, combined with energy-efficient design heuristics, offer significant potential to support early design decisions. The existing tools and the potential for their improvement are discussed in this section.

Attempts to provide computer-aided support to design generally have relied on techniques from operations research (Gero 1975). These techniques use mathematical models of a well-structured, sequential design process to explore a set of possible solutions for some near-optimal subset. The difficulty for design problems of general interest is that these techniques are not workable because the solution sets are generally too large and too ill-defined. The real process is iterative, recursive and interactive, and the resulting complexity is difficult to deal with. Consequently, existing tools that tend to linearize the process lead to far from optimal designs with higher than necessary energy costs.

An emerging alternative using heuristics recognizes that design is not a strictly linear process (Gero et al. 1984). However, approaches to solve design problems using heuristics have limitations because they do not ensure a near-optimal solution. They are only as good as the knowledge upon which they are based.

Because early design has the most significant impact on life-cycle costs (see Figure 2.6), it should receive the maximum possible designing resources. Current approaches to building design allow thorough evaluation of only a limited number of alternatives. The quality of the early design stage will

benefit most from the greatly increased number of design alternatives that can be evaluated using automated support systems and the depth to which they can be evaluated. This is one capability that would be provided by the technologies resulting from the AEDOT project.

More extensive reviews of current research on the design process and on emerging design technologies are included as Appendixes C and D.

2.2.3 Software

Energy design tools are available in two varieties, computer-based and manual. Current computer-based tools are primarily for design analysis, not design synthesis, and are not designed for the way architects work (Schuster 1984). The most significant capability of these analysis tools is their ability to treat (with varying sophistication) the complex building subsystem interactions described in Section 2.1.1. Examples of current computer-based tools are DOE-2, BLAST, TARP, ESP, and ASEAM2. Although these tools have added enormously to the understanding of how buildings use energy, they provide no support during design synthesis, the critical period when major decisions affecting energy consumption are made.

A designer needs several kinds of assistance in making energy-related design decisions:

- identifying design opportunities that reduce energy use at appropriate times in the design process
- identifying good design strategies for implementing the most cost-effective opportunities suitable for each particular building
- developing detailed design solutions for the selected design strategies.

Design professionals currently must rely primarily on their own expertise on energy-efficient design to guide the design process, but few have this expertise. Some design synthesis tools that provide modest direction to the designer are available. However, these are just computerized implementations of early manual analysis procedures contained in handbooks and are overly simplistic. They do not accommodate the complex interactions inherent in energy-efficient design. The energy-saving opportunities they identify are

therefore very limited. Examples of such design aids include Pre-design Energy Analysis (DOE 1980) and The Small Office Building Handbook (Burt Hill 1985), which does handle some interactions.

Efforts to resolve the shortcomings of these simple design tools have largely recommended the use of conceptual design tools during the early design stages, reserving more sophisticated computer-based models for later design (refinement) stages. However, this does not resolve the problem of adequately supporting exploration of multiple alternatives early in the design process. Computer-based support in these early design stages would greatly increase the number of alternatives designers are able to consider. At the same time, such systems would provide information concerning the effects of design changes on energy consumption early in the process when it has the most impact.

Another problem with current energy design tools is their inability to support decisions constrained by multiple criteria, which characterize the design process, or the qualitative nature of many of the design criteria. For building design criteria such as aesthetic appeal, glare potential, and access to view, appropriate variables or performance indices for effective communication and evaluation do not currently exist. For energy efficiency to become effectively integrated into the design process, the visually oriented nature of architectural design must be recognized. More extensive use of images to aid the designer in the important process of evaluating and communicating design decisions is needed.

Properly designed, computer-based systems for design assistance could overcome many of these problems. At the very least, these systems could speed up the process, allowing more alternatives to be considered at an affordable design cost. The emerging technologies of knowledge-based systems, integrated CABD, and sophisticated imaging systems provide the basis for an unprecedented opportunity to develop this support, even for qualitative design decisions. A comprehensive review of ongoing work in these areas is included in Appendix D.

2.2.4 Computer Hardware

Commercially available hardware has undergone substantial improvements in the last decade, in terms of both absolute performance capabilities and performance per dollar invested in hardware. Nevertheless, "affordable" hardware with the capabilities necessary for the proposed advanced energy design tool probably does not yet exist. However, the adequacy of current hardware cannot be formally assessed until computer processing requirements for the AEDOT technologies are established. These requirements would be established early and updated throughout the project. However, based on just the expected imaging capabilities of the design systems, microcomputers that currently cost less than \$20,000 appear to be inadequate. For comparison, the distribution of the cost of hardware currently in architecture/engineering firms is shown in Figure 2.7. This distribution establishes a preliminary cost target for computer systems for implementing the AEDOT technologies, but this target may very well change during the project.

FIGURE 2.7. Distribution of Costs for CADD Systems Currently Owned by Architectural and Engineering Offices (Architectural Record 1985)

Advances in computer technology will surely occur while the AEDOT project is under way. Officials at IBM, Compaq, Intel, and Motorola (Brownstein 1988; Language Technology 1988; Lang 1987) suggest a desktop microcomputer environment available in 5 years that will be much more advanced than that available today (see Table 2.2). Changes in computer hardware over the next decade will likely exceed all current expectations. The AEDOT project must track, adapt to, and plan for these changes.

TABLE 2.2. Predicted Microcomputer Features Available Within 5 Years (Brownstein 1988; Language Technology 1988; Lang 1987)

Feature	Characteristics
Processor type	16 megabytes of random access memory on motherboard, expandable up to 4 gigabytes
Processor speed	40 million instructions per second (e.g., in the proposed Intel 80586 or Motorola 68050)
Buses	Separate buses for memory, processor, and input/output at speeds of up to 50 megahertz
Caching	Four 4-megabyte caches: memory, data, processor look ahead, and operating system cache
Storage	20-megabyte 3-1/2-inch disk drives
Mass storage	1-gigabyte nonremovable erasable optical disk and a 400-megabyte removable disk drive
Monitor resolution	2000 by 2000 pixel with an essentially unlimited number of colors
Printer rasterizer	Onboard conversion of files with standard graphics format into code readable by laser printer engines
Communications	9600-baud modem on board
Audio	Microphone built into keyboard and 3-inch stereo speakers for compact disk quality audio

3.0 CONCEPTUAL DESCRIPTION OF AEDOT CAPABILITIES AND CHARACTERISTICS

The general capabilities and characteristics of advanced energy-efficient building design and operation technologies that should be developed in the AEDOT project are described in this section. Also included is a scenario illustrating the use of a system that incorporates these technologies.

The capabilities and characteristics identified here should be viewed as precursors to the project requirements. The first major task in the project (the Requirements Analysis, see Section 5) should be to rigorously determine requirements that build upon these capabilities and characteristics. That task would provide a requirements specification, a conceptual design, and a detailed approach for developing the AEDOT technologies.

3.1 GENERAL CAPABILITIES

The technologies developed by this project would provide cost-effective computer-based assistance for the design and operation of energy-efficient buildings. The products of AEDOT would assist in

- identifying energy conservation opportunities during design
- identifying non-energy design decisions that could adversely impact building energy efficiency
- identifying and developing strategies to take advantage of the energy conservation opportunities (i.e., approaches for implementing these conservation opportunities)
- developing design solutions that implement these strategies (i.e., procedures or methods for implementing the strategies)
- developing and implementing operation and maintenance strategies for use after design.

Distinctions between the first four items and the boundaries between them are fuzzy and not well defined. One purpose of the Requirements Analysis is to provide more precise definitions of these capabilities.

3.2 CHARACTERISTICS

A computer-based energy design and operation environment developed by the AEDOT project should have the following characteristics that are classified into five categories:

- general characteristics
 - suitable for inclusion in, or structured to be linked to, a variety of commercial CABD systems
 - applicable to a broad range of commercial buildings, building uses, climates, and other conditions
- user interface features
 - accommodate the needs of individuals responsible for making energy-related decisions during building design and operation
 - accommodate different energy-related skill and experience levels within each profession, providing guidance necessary for use of the system
- design-related features
 - facilitate the interactive and recursive nature of the design process
 - support parallel development of several alternative design schemes
 - support the visual nature of design
 - provide assistance for evaluating both quantitative and qualitative design criteria
 - encourage interaction among design participants, i.e., members of the design team, owners, users, operations professionals, and other affected parties
- operation-related features
 - support the transfer of information between design and operation (in both directions)
 - provide advice on energy-efficient operation

- intelligent features

- provide advice leading to reasonable conclusions in an uncertain environment
- include a good explanation facility that can provide justification for the system's advice and decisions
- include a dynamic knowledge base that can change and grow as additional knowledge and experience are acquired and as new technologies are developed.

Several of these characteristics span more than one category. To clarify the significance of these characteristics and show how they might be used, a scenario describing the use of a design system based on AEDOT technologies is provided in the following section.

3.3 USE SCENARIO

This scenario illustrates some of the uses, capabilities, and characteristics of a system built from the technologies proposed for development in the AEDOT project.

George McMoore, AIA, sits down at his workstation and adjusts his reading glasses. It is May 1998; George's architectural firm has been commissioned to design a 60,000-square foot regional office and research facility for General Genetics, a Fortune 500 firm.

George's firm is equipped with the state of the art in intelligent computer-aided building design and drafting systems (ICADD). It has the latest in advanced imaging software so that George can assess the visual quality of his designs. The ICADD incorporates several knowledge-based systems to provide design advice, including the EDA developed by DOE.

In addition to automatic access via modem to several national databases, ICADD also accesses several resident databases on the workstation read-only storage unit (i.e., mass storage disks). These disks hold the equivalent of several hundred thousand pages of information and images. Several different companies maintain the databases that reside on these disks and provide public access via annual subscription. These companies include Sweets building

products, Codeworks' regional building code file, and Means cost data. George's mass storage unit also holds the three most current professional society information handbooks:

- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 1993 Handbook of Fundamentals
- 1994 Illuminating Engineering Society of North America (IES) Lighting Handbook
- American Institute of Architects (AIA) Graphic Standards.

George is often amazed that this entire system costs only slightly more than his first personal computer (PC) CABD system of 10 years ago.

George is about to begin conceptual design of the building after completing the facility programming last week (using his workstation as the basic resource). He is frustrated because the client wants a high image building, but is very conservative about using technologies without long track records. The client is skeptical of several new building design strategies that George favors.

Also, the construction cost budget is small, relative to the client's requirements for the building. Because the building's operating budget will be the responsibility of a different division of the client's firm, George is not optimistic about getting approval for trading increased construction costs against lower operating costs, regardless of the return on investment. The client prefers a compact building (assuming it will keep costs down), while George is convinced that a building form focused on several atriums will produce a better, more cost-effective solution.

He gets to work. By pressing an icon on the computer screen, he accesses the space planning component of the ICADD system to generate a basic set of three floor plans based upon the Facilities Program stored in the database. He specifies standard envelope features including substantial amounts of glass (greater than 40%) and decides to investigate the energy implications.

He presses the icon for the EDA. George notes that 10 years ago, few people cared if buildings were energy-efficient. Things have changed; because

energy prices have doubled in the past decade, energy has a high priority in building design.

He asks the EDA for information on energy-use patterns for standard office buildings. The program automatically retrieves energy and demand rate schedules by modem from the utility bulletin board. George selects a building similar to his, and the database produces several sets of bar charts for typical lighting/HVAC system combinations, each set including monthly and annual loads, energy use, peak demands, and energy costs. Color coding ranks the priority of energy conservation opportunities by end use; in terms of energy cost, lighting and cooling are the two highest energy priorities.

George next presses the icon for identifying energy strategies. At first, he wants a summary of only the most important strategy areas. He knows that the strategies must meet the client's general goals and objectives from the facility program. The EDA produces the following summary list:

- Reduce lighting energy use.
- Downsize the air-conditioning system.
- Reduce solar gain through the windows.
- Select different lighting and HVAC systems.

He requests further detail on lighting strategies and obtains a list of the 10 top strategies along with relative estimates of cost, energy, and other design impacts. George selects three lighting strategies, one of them the now quite common daylight dimming controls. When George chooses this strategy, the EDA prompts that high-performance glazing should be considered. He does, and at the same time specifies that trees on the wooded site will shade the windows on the east, south, and west elevations.

Next, he requests generic lighting and HVAC system selection options. Using the EDA ranking of the options established by the ICADD through comparison against program goals and requirements, he makes initial lighting and HVAC system selections. The EDA informs George that the energy performance levels are good and that the overall project is within budget.

At this point he decides he wants to confer with his consultants. He mails his project data files electronically to his consultants for review, and sets up a conference call for the next day with his electrical, structural, and mechanical engineers, and lighting design consultant.

The next day, as a result of feedback from his teleconference, George makes a number of refinements, including an important lighting control strategy, and changes the HVAC system to a hybrid system that had not appeared on his list (the ICADD notes these changes and updates the appropriate general information data- and knowledge bases). The mechanical engineer will develop some specifications for the system and electronically mail them to George.

He switches to ICADD design mode, adds a structural system, and develops specific wall, fenestration, roof, ceiling and internal partition assemblies by modifying manufacturers' assemblies retrieved from mass disk storage. George then requests an updated cost estimate based on the latest available costs from the Means database. Construction cost is actually within budget at this point!

The system has been providing ballpark energy and cost estimates of decisions, but now George wants to see details of the energy cost consequences of his design decisions to date. From within the EDA, he calls up Energy-2, the latest energy analysis program. It displays both the building and the results graphically as calculations proceed. He is also able to change building components on the fly and watch the consequences of these decisions. George uses many default values this early in the design process. The calculation proceeds.

George is now about two-thirds of the way toward his energy objective of designing a building that uses 35% less energy than the standard building he first assessed.

George now starts working on his more innovative design concept. In the ICADD sketch mode, he comes up with two promising concepts. The building shapes are more interesting, the internal spaces are more varied, and almost all building occupants will have direct view outside to the wooded site (in addition to views to interior atria). By careful use of the design databases

and strategy identification expertise, the construction cost of one of the alternatives is only 1% higher than the base building but has an additional 20% reduction in estimated energy costs. George prompts the ICADD for plots of the life-cycle costs of both the base building and the selected alternative. George has now surpassed his energy performance objective.

George uses the ICADD three-dimensional modeling capabilities to produce internal and external color images of the base building and the alternative. He hopes that the client will accept the alternative, even though its initial cost is slightly higher, because its image and spaces are much more interesting than those of the base building.

The client is elated with the reduced life-cycle costs, improved amenities, and image of the alternative design. The 1% cost difference is discussed with General Genetics headquarters and approved after the amenity benefits to the workers and the life-cycle cost savings have been reviewed.

As the project proceeds, George and his engineering consultants use further elements of the design and decision tool to assist in detailed design of the lighting, HVAC, and envelope subsystems and components. This results in slight cost reductions and further improvements to the building energy performance. Another 8% reduction in estimated energy use is obtained.

During construction, the ICADD system provides more assistance to the design team by assessing impacts of construction change orders. Then the building commissioning package is delivered to the owner. Part of this package is a set of computer-readable data to assist the building operator in properly operating and managing the building for energy efficiency. Arrangements have also been made for George's ICADD to receive data on performance from an advanced operating system onsite. The ICADD will use these data to evaluate the actual effectiveness of strategies used in designing this building and to modify its knowledge bases, if necessary.

and strategy identification expertise, the construction cost of one of the alternatives is only 1% higher than the base building but has an additional 20% reduction in estimated energy costs. George presents the ICAD for jobs on the life-cycle costs of both the base building and the selected alternative. George has now surpassed his energy performance objective.

George uses the ICAD three-dimensional modeling capabilities to produce internal and external color images of the base building and the alternative. He hopes that the client will accept the alternative, even though its initial cost is slightly higher, because its image and spaces are much more interesting than those of the base building.

The client is elated with the reduced life-cycle costs, improved aesthetics, and image of the alternative design. The 1% cost difference is discussed with General Services Headquarters and approved after the agency benefits to the workers and the life-cycle cost savings have been reviewed.

As the project proceeds, George and his engineering consultants use further elements of the design and decision tool to assist in detailed design of the lighting, HVAC, and envelope systems and components. This results in slight cost reductions and further improvements to the building energy performance. Another 2% reduction in estimated energy use is obtained.

During construction, the ICAD system provides more assistance to the design team by assessing impacts of construction change orders. Then the building commissioning package is delivered to the owner. Part of this package is a set of computer-based data to assist the building operator in properly operating and managing the building for energy efficiency. Arrangements have also been made for George's ICAD to receive data on performance from an advanced monitoring system on-site. The ICAD will use these data to evaluate the actual effectiveness of strategies used in designing this building and to modify its knowledge base, if necessary.

4.0 BENEFITS OF THE AEDOT RESEARCH PROJECT

The AEDOT project would have far-reaching benefits to building owners, building users, and the entire nation. The anticipated benefits to each of these groups are discussed in this section. Building design and operation professionals would also clearly benefit from the project; because these benefits have been discussed throughout previous sections, they will not be reiterated here.

4.1 BENEFITS TO THE NATION

The potential national benefit to be realized from the design of more energy-efficient commercial buildings is substantial. The contributions that could be made by improved end-use efficiency in the four major sectors of the U.S. economy are shown in Figure 4.1. If energy-use intensities (or

FIGURE 4.1. Contributions of Energy Resources, Including Improved End-Use Efficiency, to U.S. Energy Supply in 1984 (Energy Information Administration 1986; Office of Policy Planning and Analysis 1985). The percentages shown are fractions of total U.S. energy consumption (99.2 quads) that would have resulted if end-use intensities had remained at 1973 levels.

efficiencies) had remained at 1972 levels, 1984 national energy consumption would have exceeded 99 quads; actual 1984 consumption was 74 quads. This 25-quad savings is a resource ranking second only to petroleum in contribution to U.S. energy supply. Although these savings are significant, commercial buildings offer even more potential for energy savings.

The contributions of each sector to national energy consumption for 1973 and 1984 and to the 25-quad savings associated with improved end-use efficiency are shown in Figure 4.2. The industrial sector performed best by contributing significantly more (49%) to savings than its national energy market share in 1973 (42%). Conversely, the commercial sector, which is composed primarily of commercial buildings, performed worst by contributing somewhat less (10%)

FIGURE 4.2. Relative Energy Consumption and Savings by Economic Sector for 1973 and 1984 (Energy Information Administration 1986; Office of Policy Planning and Analysis 1985). The shaded bars (third in each group) represent the fraction of the total 25.1-quad savings attributable to improved end-use efficiency in each sector.

than its market share (13%). The lagging performance of the commercial sector is also apparent in Figure 4.3, where energy-use intensities in 1972 and 1984 are compared for each sector.

The goal of the AEDOT project is to increase the energy efficiency of the commercial buildings sector. Conservative estimates, based on recent research on building energy performance standards (AIA 1980), indicate that with no additional first costs, at least 15% of the energy now used in new buildings could be saved using readily available energy-efficient building design knowledge. If more measures requiring modest additional first cost (with payback periods of less than 3 years) are considered, this estimate increases to approximately 30%. Early building system integration research suggests that, by using building subsystem integration techniques, savings of 60% could

FIGURE 4.3. Relative Energy-Use Intensities (EUIs) by Economic Sector (Office of Policy Planning and Analysis 1985)

be achieved (Stoops et al. 1984; Burt Hill 1985; NAHB 1987; Rosenfeld and Hafemeister 1988). Estimates of the value of these savings for new commercial buildings, plus similar savings from retrofit of existing buildings, projected over 15 years, are illustrated in Figure 4.4. The most conservative of these estimates, therefore, places the cumulative savings available in both new and retrofit buildings at approximately \$50 billion (1986 \$) over the first 15 years. All estimates in Figure 4.4 assume no escalation in fuel costs and include only direct savings on fuel expenditures. Additional indirect savings associated with displaced electrical generating capacity for the future are not included but could be significant.

FIGURE 4.4. Cumulative Projected Dollar Savings from Improved Energy Efficiency in New and Retrofitted Commercial Buildings

Because petroleum resources account for less than 8% of the end-use energy requirements and less than 5% of the energy expenditures in commercial buildings, the direct impact of this proposed research on net energy imports, especially oil, will probably be negligible. However, as recommended by the White House Conference on Productivity (1984), the value of this research to the nation may best be measured in terms of its benefit to productivity for both the private and public sectors. With the U.S. currently spending up to 75% more than its trading partners for energy requirements [measured in terms of energy costs per dollar of the gross national product (GNP)] (Rosenfeld et al. 1987), the reduction in energy overhead in the commercial sector resulting from this project could also contribute to increased U.S. productivity and competitiveness in international markets.

4.2 BENEFITS TO BUILDING OWNERS

Building owners benefit directly when the costs of operating their buildings decrease and indirectly from benefits to the nation. However, two factors obscure the magnitude of the benefits from most building owners. First, owners generally give disproportionate priority to minimizing design and construction costs over life-cycle costs. Life-cycle costs are often not adequately considered in building design decisions. Second, even for owner-occupied buildings, facility costs (i.e., design, construction and operating costs) are generally small when compared with payrolls, making energy costs appear insignificant.

Estimates used by the National Academy of Sciences Building Research Board (1984, 1985) suggest that design and construction costs together are about one-fifth to one-sixth of total facility life-cycle costs (see Figure 4.5). As shown in Figure 4.5, design costs alone amount to only about 1% of a building's total life-cycle costs. Operating costs represent nearly 80% of total costs. As a result, increases in design costs that result in substantial decreases in operating costs are repaid many times over during the building lifetime. Designers who effectively include energy use and operating costs as design criteria will be able to better advocate the long-term, life-cycle interests of owners.

FIGURE 4.5. Relative Magnitude of Typical Office Building Life-Cycle Costs (Building Research Board 1984; GAO 1978)

Utility costs are the largest component (over 40% in 1985) of building operating costs, as discussed in Section 2. They are also quite variable, and the costs most easily reduced below current levels (see also Appendix A). An example of the potential benefits associated with reducing operating costs is shown in Figure 4.6 in an analysis of life-cycle cost components for a prototypical five-story office building. Although costs for other types of commercial buildings vary considerably from these, Figure 4.6 does highlight the importance of energy.

Studies by the Building Research Board (1984, 1985) have also identified avoidable operating costs that result from building-specific information that is lost over the building's life cycle. The use of integrated, building-specific databases, that could be made feasible by this project, would facilitate information transfer and lead to additional operating cost savings that are not limited to savings associated directly with energy. Worker productivity may also increase as a consequence of better designed buildings.

FIGURE 4.6. Analysis of Life-Cycle Cost Components Based on Prototypical Building [Means Company 1986; BOMA 1986; Institute of Real Estate Managers (IREM) 1986]

4.3 BENEFITS TO BUILDING USERS

To the extent that there is a trend toward tenants paying utilities in commercial office buildings, the benefits of energy-related savings will increasingly be shared by building users and tenants. Beyond this trend, however, building users will benefit most from improved indoor environmental quality and the associated beneficial effects on occupant productivity.

Although the relationship between environmental factors (i.e., spatial, visual, thermal, acoustic, and air quality) and productivity is not well understood(a), definite links have been demonstrated (McNall 1979). Furthermore, the role of environmental factors in occupant productivity is thought to be gaining in importance due to the widespread introduction of automated information technologies (Hartkopf et al. 1986). A 1980 industry survey performed by Steelcase Corporation found that visual and thermal comfort were included in the four most important environmental factors identified by executives and clerical workers. The design technologies that would result from this project would help improve all aspects of the indoor environment by providing building design professionals with an improved ability to assess and include such qualitative criteria as visual and thermal comfort.

As the links between environmental factors and productivity become better defined, occupant productivity will become a more salient building design criterion. This may lead to a design decision process that proceeds from the inside of a building out, giving greater emphasis to user satisfaction. This would place greater importance on end-user participation in both building design and operation. The products of AEDOT would support a feedback loop in which building design professionals learn from data, including feedback from users, on the performance of buildings they have designed.

-
- (a) Current prescriptive standards for these environmental factors do not adequately consider the way in which these factors interact with one another in influencing productivity.

5.0 RESEARCH AND DEVELOPMENT PLAN

In this section, a proposed multiyear plan for the AEDOT project is described. Information is presented on these aspects of the plan:

- approach
- overview
- elements and tasks
- management and coordination
- estimated costs and level of effort.

Achievement of the plan would result in a set of computer-based technologies for assisting in all stages of the building life cycle. These technologies would then be transferred to industry for further development and incorporation into advanced commercial quality CABD and building operation systems.

5.1 APPROACH

Initial project activities should focus on development of a system for energy-efficient design. The domain of design-system research, shown in Figure 5.1, includes energy design components, system control components, knowledge bases, some energy databases, and imaging and visualization technologies for interfaces. The domain does not include development of new fundamental knowledge of building energy performance or new energy analysis tools. Development of operation technologies would begin later in the project, although the transfer of information between the design and operation stages would, by necessity, be considered in the analysis of AEDOT requirements early in the project. Consequently, the early objectives focus on design rather than operation. The experience acquired during early work on design would be used to help formulate the objectives for research on operation technologies.

FIGURE 5.1. Domain of AEDOT Research (adapted from Heidell and Deringer 1987)

5.2 OVERVIEW

The major elements of the project plan are identified in Figure 5.2. Each element is positioned with the appropriate project time line to indicate its temporal relationship to the overall project.

During the first 1.5 years of the project, work would focus primarily on specifying the project requirements, formulating an overall structure for the AEDOT systems, and identifying and assigning priorities to major research and

FIGURE 5.2. Schedule of Elements Comprising the AEDOT Research Project

development tasks. The entire building life cycle should be addressed in the Requirements Analysis, to ensure that interactions between the different stages are adequately considered. The primary focus, however, would be on specifying the requirements for design technologies. The success of the overall project would depend on proper execution of these tasks. They would establish the course for research and development that would be undertaken to meet the requirements.

Preliminary work to develop a testbed for component integration should begin at the end of the first year, before the Requirements Analysis is completed. Research on a few high priority topics (e.g., computer visualization) also would begin at that time. The high priority status would be assigned

only to topics that are identified during the Requirements Analysis as clearly essential to successful completion of the project.

After the Requirements Analysis is completed, the focus would shift to research into the identified fundamental problems, as well as development of prototype systems and the components comprising them. Prototypes would be developed for both individual components and integrated (but not necessarily complete) systems. As work progresses, the building design process would become better understood, unanticipated impediments to development would be identified, and technological advances (e.g., in computer technology) outside this project would occur. New research problems and development tasks would evolve and shape the course of the AEDOT project. To adapt to these changes, the requirements specification should be updated from time to time.

At approximately 3.5 years into the project, research and development on advanced operation technologies should begin. This would be started with a requirements analysis that specifically focuses on operations and the exchange of information between operation and design. The product of this requirements analysis would be a detailed research plan for operation technologies. Part of the analysis would involve assessment of the industry that manufactures and markets energy management and control systems (EMCS), to ensure that this aspect of the project focuses on developing operation technologies that the industry is unlikely to develop independently. This work would address the operation of both new and existing buildings, ultimately affecting an even greater number of buildings.

The primary concern during the last year of the project would be transfer of the AEDOT technologies to industry. The project team would work with the CABD industry to incorporate the energy design technologies resulting from the AEDOT project into advanced CABD systems. The EMCS industry is likely to be the industry to utilize the advanced operation technologies developed under this project. Although dissemination of the results of this project to industry would be completed in this stage, interaction with industry should be established and maintained over the entire project. Industry representatives could help guide the project by participation on an advisory group. The status of all appropriate industries and their products would be carefully assessed

during the Requirements Analysis and monitored throughout the life of the project. The dissemination of AEDOT technologies completed in the last year of the project would be the culmination of these efforts to interact with industry.

5.3 ELEMENTS OF THE PLAN

The activities comprising the proposed AEDOT research and development plan (see Figure 5.2) are described in detail in this section. Activities that would begin early in the project are detailed more extensively because the Requirements Analysis would largely determine the specific research and development work that should follow. Consistent with this, Section 5.3.1 describes the Requirements Analysis, Section 5.3.2 describes System Development with most of the detail provided representing work recommended for the first 2 years, and Section 5.3.3 concerns other research and development activities that would be defined better by the Requirements Analysis.

5.3.1 Requirements Analysis

The Requirements Analysis is the first major element of the AEDOT project plan.

Objective

The objective of the Requirements Analysis is to provide in-depth understanding of the building design process, energy design methodologies, and appropriate computer science technologies. These assessments would provide the basis for the specific research and development tasks necessary to develop the AEDOT technologies.

Scope

The AEDOT project should be concerned with the entire building life cycle. However, the Requirements Analysis would focus primarily on the design stage. The other stages would be examined in a general way to determine their relationships to design, particularly with respect to how the flow of information between stages of the life cycle might be used to increase energy efficiency. The results of this examination would impose additional requirements on the

design technologies and help establish the scope of work on operation technologies recommended for later in the AEDOT project.

Although AEDOT concepts are applicable to both design of new buildings and modification of existing buildings, the Requirements Analysis would be focused on the former. The requirements associated with existing building modification/rehabilitation would be determined when the work on operation technologies begins later in the project.

Approach

The approach to analyzing the requirements would involve evaluating and integrating the knowledge and experience of four groups:

- the Requirements Analysis team
- the AEDOT advisory group
- industry representatives
- academic researchers.

The Requirements Analysis team would extract and integrate the knowledge required to satisfy the objectives of this task. The team should consist of two to four persons who collectively possess

- knowledge of building sciences
- experience with implementing complex processes into an artificial intelligence (AI) framework
- formal experience with eliciting information from other people
- experience with knowledge acquisition about complex processes
- knowledge of the general process of design
- knowledge of computer science and technology.

The AEDOT advisory group should include six to twelve members from Pacific Northwest Laboratory (PNL), Lawrence Berkeley Laboratory (LBL), DOE Office of Buildings and Community Systems (OBCS), universities, professional societies, and industry. Serving in a consultant capacity, this committee would review the work of the Requirements Analysis team, periodically evaluate the direction

and progress of the Requirements Analysis element, and provide guidance to ensure that the objectives of this element remain consistent with the overall goals of the AEDOT project.

The industrial and academic sectors represent the principal sources of knowledge for the Requirements Analysis. Selected persons from these environments would be consulted for knowledge of the design process, automation technology, man/machine integration (human factors) issues, and AEDOT system requirements. Industrial participants would come from architecture/engineering (AE) firms, energy-efficient building design teams, CADD and CABD manufacturers, and firms spanning a number of other computer technologies.

Working with these groups, the Requirements Analysis team would focus on knowledge in the areas listed in Table 5.1. Descriptions of these areas of knowledge are provided in Appendix F.

Tasks

The tasks for the Requirements Analysis are divided into three general categories: development of a detailed execution plan, acquisition of knowledge, and documentation of results. The sequence and timing of these tasks are shown in Figure 5.3. Descriptions of the tasks follow. The Requirements Analysis team would have responsibility for completing all tasks. However, specific components of the work would be assigned to other working groups with relevant expertise.

Development of an Execution Plan. This task involves developing a detailed plan for executing the Requirements Analysis. Once the Requirements Analysis team is established, the primary activity would be development of detailed procedures for performing the Requirements Analysis, including developing protocols for interviewing and documenting interview sessions, developing conventions for documenting other work, establishing schedules, and assigning responsibilities.

Knowledge Acquisition. The knowledge acquisition task would involve literature review, interviews, conferences, and invited meetings.

TABLE 5.1. Principal Areas Addressed in the Requirements Analysis

Major Category	Subcategory
Building design	<ul style="list-style-type: none">• Energy design methodologies• Building design process• Building life cycle
Computer automation	<ul style="list-style-type: none">• Hardware and software• System integration• Graphics and visualization• Information input/output• Artificial intelligence and knowledge representation
Man/machine interaction	<ul style="list-style-type: none">• Task allocation• Human factors• Intelligent interfaces

Literature review is the initial knowledge acquisition activity. Appropriate literature would be reviewed concerning the building (and energy-efficient building) design process, computer automation, and man/machine integration. These reviews would extract background knowledge on basic concepts and determine the state of the art of each area of concern.

Literature review alone probably would not provide sufficient detail about the design process, designer needs, and recent advances in computer

FIGURE 5.3. Sequence and Timing of Requirements Analysis Tasks

automation. Interviews would be used to acquire additional detailed knowledge, providing information not available in literature.

Various techniques used by knowledge engineers for knowledge elicitation should be used as appropriate to the purpose of each interview. These techniques include conducting both structured and unstructured interviews and observing experts work on familiar tasks, limited information tasks, constrained processing tasks, and "tough cases" (Hoffman 1987).

Architects and design teams would be interviewed to determine how building design is performed by teams that do and do not include energy efficiency as a primary consideration in design. Determining the needs, desires, and idiosyncrasies of building designers would be another important objective of these interviews.

Some aspects of computer automation would require a greater depth of knowledge than can be acquired through conventional means such as literature

reviews and conferences. Addressing these issues would require interviews with appropriate people having knowledge of state-of-the-art computer automation technology and a thorough conceptual understanding of recent advances in the field.

Conferences would be a vehicle principally for acquiring information pertaining to automation technology (including CABD and CADD) and its use in engineering and design. A certain amount of state-of-the-art knowledge related to computer automation is often so new that this information is not yet published. Conference attendance would allow the team to acquire this knowledge through formal presentations, proceedings, poster sessions, industry product displays, and face-to-face communications. Conferences also provide a forum in which to meet experts in the field and to review and acquire information from many sources at the same time.

Invited meetings with a limited number of participants would be held as needed to acquire specific information. Decisions to hold such meetings would be based largely on the results of the other knowledge acquisition activities. These meetings would help initiate industry involvement in the AEDOT project, fill information gaps, and foster interaction among experts, possibly raising issues that might not otherwise be considered. Meetings would be both informal round-table discussions focused by a predetermined agenda and formal workshops or symposia.

Documentation. The information gathered in the Knowledge Acquisition task would be formalized and documented in this task. Six major elements would be documented:

- design process knowledge
- computer automation technology
- man/machine integration
- requirements specification
- conceptual design specification
- approach specification.

Each is discussed below.

Design process knowledge characterizes the primary and secondary results of building design and the processes by which they are obtained. This includes design stages, design models, and knowledge characterizing and used in energy-efficient building design. This specification also includes knowledge that establishes the relationships between all stages of the building life cycle.

Findings concerning the current and predicted status of the computer automation technology required for developing the AEDOT concept would be documented. This would include information about hardware, software, system integration, AI, knowledge representation, computer graphics and visualization, and information input/output. Documentation of the Requirements Analysis would establish the automation technology requirements, the current status of these technologies, and developments required before implementation of AEDOT would be possible. Throughout all phases of the project, advances in computer technology should be continually followed and analyzed with respect to applicability to AEDOT. The documentation of the Requirements Analysis would allow us to judge the feasibility of developing specific individual AEDOT technologies.

Man/machine integration issues, concerns, and technology related to task allocation and human factors should be assessed and documented. These factors are tied strongly to the building design process and the habits and idiosyncrasies of the people who would use the AEDOT products. The findings of the Requirements Analysis and additional research in man/machine integration that they call for would have particular significance to the development of appropriate user interfaces that establish the link between humans and the machine. Success in addressing these issues would ultimately determine the usability of the technologies that result from the AEDOT project.

The requirements specification document would specify what the system must provide with respect to operational and administrative concerns. The operational requirements would describe capabilities, features, processing, system input/output, and transformations of input and output. The administrative requirements would describe the design life cycle, what tools are necessary for the design operations, how and in what form design information must be

maintained during the design process, and requirements based on how firms and design teams carry out projects.

The conceptual design specification document would describe how the system should meet the requirements. This specification establishes a general structure for the design system, identifies key system components and their functions, and characterizes the nature of the links between these components. The results would establish the point of departure for Design Component Development and System Development.

All major research and development tasks would be specified in the approach specification document. Also included would be a prioritization of these tasks, the current status of the problem associated with each task (e.g., whether work is at the proof-of-concept stage, ready for development of operational prototypes, or sufficiently developed for inclusion in production systems), products required from each task, strategies for research and development, and required levels of effort.

5.3.2 System Development

System Development is the second major element of the proposed AEDOT project.

Objectives

The primary objectives of the System Development element would be

- to enhance understanding of the AEDOT requirements
- to ensure the quality and usability of systems developed by the project
- to facilitate industry interaction
- to interactively develop the AEDOT concept.

The System Development element would provide further understanding and insights into the design process and issues associated with automation of this process. Because integration is incremental, it should provide appropriate opportunities to evaluate existing concepts and requirements and make necessary revisions. Modifications to the research and development program may also be necessary as new problems and needs are identified in System Development.

The key AEDOT objective should be to promote and develop an automated design technology that provides energy analysis as an integrated part of the design process. However, if the technology developed has poor quality, is difficult to use, or does not integrate well into the overall design scheme, then the technology will never be used. Therefore, a necessary objective of the System Development element should be to help develop appropriate, high-quality, user-friendly, automated energy design aids.

Scope

System Development would involve integrating the different AEDOT components into a single operational environment. This environment would provide for system research, development, and analysis. The tasks comprising this element would help identify and evaluate research requirements, development issues, and unforeseen impediments to development. In addition, this element would provide, by use of a testbed, a focus for industry interaction and standardization.

Approach

The general approach to accomplishing the System Development objectives would include three major tasks:

- Develop a testbed environment.
- Perform component and system analysis.
- Provide prototypes that demonstrate AEDOT concepts and capabilities.

The relationship between these is shown in Figure 5.4. The testbed would provide a hardware and software environment for linking individual components to form systems. Analysis would provide the required testing and evaluation of components and systems. Selected systems would be classified as prototypes and preserved for use in demonstrations and for more extensive testing.

The subsections that follow provide more detail about the AEDOT components, the testbed, and component/system analysis.

Preliminary AEDOT Components. The AEDOT components are hardware and software systems that provide the capabilities required to achieve the proposed AEDOT project goals. Components that might be tested and integrated during

FIGURE 5.4. Relationships Between the Three Components of System Development

the AEDOT project include CABD systems (software and hardware), user interfaces (CABD, visualization, and stand-alone), energy design tools (developed by DOE and others), design process knowledge (facts and rules), energy-efficient design knowledge, energy analysis tools, design instances, inference mechanisms, and knowledge representation schemes. Figure 5.5 illustrates the relationship between each of these components and the testbed. The components shown and listed are examples; the actual components would be identified in the Requirements Analysis.

Testbed. The testbed would be a computational environment for integration, testing, evaluation, and demonstration of AEDOT components. The testbed would be continually developed as project needs dictate and automation technology improves. Because a dynamic testbed would be needed, it would be developed incrementally as components become available, with maximum built-in flexibility.

Integration distinguishes the proposed AEDOT project from other efforts to develop energy design tools. As a result, the project would necessarily require integrating a diverse set of components. Without adequate integration,

FIGURE 5.5. Preliminary AEDOT Components and Their Relationships to the Testbed

the project either would fail or would provide a system that few, if any, design professionals would use. The testbed would provide the capability to integrate hardware and software components early in the project. The testbed also would have a strong relationship to AEDOT requirements and objectives because integration should be a principal goal of the AEDOT project. It would provide the foundation upon which other work would be built. The integration activity would increase the quality and usability of the resulting technologies through feedback as individual components and systems are tested and evaluated.

The testbed environment would comprise hardware, system software, AEDOT component software, and testbed software. The hardware elements would provide computing capabilities and include disk storage, system console, input/output components, and networking hardware. The system software would provide a basic

environment for software development, maintenance, and integration. The system software would consist of one or more operating systems, editors, compilers, graphic systems, database management systems, debuggers, and networking software. Component software consists of software modules that would provide AEDOT functions. Examples of component software are energy design tools, knowledge representation schemes, and commercial CABD systems (see Figure 5.5). Testbed software consists of modules that would provide the testbed with the capability to perform its function. The testbed software can be partitioned into control and configuration-management software (see Figure 5.6).

Two major functions of the testbed would be to provide intercomponent communication, which is the principal task of configuration, and system control.

Analysis. Analysis (see Figure 5.4) is a stage in the development life cycle of a system. The stages of the life cycle consist of requirements definition, research, component development, component integration, and analysis (see Figure 5.7). Stages interact in both the downward and upward directions (i.e., feedback and iteration not explicitly shown occur). The requirements

FIGURE 5.6. Testbed Software by Function

FIGURE 5.7. System Development Life Cycle

would determine the specific research and development issues that must be addressed. As the research and development progresses, new requirements might also be identified.

When an individual developer has completed a component (in either final or intermediate prototype form), it would be integrated into the system via the

testbed. After the component is bound to the testbed, it would be analyzed with respect to its individual capabilities and as an integrated element in a system. The analysis would be performed in two stages; each stage would have two substages (see Figure 5.8). Testing must be performed first. Upon successful completion of the testing stage, the component or system would proceed to the evaluation stage.

Testing involves determining the correctness and completeness of the component compared to its required capabilities. Testing would be performed first on individual components and then at the system level. Systems are combinations of components linked to provide a set of functions. As an example, the integration of an interface component, CABD package, and database could define a system that would provide the functional capability of specifying and viewing a building.

Evaluation involves examining the component or system with respect to the AEDOT requirements it should satisfy. A metric is specified, and the component or system is evaluated against this metric. Metrics would include items such as a measure of the degree to which requirements are satisfied,

FIGURE 5.8. Stages of Analysis

percentage of requirements satisfied, a measure of ease of use, measures of human factors, and speed of execution. Based on their capabilities, selected components and systems (i.e., states of the testbed) would be classified and used as prototypes.

Individuals involved in component and system analysis would include (but would not be limited to) the following:

- testbed development team
- component developers
- individuals interviewed and participating in system testing.

Tasks

System Development should be a dynamic activity with tasks repeatedly executed as required throughout the life of the project. The approximate sequence and timing proposed for the System Development tasks are shown in Figures 5.9 and 5.10. The first three tasks (determine task execution plan, build demonstration, and specify testbed conceptual design) would be performed during the first 1.5 years of the project; the remaining steps would be performed after completion of the Requirements Analysis.

Determine Task Execution Plan. This step would involve developing a well conceived, detailed plan for executing the System Development task.

Build Demonstration. This step would involve determining, specifying, and building a demonstration system with limited capabilities. The objective of this demonstration would be to illustrate a selected set of AEDOT capabilities and to provide experience and insights into testbed construction. Later demonstrations would build upon prototypes that evolve from systems analysis (see Figure 5.4).

Specify Testbed Conceptual Design. Based on needs determined in the Requirements Analysis and knowledge acquired in building the initial demonstration, the testbed requirements would be defined. A conceptual design for the testbed would then be developed from these requirements.

FIGURE 5.9. Sequence and Timing of System Development Tasks

Determine Status of AEDOT Components. This task involves specifying and evaluating the status of all AEDOT components by determining which components are already developed and which should be developed in the near term. For each component (as a minimum) the following properties would be specified:

- manual versus automatic implementation
- computer hardware requirements
- computer software requirements (languages, tools, and operating systems)
- functional capabilities.

Develop the Testbed. This task would consist of specifying the design, purchasing hardware and software, implementing the design, developing operation and administrative procedures, and documenting the testbed.

Specification of the testbed design would be an iterative exercise consisting of modification to the conceptual design, specification of logical

FIGURE 5.10. Sequence and Timing of System Development Tasks Over the First 1.5 Years of the Project

functions, identification of a testbed hardware and software environment, and specification of physical functions. The initial conceptual description should be determined prior to this task (see Specifying Testbed Conceptual Design). Modifications to this and the resulting conceptual descriptions would be determined largely by developments in component and automation technology.

Logical functions for the testbed would be determined from the conceptual design. These functions provide the means to implement testbed requirements independently of the type of hardware and software used to implement the functions. Based on these functions and the conceptual design, a hardware and software environment must be specified. Additional testbed requirements would arise from the computational environment selected, which would affect the physical functions of the testbed.

Implementing the testbed design would involve setting up hardware and developing and installing software. A portion of the testbed would be

commercially purchased hardware and software. Implementation of purchased testbed components would consist of setup, installation, and verification. The remaining portion of the testbed software would be designed and developed as a part of the AEDOT project (under Component Development, see Section 5.3.3). Installation and verification of these software components would be done in the testbed environment and would continue throughout the project.

Procedures for testbed operation and administration should be developed once the testbed is installed. They would specify how the testbed should be used, maintained, and modified.

The testbed would also be documented carefully. Documentation would include the requirements, conceptual design, detailed design, and modifications made during development and use.

An example of the proposed testbed environment is shown in Figure 5.11. A production system would not require the depicted PC systems; however, they

FIGURE 5.11. Example of the Testbed Hardware Environment. The PCs shown may be from different manufacturers and/or use different operating systems.

could be implemented if desired. Architectural/engineering firms that might invest in an AEDOT commercial system will most likely already have some PC hardware. These firms cannot afford to scrap their existing hardware, software, training, and experience in order to implement an AEDOT system. An AEDOT system should be integratable into the existing office automation environment. For this reason, it is important that the AEDOT project demonstrate the capability of integrating the AEDOT technologies with these existing computer systems.

Integrate Components. Component integration consists of installation of a component into the testbed. Components would consist of other hardware and software. Integration of hardware would involve physically connecting the component hardware to the testbed hardware. Software integration would consist of installing the software on the appropriate hardware and providing the capability for the component software to communicate with the rest of the system residing on the testbed.

Perform Analysis. Analysis would involve

- specifying analysis procedures
- analyzing components
- analyzing systems (including prototypes)
- documenting the analyses (including procedures, results, and conclusions).

Analysis should begin during construction of the initial demonstration. It (and integrating components) would become the focus of System Development as the project continues (see Figure 5.2). The testbed would evolve, and more complete system prototypes would be produced.

The prototypes provided by the System Development element would be used in demonstrations throughout the project to illustrate AEDOT concepts and progress. They would be used to communicate concepts to design experts and users and for rigorous system analysis (testing and evaluation). As the project proceeds, results from system analysis would be used to provide feedback for updating project requirements and to further specify, coordinate, and manage research and component development. In the final 2 years of the proj-

ect, prototypes would be used primarily to demonstrate products of the AEDOT project as part of dissemination of the AEDOT technologies.

5.3.3 Other Elements

After the Requirements Analysis is completed, the focus of the project would turn to development of the AEDOT components and system. The major activities (see Figure 5.2) would then be

- design process research
- design component development
- system development (see Section 5.3.2)
- operations requirements analysis
- operations process research
- operations component development
- dissemination of AEDOT technologies.

The requirements would continue to evolve (indicated by the dashed line in Figure 5.2) as this research progresses.

Design Process Research, Design Component Development, and System Development must be tightly coupled. All three activities should be started around the end of the first year of the project, but at a minimal level of effort until the Requirements Analysis is completed. Design Process Research would address issues not answered during the Requirements Analysis. This research would concern fundamental questions relevant to development of design components and systems.

Design component development would involve developing not only components that assist in specific design tasks, but also components required to implement the design components (e.g., inference mechanisms, databases, knowledge representation schemes, and user interfaces). Development of each component would require a smaller-scale, but very detailed, analysis of requirements for the specific need that the component satisfies. When ready, prototypes of components would be integrated with others and evaluated under System Development. Results from evaluation would then be fed back to the developers and used to

guide further development. Some component prototypes could represent intermediate stand-alone products that could be transferred to ultimate users before the entire AEDOT project is completed.

Requirements for operation technologies would be examined initially as part of the Requirements Analysis. However, that examination would be pursued only to the depth necessary to determine the links between building design and operation and their impacts on design requirements. Work on operations technologies would be reserved for midway through the project. The Operations Requirements Analysis, which would begin in the third year of the project, would specify building operation requirements and identify research and component development needed for development of operation technologies.

Operations Process Research and Operations Component Development activities should be initiated at completion of the Operations Requirements Analysis. As with design, these two activities are tightly coupled and should proceed concurrently. The activities would be directed toward the development of design and operation tools that exchange information and provide optimal building performance.

Dissemination of AEDOT products would be the final element of the project. During the project, information on AEDOT would be disseminated through publications, conference presentations, involvement in specialized topic symposiums, workshops with industry, and demonstrations. The purposes of these activities would be to publicize the AEDOT project (its developments and findings) and to increase active industry (both AE and CABD) involvement in the project. Intermediate stand-alone products would be transferred to industry and end users as they are developed throughout the project. In the final 1.5 years of the project, focus would turn to preparation of system documentation and final reports, development and demonstration of final system prototypes, and transfer of the AEDOT products to industry.

Dissemination of technologies could involve jointly developing and implementing an AEDOT system with industry. Much of the knowledge and experience needed to build an AEDOT system and utilize AEDOT would reside in individuals who played principal roles in component and system development activities.

This information should be documented thoroughly (throughout the project), and final prototypes of the design and operation systems (or possibly one integrated system) should be available for demonstration of all AEDOT capabilities.

However, the development experience itself would still be held by the project participants. Because of this, continued joint development and implementation of an AEDOT system with industry might be the most expeditious means of getting the technologies into the hands of building designers and operators.

5.4 MANAGEMENT AND COORDINATION

In this section, the organizational structure for management of the AEDOT project is described. Use of private sector researchers and coordination with industry are also discussed.

5.4.1 Management

Program management should be provided through several activities. The proposed organizational structure for the AEDOT project is shown in Figure 5.12. Management at PNL would be responsible for establishing project goals and developing plans in consultation with OBCS and then implementing those plans.

Technical activities in this project would be executed according to an annual operating plan that would be developed at PNL in consultation with OBCS, the other national laboratories involved, major private-sector subcontractors, and the AEDOT project advisory group. The annual operating plan would specify a detailed organizational structure and work breakdown structure, along with milestones, schedules, and budgets for all major project elements. Detailed monthly technical and financial reports would be prepared for and reviewed by OBCS. These monthly reports would provide technical highlights, the financial and milestone status, and identification of technical and administrative issues requiring resolution.

The AEDOT advisory group, consisting of six to twelve members, should be formed early in the project. This group would serve in a consultant capacity. It would be composed of individuals from OBCS, PNL, LBL, universities, and industry. Initially, members of the group would be selected from persons who have participated in the development of this document. This group would be

FIGURE 5.12. Organizational Structure for the AEDOT Project. The complete branching structure is shown only for System Development (Task Group 2). All other tasks have a similar structure.

supplemented by industry representatives identified during the Requirements Analysis. Involvement of industry representatives would help ensure that project goals remain consistent with industry needs and developments. The group would meet periodically to assess the status of the project, review work in progress, evaluate the direction of the project, and provide guidance to

ensure that the overall goals of the AEDOT project are met. Ultimate responsibility for direction of the project, however, would be with PNL, subject to the approval of OBCS.

All major project elements would be assigned a task leader. Most of these elements would be identified during the Requirements Analysis, although some already exist and others could be identified as the project progresses. A core task group would plan and perform activities under each task. Consultants, university and industrial researchers, other national laboratories, building designers, and building energy experts would be subcontracted for specific research and development activities in a balanced program with in-house efforts. For example, many modules (under Task Group 3 in Figure 5.12) that address specific parts of building design would, in all likelihood, be developed by researchers outside PNL who are already working on particular design problems. Integration and testing of those component modules would then be done at PNL (under Task Group 2).

Technical reviews of each task should be held periodically to assess progress. Private sector researchers and industry representatives should be invited to participate in these reviews as appropriate for the task. For program elements that investigate particularly complex technical issues or that depend on industrial developments or research outside this project, the project management would convene special technical review committees. These committees would be composed of leading experts in appropriate fields and representatives of major organizations with particular interests in the issues. The technical review committees would provide technical advice on relevant research and on the most promising technical directions. These committees would also enhance the exchange of information with industry and maintain industry involvement.

5.4.2 Industry Coordination

Industry interaction would be essential to the success of this project. Involvement of CABD manufacturers would help ensure that the technology developed is compatible with commercial CABD systems and advances in that field over the life of the project. Interaction with the building design

community would possibly be even more important, as its members would represent the ultimate users of the design technologies. Building designers should become involved at the earliest stages of the Requirements Analysis as consultants and interviewees. As the proposed work on operation technologies begins, building operators and representatives of the EMCS industry should also become important participants in this project.

Several mechanisms for industry involvement should be established, including participation on the AEDOT advisory group and on technical review committees, as sources of expert knowledge on building design, energy-efficient buildings, and computer-aided building design, in the testing of prototypes, and as participants in a forum to share the results of this project and information on industrial developments. Most of these have been discussed previously in this report, with the exception of the industry forum.

A CABD industry forum should be formed to promote the exchange of information on industry developments and plans and to review the directions and progress of the AEDOT project. The management of the AEDOT project would work toward establishing an industry consortium to fund specific components of the research. Parts of the work might be separated as distinct but related projects and funded by the industry consortium, which would then share the results among member firms.

5.5 ESTIMATED COSTS AND LEVEL OF EFFORT

The technical activities planned for the AEDOT project span a broad range of topics, requiring a number of researchers having different expertise. As a result, the project would involve researchers from PNL, LBL, and universities, as well as building designers, architectural/engineering firms, and the computer (hardware and software) industry. Responsibility for each task should be allocated to the person or team with appropriate experience and expertise. In addition, all tasks must be adequately coordinated to meet the goals of the AEDOT project. The plan of activities is described in Section 5.3. The management and organization described in Sections 5.2 and 5.4 provide the necessary coordination.

The project is proposed for a period of 9 years at a total cost of approximately \$27 million. Total funding requirements are shown as functions of time in Table 5.2. More detail is provided for the first 7.5 years in Tables 5.3 and 5.4. Because activities after the first 1.5 years would depend on the findings of the Requirements Analysis, specific tasks and costs proposed are less certain. Consequently, the details provided for years 1.5 through 7.5 must be interpreted with some caution, and no details are provided for the last 1.5 years. Completion of the Requirements Analysis would eliminate much of this uncertainty by providing a formal specification of the specific research and development activities required to satisfy the AEDOT objectives.

The potential impacts of the design and operation technologies that would result from the AEDOT project are unprecedented. This project could provide building designers with the ability to design cost-effective, energy-efficient buildings much quicker than possible today and without the huge time investment now required to become building energy experts. The benefits resulting from the AEDOT project (\$50 to 200 billion direct savings over the first 15 years; see Section 4) would greatly overshadow the cost of this project by comparison. The AEDOT design and operation environments would have the potential for far greater impact than any other energy information transfer activity to date.

TABLE 5.2. Funding Requirements for the DOE Advanced Energy Design and Operation Technologies Project

Project Years	Estimated Total Funding Required
0 - 1.5	\$1.95M total
1.5 - 7.5	\$3.45M/year
7.5 - 9	\$3.00M/year

TABLE 5.3. Funding Requirements During the First 1.5 Years by Project Element

Activity	Funding Required
Requirements Analysis	\$1.3M
System Development	\$400K
Component Development	\$250K

TABLE 5.4. Funding Requirements for Years 1.5 through 7.5
by Major Activity

Activity	Funding Required
Design Process and Operations Process Research	\$850K/year
Component Development (Design and Operations)	\$1.7M/year
System Development	\$900K/year

Activity	Funding Required
Requirements Analysis	\$1.3M
System Development	\$900K
Component Development	\$850K

6.0 REFERENCES

- Adams, R. C., D. B. Belzer, J. M. Fang, K. L. Imhoff, D. H. Lax, R. J. Moe, J. M. Roop, and A. R. Wusterbarth. 1985. A Retrospective Analysis of Energy Use and Conservation Trends: 1972-1984. PNL-5026, Pacific Northwest Laboratory, Richland, Washington.
- American Institute of Architects (AIA). 1980. Life Cycle Cost Study of Commercial Buildings - Final Report. Washington, D.C.
- Architectural Record. 1985. "The Results of a RECORD Survey: How Are Firms With Computers Faring and What Are the Nonusers Waiting For?" Architectural Record 173(7):37-41.
- Brownstein, M. 1988. "To Boldly Go Where No PC Has Gone Before" InfoWorld 10(6):21.
- Building Owners and Managers Association International (BOMA). 1986. 1986 BOMA Experience Exchange Report - Income/Expense Analysis of Office Buildings. Washington, D.C.
- Building Research Board. 1984. Report from the 1984 Workshop on Advanced Technology for Building Design and Engineering. National Academy of Sciences, Washington, D.C.
- Building Research Board. 1985. Report From the 1985 Workshop on Advanced Technology for Building Design and Engineering. National Academy of Sciences, Washington, D.C.
- Buildings. 1985. "Productivity: Equating People and Profits." August 1985, 79:78.
- Burt Hill Kosar Rittelmann Associates. 1985. Small Office Building Handbook: Design for Reducing First Costs and Utility Costs. Van Nostrand Reinhold, New York, New York.
- Crawley, D. B., R. S. Briggs, J. W. Jones, W. W. Seaton, J. E. Kaufman, J. J. Deringer, E. W. Kennett. 1987. Development of Whole-Building Energy Design Targets for Commercial Buildings - Phase I Planning, Volume 2: Technical Report. PNL-5854 Vol. 2, Pacific Northwest Laboratory, Richland, Washington.
- Dell'Isola, A. J. 1982. Value Engineering in the Construction Industry. Van Nostrand Reinhold, New York, New York.
- Dorfman, J. 1985a. "CAD/CAM Past, Present & Future (Part 1)." Design News. February 18, 1985, 41:171-178.
- Dorfman, J. 1985b. "CAD/CAM Past, Present & Future (Part 2)." Design News. March 4, 1985, 41:125-130.

- Dryden, R. L. 1985. Design News. "Computers Spur Productivity." 40(13):57-60.
- Edmunds, J. 1986. "1986 Census of Firms." Consulting Engineer 66(6):40-47.
- Energy Research Advisory Board (ERAB). 1985. Guidelines for DOE Long-Term Civilian Research and Development. DOE/S-0042, Volume 5, Office of Energy Research, U.S. Department of Energy, Washington, D.C.
- Energy Information Administration (EIA). 1986. State Energy Data Report - Consumption Estimate, 1960 - 1984. DOE/EIA-0214(84), U.S. Department of Energy, Washington, D.C.
- Filey, R. D. 1985. "Three Emerging Computer Technologies Boost Value of, Respect for Facilities Function." Industrial Engineering 17(5):27-39.
- Gallagher, R.T. 1984. "CAD Program Melds 28 European Labs." Electronics 57(4):80.
- General Accounting Office (GAO). 1978. Computer-Aided Building Design. LCD-78-300, Washington, D.C.
- General Accounting Office. 1980. Use Of Computers By Firms Providing Architect-Engineer Services to Federal Agencies. LCD-81-2, Washington, D.C.
- Gero, J. S. 1975. "Architectural Optimization - A Review." Engineering Optimization 1(3):189-199.
- Gero, J. S., A. D. Radford, R. Coyne, and V. T. Akiner. 1984. "Knowledge-Based Computer-Aided Architectural Design." In Knowledge Engineering in Computer-Aided Design, pp. 57-88. North Holland, New York, New York.
- Hartkopf, V., et al. 1986. "The Development of Intelligent Systems Toward Total Building Performance." In The Second Century of the Skyscraper. Van Nostrand, New York, New York.
- Heidel, J. A., and J. J. Deringer. 1987. Developing an Energy Design Tool--Phase I Report. PNL-5709, Pacific Northwest Laboratory, Richland, Washington.
- Hoffman, R. R. 1987. "The Problem of Extracting the Knowledge of Experts from the Perspective of Experimental Psychology." AI Magazine 8(2):53-67.
- Institute of Real Estate Managers (IREM). 1986. Income/Expense Analysis - Office Buildings Downtown and Suburban. Chicago, Illinois.
- Lang, L. 1987. "Micros and Workstations: Price vs. Power." Design Graphics World 11(10):10.
- Language Technology. January/February 1988. "NewSpeak." 5:35.

McNall, P. E. 1979. "The Relationship of Thermal Comfort to Learning and Performance: A State-of-the Art Review." ASHRAE Transactions. Vol. 86, Part 1, pp. 759-767.

Means Company, Inc. 1986. Means Square Foot Costs. R. S. Means Company, Inc., Kingston, Massachusetts.

Morse, R. S. 1976. "Innovative Technology: What is its Impact on U.S. Economy?" Professional Engineer 46(8):14-19.

Naegele, T. 1986. "Expert System Cuts Chip Design Time by Up to 50%." Electronics 59(12):25-28.

National Association of Home Builders (NAHB). 1987. Cutting Costs in Multifamily Housing: Case Studies in Energy Savings. Washington, D.C.

New York Times. 1986. "Architects Sign In for a New Tool." October 12, 1986, Sec. 12, p. ED28.

Office of Policy Planning and Analysis. 1985. Energy Use Trends in the U.S. 1972-1984. U.S. Department of Energy, Washington, D.C.

Pacific Northwest Laboratory. 1986. Building Systems Integration Research -Recommendations for a U.S. Department of Energy Multiyear Program Plan. PNL-5696, Pacific Northwest Laboratory, Richland, Washington.

Palmer, M. A. 1981. The Architects Guide to Facility Programming. McGraw-Hill, Inc., New York, New York.

Piette, M. A., L. W. Wall, and B. L. Gardiner. 1986. "Measured Performance." ASHRAE Journal 28(1):72-78.

Practice Management Associates, Ltd. 1986. PSMJ Financial Statistics Survey Exclusively for Design Firms. Practice Management Associates, Ltd., Newton, Massachusetts.

Rosenfeld, A. H., and D. Hafemeister. 1988. "Energy-Efficient Buildings." Scientific American 258(4):78-85.

Schuster, K. 1984. "Computers: What Some of the Smaller Offices Are Doing." Architectural Record 172(12):31-39.

Stoops, J. L., J. J. Deringer, S. Moreno, and H. P. Misuriello. 1984. Summary Report: The BEPS Redesign of 168 Commercial Buildings. PNL-5123, Pacific Northwest Laboratory, Richland, Washington.

U.S. Department of Energy (DOE). 1980. Predesign Energy Analysis. (Energy Graphics.) DOE/CS-0171, Washington, D.C.

White House Conference on Productivity. 1984. Report to the President of the United States on Productivity Growth: A Better Life For America. PB 84-159136, U.S. Department of Commerce, Washington, D.C.

- Means Company, Inc. 1989. Means Square Foot Costs. R. S. Means Company, Inc., Kingston, Massachusetts.
- Morris, R. S. 1975. "Innovative Technology: What is its Impact on U.S. Economy?" Professional Engineer 45(8):14-19.
- Nasr, T. 1980. "Expert System Cuts Chip Design Time by Up to 50%." Electronics 53(12):52-53.
- National Association of Home Builders (NAHB). 1987. Cutting Costs in Multifamily Housing: Case Studies in Energy Savings. Washington, D.C.
- New York Times. 1986. "Architects Sign in for a New Tool." October 15, 1986, 20C, p. C03B.
- Office of Policy Planning and Analysis. 1982. Energy Use Trends in the U.S. 1973-1984. U.S. Department of Energy, Washington, D.C.
- Pacific Northwest Laboratory. 1986. Building Systems Integration Research Recommendations for a U.S. Department of Energy Multi-Year Program Plan. PNL-5586, Pacific Northwest Laboratory, Richland, Washington.
- Palmer, M. A. 1987. The Architects Guide to Facility Programming. McGraw-Hill, Inc., New York, New York.
- Petrie, M. A., L. W. Wall, and B. L. Gardner. 1985. "Measured Performance." ASME Journal 25(1):72-78.
- Practice Management Associates, Ltd. 1986. PMI Financial Statistics Survey: Exclusively for Design Firms. Practice Management Associates, Ltd., Newton, Massachusetts.
- Rosenfeld, A. H., and D. Holmstrom. 1983. "Energy-Efficient Buildings." Scientific American 258(4):78-82.
- Schuster, K. 1987. "Computers: What Some of the Smaller Offices Are Doing." Architectural Record 172(12):31-39.
- Stacy, J. L., J. L. Derringer, S. Moore, and W. P. Mistrall. 1984. Summary Report: The 1982 Redesign of 188 Commercial Buildings. PNL-5123, Pacific Northwest Laboratory, Richland, Washington.
- U.S. Department of Energy (DOE). 1980. Predesign Energy Analysis (PEEA). DOE/EE-011, Washington, D.C.

APPENDIX A

DIMINISHING DEMAND FOR DESIGNING ENERGY-EFFICIENT BUILDINGS

APPENDIX A

DIMINISHING DEMAND FOR DESIGNING ENERGY-EFFICIENT BUILDINGS

Conventional wisdom links the economic benefits of energy-efficient buildings with world energy (oil) prices. As the price of foreign oil has dropped recently, so have public concern for energy conservation and the demand for energy efficiency in buildings. However, electricity costs constitute a major portion of building energy costs, and electricity costs depend only marginally on world oil prices.

In this context, the economic benefit available from energy-efficient building design is greater than it has ever been. While the price of oil has fallen in recent years, as shown in Figure A.1, the energy-related cost of operations for commercial buildings has grown, both in constant (inflation adjusted) dollars per square foot and in share of total operating costs, shown in Figures A.2 and A.3, respectively [Building Owners and Managers Association (BOMA) 1986; Institute of Real Estate Managers (IREM) 1986]. This real increase in the energy-related component of building operating costs has, therefore, occurred despite falling oil prices. This can be attributed to several factors:

- The end-use of oil as a fuel source in buildings has steadily dropped, as indicated in Figure A.4, until it currently represents less than 5% of total commercial building energy expenditures, as shown in Figure A.5 (EIA 1986b, 1986c).^(a)
- The contribution of fuel (especially oil) to the overall cost of electricity has decreased, as Figure A.6 shows (Geller et al. 1987).
- Natural gas prices have increased significantly, as shown in Figure A.1 (EIA 1984, 1986a), while natural gas use has increased only slightly (see Figure A.4) (EIA 1986c).

(a) Figure A.4 presents trends based on consumption estimates for the entire commercial sector composed primarily, but not exclusively, of commercial buildings.

FIGURE A.1. Commercial-Sector Energy Prices by Source (EIA 1986a)

Despite the increase in economic benefits associated with energy conservation, demand for conservation in buildings has decreased. This is the result of several factors that prevent the private sector from correctly perceiving the full economic benefit available from energy-efficient buildings.

Building owners and operators are generally unaware of the potential savings available through energy-efficient design of buildings. Their two best sources for this type of information are building equipment manufacturers and shared experience within the professional community of building owners. Equipment manufacturers generally do a good job of marketing the benefits of their more energy-efficient products. However, the benefits associated with good designs that integrate energy-efficient equipment with other building subsystems are not marketed well by the building design industry.

FIGURE A.2. Average Operating Costs by Component for Commercial Office Buildings (BOMA 1986; IREM 1986)

Forums for the exchange of information on experience, such as those provided by the BOMA and the IREM, are also very helpful. However, the surveys these organizations sponsor tend to reveal the average efficiency levels of the existing building stock rather than providing a clear picture of more energy-efficient, attainable performance levels. As a result, the demand for energy-efficient building design tends to be determined primarily by three factors:

- sharp increases in energy costs
- energy service interruptions
- perceived threat of either of the other two.

FIGURE A.3. Average Fraction of Total Operating Costs by Component for Commercial Office Buildings (BOMA 1986; IREM 1986)

Recent history reveals that world energy supplies have an enormous influence on national economic interests. Experience also demonstrates that market prices for energy cannot be controlled, nor can changes in prices be anticipated with a precision commensurate with the influence they exert (Getschow 1982). The anticipated threat of supply shortages and price increases has probably contributed the most to demand for energy-efficient buildings in the past. Under the current situation with an oil supply glut, there is little perceived threat of either sharp price increases or supply interruptions.

Another reason why steadily increasing real costs of energy-related building operations have not received more attention is a significant shift

FIGURE A.4. Commercial Sector Energy Consumption Share by Source (noncumulative) for the period 1960-1984 (EIA 1986a)

in the commercial building ownership profile. In 1980, corporations and individuals owned approximately 60% of commercial office building space, while developers owned 30%. By 1985, these proportions had nearly reversed, to 36% and 49%, respectively (Buildings 1986). This trend represents a significant change in the number of commercial office buildings that pass these escalating energy-related operating costs to new owners and tenants after construction.

The apparent contradiction between decreasing demand and increasing potential economic benefits of energy conservation reveals a misconception among users of building design services. It also reveals that the building design industry is not well structured to overcome these misconceptions and deliver the benefits available from fully applying current knowledge in energy-efficient building design.

FIGURE A.5. Nonresidential Building Energy Expenditures by Source for 1983 (EIA 1986b)

FIGURE A.6. Fuel Expense as a Component of Average U.S. Retail Price of Electricity (in constant 1985 \$) for 1980-1985 (Geller et al. 1987; reproduced with permission from the Annual Review of Energy, Vol. 12, copyright 1987 by Annual Reviews Inc.)

REFERENCES

Building Owners and Managers Association International (BOMA). 1986. 1986 BOMA Experience Exchange Report - Income/Expense Analysis of Office Buildings. Washington, D.C.

Buildings. 1986. "BOMA Convention Review." August 1986, 80:67-68.

Energy Information Administration (EIA). 1984. State Energy Price and Expenditure Report: 1970 - 1981. DOE/EIA-0376(81), U.S. Department of Energy, Washington, D.C.

Energy Information Administration (EIA). 1986a. State Energy Price and Expenditure Reports - 1983. DOE/EIA-0376(83), U.S. Department of Energy, Washington, D.C.

Energy Information Administration. 1986b. Nonresidential Building Energy Consumption Survey: Commercial Buildings Consumption and Expenditures 1983. DOE/EIA-0318(83), Energy Information Administration, U.S. Department of Energy, Washington, D.C.

Energy Information Administration. 1986c. State Energy Price and Expenditure Reports - Consumption Estimate 1960 - 1984. DOE/EIA-0214(84), U.S. Department of Energy, Washington, D.C.

Geller, H., J. P. Harris, M. Levine, and A. H. Rosenfeld. 1987. "The Role of Federal Research and Development in Advancing Energy Efficiency: A \$50 Billion Contribution to the U.S. Economy." The Annual Review of Energy, Vol. 12, pp. 357-395.

Getshow, G. 1982. "More or Less Oil Will Go Up or Maybe It Won't: Energy Experts Are Gun-Shy After Forecasts, for Years, Haven't Turned Out Well." Wall Street Journal, May 5, 1982, Vol. 106, p. 1, col. 4.

Institute of Real Estate Managers (IREM). 1986. Income/Expense Analysis Office Buildings Downtown and Suburban. Chicago, Illinois.

REFERENCES

- Building Owners and Managers Association (BOMA). 1986. 1986 BOMA Expense Report - Income/Expense Analysis of Office Buildings. Washington, D.C.
- Buildings. 1985. "BOMA Convention Review." August 1985, 80:87-88.
- Energy Information Administration (EIA). 1984. State Energy Prices and Expenditure Report: 1970 - 1981. DOE/EIA-0375(81). U.S. Department of Energy, Washington, D.C.
- Energy Information Administration (EIA). 1983. State Energy Prices and Expenditure Report: 1982. DOE/EIA-0375(83). U.S. Department of Energy, Washington, D.C.
- Energy Information Administration. 1986b. Nonresidential Building Energy Consumption Survey: Commercial Buildings Construction and Expenditures 1983. DOE/EIA-0185(83). Energy Information Administration, U.S. Department of Energy, Washington, D.C.
- Energy Information Administration. 1986c. State Energy Prices and Expenditure Report - Washington Estimate 1980 - 1984. DOE/EIA-0214(84). U.S. Department of Energy, Washington, D.C.
- Gelfert, H., G. P. Harris, M. Levine, and A. R. Rosenfeld. 1987. "The Role of Federal Research and Development in Advancing Energy Efficiency: A 250 Billion Contribution to the U.S. Economy." *The Annual Review of Energy*, Vol. 12, pp. 357-395.
- Gordon, D. 1982. "More or Less Oil Will Go Up or Maybe It Won't: Energy Experts Are Gun-Shy After Forecasts for Years Haven't Turned Out Well." *Wall Street Journal*, May 5, 1982, Vol. 108, p. 1, col. 4.
- Institute of Real Estate Markets (IREM). 1985. Income/Expense Analysis Office Buildings Downtown and Suburban. Chicago, Illinois.

APPENDIX B

CHARACTERISTICS OF THE BUILDING
DESIGN AND CONSTRUCTION INDUSTRY

APPENDIX B

CHARACTERISTICS OF THE BUILDING DESIGN AND CONSTRUCTION INDUSTRY

The most salient characteristic of the buildings industry is its size. In the United States, almost 5% of the labor force is employed in or depends for employment on the buildings industry. The industry also accounts for almost 10% of the nation's gross national product (GNP). By comparison, the automobile and steel industries combined account for only 5% of the GNP [General Accounting Office (GAO) 1978, p. 2].

However, the diverse and decentralized nature of the building design and construction industry is not often recognized. Almost 1 million general and specialty contractors are involved in construction. This includes over 25,000 building materials suppliers and members of 15 major building and construction trade unions and at least 180 building industry-related trade associations. They design and construct buildings in more than 10,000 building code jurisdictions that are members of three model code organizations (Crawley et al. 1987).

The building design industry is equally diverse, composed of some 17,000 architecture firms (in 1983) and 20,000 engineering firms (in 1986), with approximately 72,000 registered architects and 90,000 professional engineers. Most of these design firms are relatively small, as Figures B.1 and B.2 show. Unlike the commercial building construction industry^(a), the commercial building design industry is not heavily dominated by a relatively few large firms. Engineering firms with fewer than 25 employees accounted for just over 50% of the total commercial design work dollar volume.

Despite its size and influence on the economic, human, and natural resources of the U.S., the building industry is far slower than any other

(a) Of approximately \$200 billion of nonresidential construction in 1983, almost 80% was built by the 200 largest members of the 17,000-member Associated Builders and Contractors.

FIGURE B.1. Relative Frequency Distribution of Architecture Design Firms by Size [American Institute of Architects (AIA) 1987]

industry to adopt new technologies. As a result, this industry has been described as a pre-industrialized craft (Daryanani 1971). The little innovation that has occurred has benefitted single interests within the industry. Innovation requiring the cooperative pooling of industry resources has been stifled by the fragmented nature of the industry and the lack of an industry organization where matters of mutual interest requiring research can be addressed (GAO 1978). To improve this longstanding failing requires carefully planned aid directed to the industry's research and technology needs. A recent report from the Energy Research Advisory Board (ERAB 1985) concluded that

Many small design firms, building companies, and component manufacturers comprise the building industry. Most private firms will undertake basic R&D activities if there are substantial and immediate monetary gains for the firm, and this is seldom possible in a fragmented industry of small firms. As a result, too little R&D is performed and must be supplemented by the government if it is to be accomplished on any substantial scale.

FIGURE B.2. Relative Frequency Distribution of Engineering Design Firms by Size (Edmunds 1986)

The proposed AEDOT research program recognizes the difficulty of undertaking significant technological development within a fragmented and undercapitalized industry. Therefore, the cooperative development of a building energy design and operation environment is proposed for the AEDOT project.

REFERENCES

- American Institute of Architects (AIA). 1987. The 1987 Firm Survey Report. Washington, D.C.
- Crawley, D. B., R. S. Briggs, J. W. Jones, W. W. Seaton, J. E. Kaufman, J. J. Deringer, E. W. Kennett. 1987. Development of Whole-Building Energy Design Targets for Commercial Buildings-Phase I Planning, Volume 2: Technical Report. PNL-5854 Vol. 2, Pacific Northwest Laboratory, Richland, Washington.

Daryanani, S. 1971. "Computers and the Building Industry." Use of Computers for Environmental Engineering Related to Buildings. Building Science Series 39, National Institute of Standards and Technology, Gaithersburg, Maryland.

Edmunds, J. 1986. "1986 Census of Firms." Consulting Engineer 66(6):40-47.

Energy Research Advisory Board (ERAB). 1985. Guidelines for DOE Long-Term Civilian Research and Development. DOE/S-0042, Volume 5, Office of Energy Research, U.S. Department of Energy, Washington, D.C.

General Accounting Office (GAO). 1978. Computer-Aided Building Design. LCD-78-300, Washington, D.C.

FIGURE B.2. Relative Frequency Distribution of Engineering Design Firms by Size (Edmunds 1986)

The proposed AEDOT research program recognizes the difficulty of undertaking significant technological development within a fragmented and uncoordinated industry. Therefore, the cooperative development of a building energy design and operation environment is proposed for the AEDOT project.

REFERENCES

- American Institute of Architects (AIA). 1981. The 1981 Firm Survey Report. Washington, D.C.
- Crawley, D. B., R. S. Briggs, J. W. Rogers, W. W. Seaton, J. E. Whitman, L. J. J. ... 1981. Development of Whole-Building Energy Design. Report for Commercial Buildings Research Planning, Volume 2. (Technical Report, PNL-3881-Vol. 2, Pacific Northwest Laboratory, Richland, Washington).

APPENDIX C

EMERGING TECHNOLOGY AND RESEARCH BASE

APPENDIX C

EMERGING TECHNOLOGY AND RESEARCH BASE

The AEDOT project plan proposes research that will take advantage of both recent and anticipated advances in several key technologies as well as recent and future research:

- knowledge-based systems
- graphics and imaging systems
- microprocessing and data storage capabilities
- software engineering techniques
- developments in integrated CAD systems
- integrated building representation databases
- building products databases
- design process research.

Each is briefly discussed in the following sections.^(a)

KNOWLEDGE-BASED SYSTEMS

Knowledge-based systems (or expert systems) are powerful tools that promise to be very useful for structuring, documenting, and distributing energy-related design expertise. Expert systems are so named because they permit storage and use of knowledge of one or more experts and because the resulting expert systems perform a narrowly defined set of tasks nearly as well as an expert. The term knowledge-based systems is broader and refers to systems that use knowledge from experts and other data sources. These systems are designed to help a competent practitioner perform near the level of an expert. The building design

(a) Mention of equipment and software by name should not be considered a recommendation or judgment on the usefulness or value thereof by the U.S. government or any of its agencies.

process is especially well suited to the application of knowledge-based systems because the design professional already knows a great deal about building design, but not much about energy-efficient building design. Therefore, the designer can benefit enormously from energy experts' knowledge if it is presented in a form usable at the correct time in the design process.

By using knowledge-based systems, experts in a particular subject area (e.g., HVAC systems, daylighting, thermal mass, lighting design) can define once, in detail, the factors that must be considered when producing an energy-efficient design. Their expertise can then be incorporated into a computer program, which can be used by building designers to improve their decisions on similar problems. The use of knowledge-based systems as energy-efficient building design support tools has the potential to improve building design decisions to the same extent that conventional computer programs have improved building designers' calculation and analysis capabilities.

Knowledge-based systems are a relatively new development in computer software. They have been the topic of research for about 10 years, but only in the last 2 or 3 years have the computer power and software tools been available to allow the cost-effective migration of knowledge-based systems from the laboratory into the mainstream of computer users.

Expert systems are computer programs in which expertise is encoded in rule statements that are then used to mimic human reasoning to make certain types of decisions. The core of expert systems is the knowledge bases or rule bases, which consist of sets of rule statements, usually of the general form "if X, then Y". The reasoning is a process of plowing through the rules, testing assertions, checking data, and asking questions until the system either knows enough to reach a conclusion or gives up trying.

Expert systems have been used successfully for many diagnostic tools but can also be applied in many areas of the design process, especially for determining the construction of the desired environment. Once a set of design criteria has been identified and an evaluation procedure has been determined, expert knowledge can be applied to generate a set of potential design solutions, which the system then ranks according to their performance with respect to

the design criteria considered. Such expert systems do not replace members of the design team, but they can play the role of consultants, specialized in specific areas of the design process. Knowledge bases hold the appropriate rules and are integrated with databases that hold the necessary data for the variables to be considered.

As the designer's role becomes more complex, tools that improve a designer's efficiency and productivity will become increasingly important. The effectiveness of such expert systems would be limited by those design criteria for which performance variables cannot be easily or satisfactorily identified and/or quantified. Even so, the use of expert systems would greatly contribute to the designer's effectiveness and efficiency by significantly reducing the number of both the design criteria and solutions the designer needs to consider. For example, if a maximum acceptable value for solar heat gain has been set as a rule in the system, the designer can forget about it and concentrate on other, nonquantitative criteria such as aesthetics, and have the system alert him/her whenever a solution might cause excessive solar heat gain.

GRAPHICS AND IMAGING SYSTEMS

Because architectural design is a visually oriented process, graphics and imaging systems should be one of the more important applications of computers in architecture. Generating predicted images therefore is critical for both communication and evaluation. Traditional hand drawing of such images (such as plans, sections, axonometrics, perspectives) is time consuming and costly.

Computer graphics technologies in the form of CADD hardware/software packages are revolutionizing the design profession. These packages have evolved from early wire frame drawings, hidden line/surface removed drawings to sophisticated raster color graphic images produced by ray-tracing and other techniques. Accordingly, the realism achieved from the CADD packages has been significantly improved, which, in turn, has led to new potential applications of computer graphics in the qualitative assessment of the visual environment. The most sophisticated software can currently be implemented only on large computers; it requires significant computational time and stor

However, with the current rate of computer hardware development, such limitations may very well be overcome in the near future.

Imaging system technologies currently show the most promise of overcoming the current limitations of computer graphics applications. In these systems, images of actual environments, scale models, documents, or images from advanced computer graphics packages can be captured electronically, stored, manipulated, transmitted, and presented. A variety of imaging systems with different levels of sophistication is already available. Although these may offer less flexibility than some traditional computer graphics, they are very efficient in image capture, storage, manipulation, and retrieval, and can render realistic representations of the environment. They have already been used widely in military and aerospace applications, particularly for robot vision and flight simulators. Photo-montage techniques can also be used in these imaging systems to allow assessments of proposed objects or buildings with a high level of realism. The tools also have the potential for allowing designers to assess the visual and qualitative aspects of design, a challenge that still eludes the profession today.

MICROPROCESSING AND DATA STORAGE CAPABILITIES

Both knowledge-based and graphics systems have been made widely available by the dramatic increase in the performance-to-cost ratio of computer equipment, especially in the microcomputer market. The microcomputer began to be widely used in business 5 years ago, with the introduction of the IBM PC. At that time a PC cost about \$5000 (\$6200 1986 dollars) and there was little software available. Now a comparable PC can be purchased for less than \$1000, and there are literally thousands of software products available in every imaginable field. The decrease in cost of minicomputers has been even more dramatic over the same time period. A Digital Equipment Corporation VAX 11/780 minicomputer system sold for about \$500,000 in 1980 (\$675,000 1986 dollars). Now there are engineering work stations with two to three times the computing power of the VAX 11/780 available for much less than \$50,000.

With the performance-to-cost ratio of minicomputers and microcomputers doubling every 18 months and with manpower costs continuing to rise, it is

inevitable that the building design process will increasingly rely on computer technology. Recent surveys by the AIA show that 40% of the building design firms in the country are now using computer systems for some part of the design process (AIA 1983, 1987). As integrated building design tools become available, it is important that an energy-efficient design component become part of these packages.

SOFTWARE ENGINEERING TECHNIQUES

Advances in software engineering are being made almost as rapidly as advances in computer hardware. Historically, computer software was unique for each application, computer system, and software development team. Very few whole programs could be moved from one type of computer to another, even to perform the same task. There was even less transfer of pieces of software from one project to another. As the field matures, software engineering is moving closer to more mature engineering disciplines where an entire entity is made from many interchangeable and easily obtainable pieces instead of being custom built from the ground up. In software engineering this trend is called modular programming.

The move toward modular programming makes it feasible for the federal government to develop software modules aimed at energy-efficient design without having to develop an entire building design program. These publicly funded modules can then be incorporated into privately developed software that is aimed at the larger problem of integrated building design. Incorporating public modules in private software overcomes two major problems. First, the development of an entire integrated building design tool is going to be a very costly effort. Many pieces of the eventual tools already exist as private domain software, and it is more effective for vendors to extend their own products rather than re-inventing the pieces as part of a large development program. Second, these tools will be very expensive in terms of both original purchase price and staff training time required to effectively use a sophisticated tool. By allowing private vendors to incorporate the energy design modules within existing tools, the users have to pay for and learn how

to use only the new modules instead of having to purchase and learn a completely new system.

DEVELOPMENTS IN INTEGRATED CADD SYSTEMS

CADD systems on the market offer different levels of sophistication with respect to their ease of use, modeling abilities, and the integration of ancillary programs for site preparation, engineering analysis, and cost estimation. CADD packages can be divided into three categories based upon hardware used and cost: 1) microcomputer-based (costing less than \$20,000); 2) minicomputer-based (costing \$20,000 to \$80,000); and, 3) high-end systems, mainframe-based (costing over \$80,000).

Microcomputer-Based Systems

Current systems provide enhanced productivity primarily for traditional drafting functions and limited design functions. To reduce data storage and CPU time requirements, the systems typically use two-dimensional data structures to produce drawings. Many have the ability to extrude lines to make three dimensions (often referred to as 2-1/2-D). Some packages offer separate 3-D sketching packages, and a few offer shading and modeling in three dimensions. Some packages offer additional modules for site work analysis, mechanical and electrical design work, thermal analysis and cost estimation.

The vast majority of systems are geared for 16-bit IBM PCs, ATs, and compatibles. Support hardware required includes a digitizing pad or mouse, a high-resolution color or monochrome graphics card, a high-resolution monitor, and a plotter.

There are many vendors of micro-based CADD systems, but the major software packages are AutoCAD, PCAD, and VersaCAD. AutoCAD is the clear leader in terms of volume of sales. AutoCAD has a relatively open architecture for its software, and there is a large, and growing, volume of third-party software (civil, mechanical, electrical) that links to AutoCAD. Also, translators exist that permit AutoCAD to interface with larger systems including Intergraph, Cadam, and Computervision.

Minicomputer-Based Systems

Several companies are packaging CADD systems on 32-bit minicomputers, primarily Digital (MicroVax II) and Prime hardware. These systems usually include an ability to support multiple work stations, integration of computer-aided engineering packages with the computer-aided drafting process, and full 3-D modeling and shading capabilities.

The minicomputer systems appear targeted to integrated architectural/engineering firms. Because of their data structures, two minicomputer packages were extensively reviewed earlier in this research effort: RUCAPS by GMW Computers, Inc., and GDS by McDonnell Douglas. These packages have robust, object-oriented, 3-D database structures. Also, both companies are developing enhancements to permit their CADD systems to be used as part of building conceptualization and design activities. Other popular minicomputer packages include the Intergraph and CalComp systems.

Mainframe-Based Systems

CADD vendors include IBM, Prime, McDonnell Douglas - McAuto, and Intergraph. Their systems offer similar capabilities to the minicomputer systems. The primary benefits include more modules integrated with the system, greater support, greater speed and more work stations.

THE FUTURE OF CADD HARDWARE AND SOFTWARE

The current revolution in computer power, memory, speed, and graphic resolution is causing rapid developments within the CADD field, which have, in turn, improved CADD software sophistication. For example, microcomputer chip storage capacities have quadrupled every three years since 1976. Disk storage capabilities have likewise grown rapidly. Both types of increase in capacity have occurred at marginal increase in cost for the new capacity. These changes make it difficult to predict the future, except to note that software and hardware will be yet cheaper and more powerful. Because this research project will produce products that will operate in a future hardware/software environment, the research approach must be flexible to take advantage of these changes and to follow the markets.

The distinctions among CADD capabilities based on mainframes, minicomputers, and microcomputers are becoming increasingly fuzzy, especially as the power of minicomputers and microcomputers increases and the costs decrease. Many of the vendors that offer software for the mainframe computer offer scaled-down packages for the minicomputer. For example, the recent advent and popularity of the Intel 80386 32-bit processor will probably enable CADD software systems now on minicomputers to be ported to high-end microcomputer systems. This will speed the availability of microcomputer CADD packages with 3-D data structures and modeling and better integration of architecture and engineering design development tools.

The current generation of minicomputers already makes the mainframe systems more suited to applications with many users. Design work at the computer screen is becoming increasingly affordable with the dramatic cost reduction of high-resolution color graphics monitors and hardware required to drive the monitors. Software is also becoming more powerful, and, as more firms purchase software, the development costs can be spread over a wider market, lowering software costs. In addition, as the market matures over the next few years, an industry shake-out will likely occur, and CADD software cost will drop. In 1985, virtually all microcomputer CADD software packages sold for \$2000 or more. In 1986, while most CADD software prices had not dropped, several microcomputer CADD systems were marketed for under \$500. Few of these are full-feature CADD software systems. One system with a reasonably extensive set of features is priced under \$100.

These software and hardware advances, including increased processing power, high resolution graphics, and optical storage devices, should permit any CADD system features now running on minis and mainframes to run on microcomputers in the next few years. These features include 3-D object-oriented, database structures, solids modeling and shading, and integrated analysis packages for civil, structural, and mechanical engineering.

INTEGRATED BUILDING REPRESENTATION DATABASES

Computer-based information technologies have been providing significant support to many of the activities within the building design process. However,

as discussed in Section 2.2, there has been little exploitation of computer-based technologies in support of design synthesis, the creative activity at the heart of the overall building design process. A significant barrier has been the difficulty in representing building information (geometric and non-geometric) in a way that it can be manipulated usefully by a computer. Much of the information that a designer uses about a building in the creative generation of design alternatives is not captured in computer databases and made available for computer-aided manipulation (McIntosh 1987). Several recent developments promise progress in this important area.

Recent significant research in CABD has focused on designing the database structures necessary to support the creative activities of design. The most significant of these has demonstrated the usefulness of relational data structures for CABD (McIntosh 1984). More recently, the application of knowledge-based systems techniques to database design has produced promising results in the computer generation of design alternatives (McIntosh 1987; Flemming 1987), computer-aided design evaluation, and consistency maintenance within the computer representation of the building design (Kalay 1985).

In addition to the work directed at supporting the creative aspects of the design process, significant recent work has been aimed at supporting the information needs of the entire building life cycle. The Building Research Board of the National Academy of Sciences has demonstrated the concept of a building-specific database for use by all building professionals involved in planning, designing, constructing, regulating, operating, or renovating buildings (Building Research Board 1984).

The significance of this area of developing research is four-fold. First, it suggests a significant vehicle to overcome many of the communication and coordination difficulties inherent in the design team approach (see Section 2.1.3). Second, it addresses the challenges associated with using diverse heterogeneous computing environments to support the overall building design process. Third, it will allow retention of much valuable information developed during the design process, which is typically lost to later (especially operations) stages. Fourth, it provides a means to help close the communication loop between building designers and building users.

BUILDING PRODUCTS DATABASES

Current market forces are causing the development of several private-sector databases. These databases are potentially important to the envisioned advanced CADD-based design tools of the 1990s. However, these databases are not being developed by CADD vendors, but by other entrepreneurial groups in the private sector, either as stand-alone databases or as databases to be linked to one or more CADD systems. Because these databases will be even more useful when linked to CADD systems than as stand-alone packages, it is only a matter of time before this is done.

Such building product and related databases now being developed include

- Sweets Catalogue of building product literature and specifications on compact disk read-only memory (CD ROM)
- computer-based building code information for state and local codes throughout the country, retrievable via software using expert system techniques
- Anderson Windows product information in computer-readable form, retrievable from the Autocad CADD system using LISP computer code available within Autocad.

Sweets Catalogue of Building Product Literature

McGraw-Hill Information Systems has produced and updated a set of catalogues of building products for some time. Many designers use this standard reference when specifying building products during building design.

For the 1989 update of the Sweets catalogues, McGraw-Hill intends to also distribute to each of approximately 30,000 customers a complete version of the product literature on machine-readable CD ROM. McGraw-Hill is also exploring the direct sales of CD ROM readers to their customers at a cost of about \$300 to \$400, significantly below currently projected costs.(a)

Significant potential savings in design time and money are possible from linking this product literature to CADD system databases via "hooks" to portions

(a) From verbal communication with H. Mileaf, McGraw-Hill Information Systems.

of the CADD drawings. The capabilities to provide such "hooks" already exist in many CADD systems.

Building Code Database

A consortium headed by Codeworks, Incorporated, is currently developing a computer-based version of major building codes. Its intent is to build a system containing the significant portion of state and local building codes throughout the country, focusing first on areas where most of the construction takes place. The approach, based upon using a few model codes as the base codes for the system, makes the seemingly formidable task of encoding the thousands of local codes a manageable one. Because most state and local codes are variations on one of these codes, the state and local codes can be addressed by encoding only those portions that vary from the base model code. Expert system software is being used to help structure the retrieval of the code data in relation to a specific building design.

The schedule calls for testing the system in the Atlanta metropolitan area in 1987 and then expanding to other metropolitan areas. The product would be provided as a service for several hundred dollars a year, plus user charges for each use of the database. The system could potentially reduce by about 75% the significant time now required for code searches during building design.^(a) Linking of this system to CADD data structures in the future would provide additional benefits. Similar benefits would result from linking Sweets catalogues to such databases.

Anderson Windows

Anderson Windows is also reportedly in the process of developing a computer-readable version of the specifications for its product line. Further details of this database development are not known at this time.

Summary

The development of these databases is ongoing. Because the work is privately funded and in the development stages, it tends not to be widely

(a) From verbal communication with D. Conover, National Conference of States on Building Codes and Standards.

publicized. Each database represents a potentially significant resource for advanced CADD systems in the future that contain "design advisor" features and knowledge-based attributes. Market forces and demand will dictate how quickly the linkages are developed between such databases and CADD systems.

DESIGN PROCESS RESEARCH

The design process aims at producing a plan or design that will result in a suitable and functional end product. Attempts to solve design problems have been based on systems analysis and operations research. Application of systems analysis usually involves modeling the design process as a straightforward, systematic, sequential process. Models using the techniques of operations research seek the optimal solution from a set of possible solutions (i.e., a solution space), given specific design constraints and measures of effectiveness.

Modifications of the systems approach have recognized the limitations of systems analysis and operations research, and are based on several principles that govern design problems and related processes. Design problems are convoluted and are not amenable to modeling as sequential processes.

According to the principles of the modified systems approach, two major tasks that take place simultaneously can be identified in architectural design: identification of the desired environment and prescription of a plan for creating the desired environment. Each of these tasks requires availability and manipulation of specific kinds of knowledge.

When identifying the desired environment, the designer determines the design criteria and their relative importance for decision making. This process creates a value system to be used later for evaluating alternative design solutions. It can be viewed as an argumentative process between the various parties interested in developing the new environment. Several of these parties may be present and involved in this process, but the interests of most are represented by others, typically the designer. The most appropriate tools for this important task are the so-called issue-based information systems. These are text databases that can help to explicitly organize the issues raised

during the design process, along with the positions taken for or against them by the parties involved or affected.

The second design task examines ways to create an environment that satisfies the design criteria. This can be considered the creative phase of design and can be further subdivided into the generation of variety and the reduction of variety. The designer first generates ideas for environments that will satisfy the specified design criteria. Each practicing designer has personal strategies for generating alternative design solutions. Several approaches have been formalized to help the designer generate ideas. The designer next evaluates the alternative solutions in preparation for deciding on a final plan.

Most of the design tools currently available are used in evaluating, not creating, alternative building designs, by providing information about building performance with respect to one or more quantitative design issues, such as energy requirements or economics. The designer evaluates the performance according to the design criteria and judges the appropriateness of the alternatives.

Design tasks are not independent. For example, the designer simultaneously generates ideas and evaluates them, constantly altering and reconstructing the image of the desired environment. What makes design complicated are the many criteria that need to be considered; complex tradeoffs often exist among them. A design solution can be viewed as a balance among many individual, sometimes conflicting, criteria.

REFERENCES

American Institute of Architects (AIA). 1983. The 1983 Firm Survey. Washington, D.C.

American Institute of Architects (AIA). 1987. The 1987 Firm Survey. Washington, D.C.

Building Research Board. 1984. Report from the 1984 Workshop on Advanced Technology for Building Design and Engineering. National Academy of Sciences, Washington, D.C.

- Flemming, U. 1987. "The Role of Shape Grammars in the Analysis and Creation of Designs." In Computability of Design, ed. Y. E. Kalay, pp. 245-272. Wiley, New York.
- Kalay, Y. E. 1985. "ALEX: A Knowledge-Based Architectural Design System." ACADIA Workshop '85 Proceedings. The Association of Computer-Aided Design in Architecture, Tempe, Arizona.
- McIntosh, J. F. 1984. The Application of the Relational Data Model to Computer-Aided Building Design. Doctoral dissertation, University of Michigan, Ann Arbor, Michigan.
- McIntosh, P. G. 1987. "Models of Spatial Information in Computer-Aided Architectural Design: A Comparative Study." In Computability of Design, ed. Y. E. Kalay, pp. 117-131. Wiley, New York.
- Schmitt, G. 1987. "Expert Systems in Design Abstraction and Evaluation." In Computability of Design, ed. Y. E. Kalay, pp. 213-244. Wiley, New York.

APPENDIX D

CURRENT RESEARCH ON KNOWLEDGE-BASED BUILDING DESIGN SYSTEMS AND KNOWLEDGE-BASED OPERATION MANAGEMENT SYSTEMS

APPENDIX D

CURRENT RESEARCH ON KNOWLEDGE-BASED BUILDING DESIGN SYSTEMS AND KNOWLEDGE-BASED OPERATION MANAGEMENT SYSTEMS

This appendix summarizes the results of a recent informal survey of current knowledge-based system (KBS) research and development activities. This summary does not purport to be exhaustive, for the survey of building-related KBS activities is ongoing. Detailed discussion is presented in this appendix only when project activities have been developed to at least a prototype phase. Projects in early development phases are cited, but little detail is given. For details of the building-related work of each research team, the reader is advised to review the technical papers referenced. For general background information on knowledge-based and expert systems, a bibliography of selected references is provided at the end of this appendix.

This summary is limited to R&D efforts for which detailed information is publicly available. Although a number of private-sector KBS activities are known to be under way, usually very little information is released about such efforts because of competitive pressures. Thus, only limited information on private-sector activities is provided in this survey.

The KBS activities identified in this survey have been classified using three main headings: building design-related R&D, building operation-related R&D, and miscellaneous building-related R&D.

Several difficulties were encountered in developing this summary, because of the complex nature of KBS and the absence of standard terminology. Different authors use radically different terminology to describe similar activities in the same subject area. In the following descriptions, we have standardized terminology as much as possible to facilitate comparisons. We acknowledge the risks involved in such standardization.

The inconsistent terminology may stem from incomplete communication among researchers in overlapping disciplines. In conducting this survey, we

encountered several interesting, but limiting, attributes of some KBS work in the buildings area. We consistently encountered researchers who were only partially aware of others who were working on KBS activities in the same area. The 1- to 2-year delay between accomplishing work and publishing the work exacerbates this situation. Also, it appears that a number of researchers are not aware of, and are not using, many available and valuable KBS technologies in their work. They appear to be using relatively simple KBS development methods and conventional programming methods with which they are already familiar. Another limitation is that some researchers do not adequately identify the details of the structural design of their KBSs in their publications. This may be attributable to the very early stage of the work. Thus, there appears to be a strong need for better communication channels in this rapidly expanding field.

DESIGN-ORIENTED KBS RESEARCH ISSUES

The brief discussion of the KBSs below indicates that much activity is under way. There is also great diversity in the methods used and in the application of KBS technology. Most of the current R&D work can be classified as

- designing building subsystems
- diagnosing building operations-related equipment
- improving the interface between KBSs and either CADD, databases, or graphics imaging systems.

The most common application of fully operational KBSs is for diagnostic tasks (Harmon, Mars, and Morrissey 1988). The results of this building-related survey indicate that there are equal levels of activity in both building diagnostics and building design. The primary difference between these two surveys is that the building-related survey focussed on building-related KBSs that are primarily still under development. The Harmon, Mars, and Morrissey survey (1988) did not consider development activity. This comparison confirms that, although design-oriented KBSs for building-related applications are not

yet available to the practicing building designer, many KBSs of this type will be available soon.

However, only one KBS was identified in the survey that focussed primarily on the design of energy-efficient buildings or energy-efficient building subsystems. This work was headed by Schmitt at Carnegie-Mellon University (CMU). Schmitt focussed mostly on the development of interconnections between existing software modules (a KBS, energy analysis programs, and databases) rather than on the development of a detailed knowledge base for energy-efficient design.

Several well developed KBSs identified in the survey are related to building operations (e.g., HVAC diagnosis, energy monitoring). However, most of these have been developed for very specific applications. Thus, even collectively they are of very limited use in the overall process of evaluating the energy performance of buildings.

The survey also indicates that most fully operational KBSs are relatively small and are implemented on IBM PCs. The larger, less common, KBSs generally require more powerful workstation environments.

Recent Conceptual Advances

Several different problem solving methods are used by the various researchers identified in this survey. To some degree, each new KBS builds on the methods used previously. However, because the field of KBS development has only recently become popular (i.e., in the last 10 years), sufficient time has not passed to accomplish a great deal of knowledge building.

Hierarchical planning is one of the most powerful methods of solving complex design problems identified in this survey. The general approach is to identify and plan the solution of the most important aspects of a design problem. The less important aspects of the problem are not addressed until after the plan for the main problem is proved adequate. This method is briefly introduced later in this appendix (under General Design-Oriented KBS). More details of this approach can be found in most good KBS reference books (see the Bibliography to this appendix).

Most current building-related KBS efforts are in the initial development stages, even though the titles of some published articles seem to imply more progress than warranted. Almost all systems now being developed have applications in problem domains with very narrow scopes (e.g., specific building material components or subsystems) because these are the easiest problems to solve. Many of the working KBSs involve less than 50 decisions. This is very small relative to many large KBSs that involve several hundred decisions.

Limitations of Currently Available KBSs

The small size of most knowledge bases indicates the limited amount of knowledge built into these KBSs. It also reflects the small number of experts generally used in the knowledge acquisition process.

Also, these early KBSs most likely will be incompatible with each other. Many researchers are working independently, each using diverse tools and methods. For the results of the research to be useful in building design applications, this approach needs to be modified. Building designers do not have the resources available to learn to use a dozen or more expert systems. Integration of these tools is necessary.

Building designers need a consolidated package that serves most of their needs, and into which new modules can be inserted. Thus, the type of software-based "design assistant" most useful to the building industry will require significant coordination among researchers. This type of coordinated software-based building design environment has not been developed yet due to a number of difficulties. Two significant problems are:

- lack of file format standards - One of the most significant obstacles is the lack of standards for file formats (especially graphics file formats). Standardized file formats are required for KBSs, CADD programs, databases, analysis tools, and graphics systems to communicate effectively. The sooner such file standardization occurs, the more cost-effective it is to accomplish.
- lack of formal conceptual structures - Formalized conceptual structures to define the interrelationships between building subsystems are only beginning to emerge. Such conceptual structures are especially lacking in the energy-related aspects of the design process. A major effort will be required to develop these conceptual structures as a basis for developing integrated KBS systems.

Future Directions for KBS Research and Development

Most current building-related KBSs do not model expert behavior very well. However, most of the researchers interviewed indicated that they have long-term plans to continue the process of incorporating expertise into their systems.

This is typical of early stages of KBS development, because prototype KBSs usually require a significant amount of enhancement before they can leave the development laboratory. Some of the more basic areas of improvement include

- debugging (error correction) of knowledge bases
- addition of more complete knowledge to knowledge bases
- updating of knowledge bases
- expansion of the domain (subject area)
- revisions required by external modifications (e.g., language update and hardware changes).

Several emerging capabilities also are being actively investigated. Some of these are introduced below.

There is a strong trend toward the integration of several existing KBSs with other existing analysis programs and databases. This is a complex task that faces many obstacles. The primary obstacle is the lack of standardization of file formats for most types of data files. Thus, an integrated KBS must be able to read and write to a large number of different file formats. Another major problem is that large KBSs can be very slow. More powerful desktop computing environments and possibly parallel processing will be needed to overcome this problem.

Another strong trend is to make KBSs more generally functional. Most existing systems are capable of solving only very small and specialized problems. These KBSs are programmed with a great deal of domain-specific knowledge. The limitation of this approach to problem solving is that these KBSs are not capable of solving new problems, i.e., problems that the KBS has not been specifically programmed to solve. The development of new methods of

knowledge representation should be of significant value in making KBSs more generally functional.

Some AI researchers suggest that the development of libraries containing various alternative problem-solving methods and procedures will contribute to development of more powerful and flexible KBSs. Also, the development of improved meta-knowledge (self-knowledge) capabilities will provide opportunities for KBSs to assist in problem solving in more common situations, such as

- identifying the existence of, and determining how to handle, misinformation
- assisting with problems that have been partially solved using other methods
- recognizing historical solution paths for similar problems.

A third area of future development will be the enhancement of user interfaces using graphics. The weak graphics capabilities of existing PCs is one of the main obstacles that restrict the graphics features of current programs. As video RAM, greater processor speeds, and interactive high-density storage media (e.g., WORM, CD-I) become available for PCs, significantly enhanced graphics features will become more common in user interfaces.

With additional investment in KBS research and development, KBSs will become much more complex but also significantly more helpful, fast, and robust.

RECENT CONCEPTUAL ADVANCES IN KNOWLEDGE-BASED BUILDING DESIGN SYSTEMS

The organizations represented in our informal survey are listed in Table D.1. Seven types of building design-related KBS activities were identified at these organizations:

• architectural design systems	• mechanical design systems
• envelope design systems	• code compliance KBSs
• electrical design systems	• building system integration KBSs.
• structural design systems	

TABLE D.1. Research and Development Organizations Surveyed

<u>Name of Organization</u>	<u>Abbreviation</u>
Pacific Northwest Laboratory	PNL
Carnegie-Mellon University	CMU
Electric Power Research Institute	EPRI
General Electric	GE
Honeywell Controls	HCTRL
Lawrence Berkeley Laboratory	LBL
Massachusetts Institute of Technology	MIT
National Institute of Standards and Technology	NIST
National Research Council of Canada	NRCC
New Jersey Institute of Technology	NJIT
Princeton University	PRIN
Purdue University	PURD
Rensselaer Polytechnic Institute	RPI
Skidmore Owings and Merrill	SOM
Stanford	STAN
State University of New York at Buffalo	SUNY
Stone and Webster Engineering Company	SWE
The Deringer Group	DG
University of Colorado	CU
University of Illinois at Urbana-Champaign	UILL
University of Massachusetts at Amherst	UMAS
University of Minnesota	UMIN
University of Sydney, Australia	USYD
U.S. Army Construction Engineering Research Laboratory	CERL
Worcester Polytechnic Institute	WPI

The KBS R&D activities within each of these seven classifications are described in the following sections. The developmental status of each KBS is shown in Table D.2.

TABLE D.2. Current Developmental Status of KBS Activities

Knowledge-Based System Type	Research and Development Organization																								
	CERL	CMU	CU	DG	EPRI	GE	HCTRL	LBL	MIT	NIST	NJIT	NRCC	PNL	PRIN	PURD	RPI	SOM	STAN	SWE	SUNY	UILL	UMAS	UMIN	USYD	WPI
Building Design																									
Architectural	1	2							2							1				2	1				
Structural		2							2						2		2							1	
Envelope								1		1										2					
Mech. Design																			2		2				
Electr. Design								2												1	1				
Code Compliance		1								1	1										1			1	
System Integration		1		1					2																
Building Operations																									
HVAC Diagnostics			2				3							1											
Infiltration										1	1	1													
EMCS										2		1		1											
Audit/Monitoring					2								1												
Miscellaneous Other																									
Construction Eng.		2													2			2							
General Mech. Design		2				2												2	2			2	2		2
CADD-Based Design	1									1							3								

NOTES: 1. Early development stage
 2. Prototype development stage
 3. Fully operational systems

Architectural Design Systems

Currently, there are not any fully developed working KBSs for the purposes of complete architectural design. Most of the KBSs address one small and very specific task within the overall architectural design process. Relatively simple KBSs for assisting in specific aspects of architectural design are being researched at the following organizations:

- Carnegie-Mellon University (CMU)
- Massachusetts Institute of Technology (MIT)
- Rensselaer Polytechnic Institute (RPI)
- State University of New York at Buffalo (SUNY)
- University of Illinois at Urbana-Champaign (UIUC)
- U.S. Army Construction Engineering Research Laboratory (CERL).

The research efforts at each of these organizations are briefly discussed below.

Carnegie-Mellon University (CMU)

Researchers in the Department of Architecture at CMU have been working on several building-related KBS R&D projects. Schmitt (1985a, 1985b, 1986, 1987a) has been working on several simple models. His focus has been the integration of intelligent assistance with existing proprietary software packages and database packages. Some of Schmitt's major contributions are in the areas of knowledge base organization, system control, and user interface development.

Three of his major research projects are:

- Building Site Location Model, a simple generative model that locates a building within a site, based on information about the site and the building. The model, written in OPS5, is based on rules extracted from the Small Office Building Handbook (Burt Hill 1985) and supplemented by additional rules derived from experts.
- HVAC Diagnosis Model, a simple model written in OPS5, was developed using the same sources as the Building Site Location Model.
- Pattern Model for Shadyside - This model, written in PROLOG, is a diagnostic and generative model based upon an onsite study of building characteristics in the Pittsburgh community of Shadyside.

These efforts use primarily IBM PC AT-based computer systems. An objective of one uncompleted project is to link various models via an interactive CADD package for a graphics-oriented user interface. They are exploring either AutoCADD or an alternative graphics package, and have chosen the C language for any special graphics programs to be developed in-house.

Recent work has involved developing ARCHPLAN, a knowledge-based architectural planning front end to an integrated building design environment that is under development at the CMU Engineering Design Research Center (Schmitt 1987b). ARCHPLAN is a KBS for conceptual design of commercial buildings. It consists of four modules that assist in building massing, distributing building functions, planning vertical circulation, and selecting a structural type. The user interface provides a graphic environment for interactive building design.

The architectural space planner, CORE, has also been developed as part of the integrated building design environment. CORE is an expert system that uses data on building configuration directly from ARCHPLAN to lay out the service core of the building.

CONTACT PERSON(S): G. Schmitt, School of Architecture, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-3528.

U. Flemming, School of Architecture, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-2368.

Massachusetts Institute of Technology (MIT)

A Cafeteria Planning KBS to aid in the architectural programming phase is being developed for IBM in the Architectural Department at MIT.

IBM ordinarily contracts out the cafeteria planning for its new facilities and has one in-house expert for overseeing the design. IBM is trying to replicate its in-house expert because that expert is too busy. Currently, MIT is working on building the knowledge base using the IBM expert system shell PRISM.

CONTACT PERSON(S): J. Conner, School of Architecture, MIT, Cambridge, Massachusetts (617) 253-8435.

Rensselaer Polytechnic Institute (RPI)

The Center for Architectural Research in the School of Architecture at RPI has developed an expert system for energy analysis in the schematic design phase (Quadrel and Kroner 1985).

The program uses the rules contained in Predesign Energy Analysis (Hart, Kurtz, and Whidden 1980) developed for DOE. This approach makes a simple assessment of internal heat gains, envelope heat gains/losses, and ventilation heat gains/losses based upon a limited amount of data. The program produces a graphic profile of heat gains and losses for each season. The system then analyzes the results in combination with the data inputs and suggests design alternatives selected from a table of alternative strategies. The tool can be used to examine the impacts of different amounts of glazing, changing the orientation of the building, or changing the effective UA of the building envelope. There appears to be little new conceptual work involved in this effort, other than the computerization of an excellent manual method.

CONTACT PERSON(S): W. Kroner, School of Architecture, Rensselaer Polytechnic Institute.

State University of New York at Buffalo (SUNY)

Professor Kalay in the Department of Architecture and a group of about 12 other people at SUNY are working on a KBS for architectural design (Kalay 1985, 1987; Kalay, Harfmann, and Swerdloff 1985; Kalay, Swerdloff, and Harfmann 1987; Swerdloff and Kalay 1986). Kalay has been involved with the development of KBSs for several years. The focus of his work has been the development of a KBS that functions as a design assistant. The design assistant allows the user to maintain control of the design process. However, it also has a feature that allows the user to direct the KBS to perform specific design tasks that the user does not know how to do.

Much of Kalay's research has focused on developing a KBS termed ALEX. The project is not focused on energy. His research team has concentrated on developing shells as part of a design tool. This large system, originally displayed on a VAX 11/750, is now running on a network of 14 Sun workstations. It is written in PROLOG using Pascal for graphics and C for data input/output.

The overall system has a CADD-like, 3-D, object-oriented, user interface integrated with the previously described models.

The ALEX system has three major parts:

- The Planning Model, based on a goal hierarchy model, searches for solutions that satisfy alternative goals and also evaluates solutions according to satisfaction of specific criteria. One of the strengths of the system is that goals can be subdivided as far as necessary. The focus for work has been single-family residences. The goal model developed appears to be working and includes defaults for items that are not known. It is easy to add options to the goals hierarchy in the Planning Model, but difficult to change the goals tree itself. The model does not directly examine building quality issues; such issues are handled indirectly as a multiplicative function of costs.
- The Database Model is an object-oriented, database structure that contains descriptive and procedural/functional frames (e.g., if door must be operable, then check for interferences). The model has consistency maintenance features and integrity constraints. A relational database is being developed that will underlie the frames.
- The Knowledge Acquisition Model, the third model, has not been started. It is postponed indefinitely and is expected to be difficult to develop.

Two specific aspects of Kalay's contributions are most valuable. The first is that the Goal Selection System provides several alternative methods for selecting the next goal to be addressed in the design process. Using this component of a KBS, the user can designate one of the automated goal selection procedures, or he can select the next goal himself.

Kalay's second valuable contribution is the Task Allocation System. This component of a KBS allows the user to choose to generate and evaluate a new design state (or candidate design solution), or else have these tasks done automatically by the KBS.

Kalay also recommends that the knowledge in the databases be grouped according to its purpose within the KBS. For example, Kalay recommends that knowledge be classified as descriptive, procedural, objective, or relational.

The main limitation of Kalay's work is that he has not developed detailed structures for some of the primary components of his KBS, even though he has

identified the need for them. His recommendations for the organization do not address a comprehensive set of design classifications. Also, Kalay has not provided very much detail of the specific knowledge required for a design-oriented KBS.

Kalay's work has also resulted in the commercially marketed integrated geometric modeling and drafting system, WORLDVIEW. It is currently being used by practicing architects and students. It is intended to become the geometric database and user interface of the knowledge-based system.

The SUNY team has also recently developed a prototype of a small expert system, ARCADE, for energy analysis in the early phases of building design. ARCADE directly interprets the graphical representation of the building. It determines orientation, floor area, glazing area, and direction of obstacles from the floor plan. Only nongraphic information (such as the intended use of the building and local climatic conditions) needs to be input alphanumerically using a keyboard. The system is written in Pascal and is implemented on an IBM PC.

CONTACT PERSON(S): Y. Kalay, School of Architecture and Environment,
State University of New York-Buffalo (716) 831-3483.

University of Illinois (UIILL)

Michael Kim has been involved in a long-range effort called the Artificially Intelligent Design Advisory System (AIDAS). AIDAS is in the early conceptual stages of development and consists of three components: the design prescriber, the designer, and the design assessor (Kim 1987). The system is viewed as an aid to design, not as a replacement. Kim views design as an art that a machine cannot do, but for which a machine can provide assistance, and his system reflects this philosophy. The design prescriber is used to define desirable properties that are derived from several design goals, including personal preferences.

A major issue in his research is how to get the designer and the program to communicate with each other, because the designer often deals with abstract concepts. The process of design is viewed as tracing up and down a teleological

hierarchical structure. The goal is to develop all three components to work in unison.

CONTACT PERSON(S): D. Burgeson, School of Architecture, University of Illinois at Urbana-Champaign, Urbana-Champaign, Illinois (217) 333-1330.

U.S. Army Construction Engineering Research Laboratory (CERL)

CERL is actively working on two architectural design KBSs, EPLAIN and ABCS. The Energy Conscious Planning program (EPLAIN) is designed to select cost-effective design strategies, given information about climatic conditions and functional use of space. The expert system was written with the KDS shell for the IBM PC. The program asks the user a series of true-false questions about the climate and use of space, and uses the answers, coded rules, and a payback analysis to make a decision table.

CERL is also developing a system for checking the habitability conditions of a design space. The program, Activity Based Checking Systems (ABCS), is written in InterLISP D. The program is based upon frames and a series of scripts, which are series of preprogrammed events. An example of a script is a visitor entering a lobby, checking with a receptionist, and then viewing some exhibits. As each of these events is triggered, the program checks for the functionality of the design: the ability to hold a conversation, adequate lighting for viewing exhibits, and so on. The system is independent of any CADD system, so the user needs to input the design data into the ABCS program.

CONTACT PERSON(S): L. Lawrie, CERL, Champaign, Illinois (217) 373-7282.

Structural Design Systems

One actively developing application area for design-oriented KBSs is the structural design of buildings. Research and development efforts are ongoing at the following organizations:

- Carnegie-Mellon University (CMU)
- Massachusetts Institute of Technology (MIT)
- Purdue University

- Skidmore Owings and Merrill (SOM)
- University of Sydney, Australia (USYD).

These research activities are briefly discussed below.

Carnegie-Mellon University (CMU)

Researchers in the Department of Civil Engineering at CMU have developed a series of KBSs for structural design. These systems include HI-RISE (for designing rectangular high-rise buildings), LOW-RISE (for preliminary design of low-rise industrial buildings), ALL-RISE (similar to HIGH-RISE but for buildings of any height), and FLODER (for analysis of gravity loads of floor plans generated by HI-RISE). These four KBSs are summarized below.

- HI-RISE assists in the preliminary structural design of rectangular buildings (Fenves and Maher 1981; Maher 1984). Based on space planning inputs, HI-RISE generates feasible structural systems.
- LOW-RISE offers engineers assistance with the structural planning, preliminary design and evaluation of industrial buildings (Camacho 1985).
- ALL-RISE is a successor to HI-RISE (Rehak, Howard and Sriram 1985; Sriram, Maher, and Fenves 1984; Sriram 1986). It offers enhanced assistance with the preliminary design of structures for many types of large buildings.
- FLODER is a KBS that assists with the design of floor framing grids (Karakatsanis 1985). It contains knowledge about architectural space functions and structural material spans.

These laboratory systems are not used for actual applications. They are all either developmental or operational prototypes. Future plans for all of these systems include the acquisition of more practical expertise from experienced structural engineers.

CONTACT PERSON(S): M. Maher, Dept of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-3777.

S. Fenves, Dept of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-2944.

Massachusetts Institute of Technology (MIT)

The conceptual design of tall buildings is being studied by a group of researchers at MIT. A KBS is being developed using object-oriented programming methods. The system is currently in a developmental prototype phase. It is relatively small and does not include backtracking or redesign capabilities. Future directions include material selection, safety, maintenance, and durability evaluation.

CONTACT PERSON(S): J. Conner, Dept of Civil Engineering, MIT, Cambridge, Massachusetts (617) 253-8435.

Purdue University

An effort is under way in the Civil Engineering Department to develop KBSs for the structural design of buildings.

CONTACT PERSON(S): J. Wright, Dept of Civil Engineering, Purdue University, West Lafayette, Indiana (317) 494-2175.

Skidmore Owings and Merrill (SOM)

In a recent effort funded by IBM, SOM developed a KBS, called the Rule Based Calculator, for the structural design of buildings. The basic approach in this effort was to find a method for extracting engineering data from analysis programs and placing it in CADD-based knowledge bases where it can be maintained. The system specifically addresses the design of concrete columns and steel beams.

The Rule Based Calculator is fully operational and is currently marketed as an optional package for a new CADD package available from IBM. The system runs on an IBM-RT in the AIX operating system. The program itself was developed in C and runs in XWINDOWS.

CONTACT PERSON(S): K. Stebbins, Skidmore Owings and Merrill, Chicago, Illinois (312) 641-5959.

University of Sydney, Australia (USYD)

A KBS for the design of retaining wall structures used in foundation engineering, called RETWALL, was developed at the University of Sydney

(Hutchinson 1985; Gero and Coyne 1986; Rosenman et al. 1986). This system is in the prototype development phase.

Currently, the system's capabilities are limited due to a lack of knowledge about design alternatives.

CONTACT PERSON(S): J. Gero, Dept. of Architectural Science, University of Sydney, Sydney, Australia.

P. Hutchinson, Dept. of Architectural Science, University of Sydney, Sydney, Australia.

Envelope Design Systems

An important application area for design-oriented KBSs is the design of building envelopes. Little current work addresses this application. Research and development efforts are ongoing at the following organizations:

- Lawrence Berkeley Laboratory (LBL)
- National Institute of Standards and Technology (NIST)
- State University of New York at Buffalo (SUNY).

These research activities are briefly discussed below.

Lawrence Berkeley Laboratory (LBL)

Steve Selkowitz is developing a plan for an advanced envelope design tool for all phases from schematic design through construction, occupancy, and retrofit of a building (Selkowitz, Papamichael, and Wilde 1986). The plan was delivered to DOE in mid-1986. The tool is conceived as containing a number of elements, including expert systems for design advice and imaging systems that provide views of interior spaces under different lighting and daylighting conditions. The tool would be ready in the 1990s and would be the result of a cooperative industry and government effort.

LBL is also working with the Architecture Department at the University of California at Berkeley to develop an expert system for daylighting design based upon the a daylighting analysis model. The program is being developed on an Apple computer system using MVP FORTH.

CONTACT PERSON(S): S. Selkowitz, LBL, Berkeley, California
(415) 486-5064.

National Institute of Standards and Technology (NIST)

A design assistant for conceptual fenestration design is in the early conceptual stages of development at NIST. The system is being developed in Fortran on an IBM PC. The approach is to use the results of a parametric analysis of a base case building developed using DOE-2, TARP, or BLAST. The design assistant will analyze the parametric data and determine the sensitivity of the hourly outputs to the primary design parameters. Based on the results of this analysis, the design assistant suggests strategies for improving the design.

CONTACT PERSON(S): S. Treado, NIST, Gaithersburg, Maryland (301) 975-6444.

State University of New York at Buffalo (SUNY)

A research group at SUNY has agreed to collaborate with the Passive Research and Development Group at Lawrence Berkeley Laboratory and Wayne Place at the University of North Carolina to work on a model that will incorporate the energy impacts of roof apertures for daylighting.

CONTACT PERSON(S): Y. Kalay, SUNY, Buffalo, New York (716) 831-3483.

Mechanical Design Systems

Another important application of design-oriented KBSs is the design of building mechanical systems (including for example HVAC equipment, piping, ductwork). Our survey indicates that this is an application area with little activity. However, there may be many inhouse development activities under way in large corporations that were not identified in the survey. Research and development efforts are ongoing at the following organizations:

- Stone and Webster Engineering Company (SWEC)
- University of Illinois at Urbana-Champaign (UIUC)

These research activities are briefly discussed below.

Stone and Webster Engineering Co. (SWEC)

Several large engineering firms are developing expert systems to aid in the most common design procedures. For example, Stone and Webster is developing an expert system to serve as a preprocessor or a postprocessor for an HVAC simulation package (Finn and Reinschmidt 1986). Their expert systems have been developed for either their inhouse VAX computer system or for a PC-based shell.

CONTACT PERSON(S): G. Finn, SWEC, Boston, Massachusetts (617) 589-1567.

University of Illinois at Urbana-Champaign (UIILL)

A KBS for the conceptual design of mechanical systems for buildings has been developed in the School of Architecture. This system has capabilities that include the conceptual design of elevators, piping, HVAC systems, ductwork, and other systems.

CONTACT PERSON(S): D. Burgeson, School of Architecture, University of Illinois, Urbana-Champaign, Illinois (217) 333-1330.

Electrical Systems Design

The design of building electrical systems (including lighting and power distribution systems) directly affects building energy performance. There may be many inhouse development activities underway in large corporations that were not identified in the survey.

University of Illinois at Urbana-Champaign (UIILL)

A KBS for the conceptual design of lighting systems is being developed at the School of Architecture.

CONTACT PERSON(S): R. Smith, School of Architecture, University of Illinois, Urbana-Champaign, Illinois (217) 333-2848.

Code Compliance Checking

Building designers must satisfy building codes and standards. Research and development efforts are ongoing at the following organizations:

- Carnegie-Mellon University (CMU)

- National Institute of Standards and Technology (NIST)
- New Jersey Institute of Technology (NJIT)
- University of Illinois (UILL)
- University of Sydney, Australia (USYD).

These research activities are briefly discussed below; other inhouse development activities may be underway in large corporations that were not identified in the survey.

Carnegie-Mellon University (CMU)

A KBS for preliminary design of structural components developed at CMU called SPEX uses information from design standard knowledge bases to develop constraints that are used to select optimal components (Garrett 1986). In many circumstances, building designers use physical behavior limitations as constraints in the design of structural components. SPEX allows the designer to automatically access design standards during component selection and analysis. The knowledge-based approach was selected because of the need to regularly update the standard criteria. In this situation, it is desirable to maintain the code information separate from the functional program that retrieves and processes the code requirements during the design process.

CONTACT PERSON(S): M. Maher, Dept of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-3777.

S. Fenves, Dept of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-2944.

National Institute of Standards and Technology (NIST)

Standards-related efforts at NIST are designed to support the development of standards, not to actually create standards. A related tool under development is the Standards Analysis, Synthesis and Expression Software (SASE). The tool, written in Fortran, is designed to provide a systematic and uniform method for analysis of standards. The program is currently being tested on a typical standard.

CONTACT PERSON(S): Kent Reed, NIST, Gaithersburg, Maryland (301) 975-5852.

New Jersey Institute of Technology (NJIT)

Members of the Building Engineering & Architectural Research Center at NJIT are actively involved in developing an expert system for evaluating compliance with the New Jersey building code. Another is described under Infiltration/Moisture. It is being developed using a commercially available shell for the IBM PC.

CONTACT PERSON(S): I. Bales, School of Architecture, New Jersey Institute of Technology, Newark, New Jersey (201) 596-3010.

University of Illinois (UIILL)

A team at the School of Architecture is involved in the development of a KBS for checking compliance with the National Electrical Code.

CONTACT PERSON(S): R. Smith, School of Architecture, University of Illinois, Urbana-Champaign, Illinois (217) 333-2848.

University of Sydney, Australia (USYD)

A KBS is under development to provide building designers with assistance in using the Australian Model Uniform Building Code (AMUBC) (Rosenman and Gero 1985; Rosenman, Gero, and Oxman 1986). The focus of this effort has been to test the feasibility of representing building codes for specification management. The system is currently a developmental prototype. Only part of the code has been implemented.

The system has been developed in PROLOG in a PC environment. Future directions include improving the explanation facility and adding more actual code requirements to the knowledge base.

CONTACT PERSON(S): M. Rosenman, Dept. of Architectural Science, University of Sydney, Sydney, Australia.

J. Gero, Dept. of Architectural Science, University of Sydney, Sydney, Australia.

Systems Integration KBSs

The design of whole buildings involves detailed knowledge of the interactions between each of the individual building subsystems (e.g., the

envelope, HVAC equipment, and lighting). No KBSs currently account for the interactions of all building subsystems. A few researchers are attempting to account for the interactions between some building subsystems. Research and development efforts are ongoing at the following organizations:

- Carnegie-Mellon University (CMU)
- The Deringer Group (DG)
- Massachusetts Institute of Technology (MIT).

These research activities are briefly discussed below.

Carnegie-Mellon University (CMU)

A group at the Engineering Design Research Center at CMU has developed a prototype Integrated Building Design Environment (IBDE). The system addresses architectural planning, structural design, and construction planning for office buildings. It consists of a blackboard, a controller, a data manager, and six process modules: the architectural planner (ARCHPLAN), the architectural space planner (CORE), the preliminary structural designer (HI-RISE), the structural component designer (SPEX), the foundation designer (FOOTER), and the construction planner (CONSTRUCTION PLANEX). The controller activates the individual processes using information on the blackboard as it becomes available. It also instructs the data manager to supply information to the processes when needed and to retrieve output data from them. The data manager and blackboard reside on a local area network so that the individual processes can reside on different computers. The system is being used as a testbed to study communication and control issues associated with integrating arrays of computer processes into a single environment.

Extensions of this work will examine integration of design critics into the environment, coordination of parallel design processes, more intelligent user interfaces and control, and more efficient data storage and retrieval.

CONTACT PERSON(S): M. Maher, Dept of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-3777.
S. Fennes, Dept of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-2944.

The Deringer Group (DG)

In an earlier phase of this project (Heidell and Deringer 1987), a long-term planning study was completed. Several important contributions to energy related KBSs include

- identification of building-related application areas
- conceptual development of two main types of energy decision models: the whole-building model and building subsystems models
- identification of the timing and sequence of major sets of energy design decisions.

The limitation of Heidell and Deringer's work is that they did not address the important issues of how to manage the large amounts of design information required during the design process, how to manage the processing of the multiple tasks that will be required, and explicitly how to make the individual design-related decisions.

CONTACT PERSON(S): J. Deringer, The Deringer Group, Riva, Maryland (301) 956-4200.

Massachusetts Institute of Technology (MIT)

A project involving the development of a computer-integrated design and construction system (CIDCIS) is underway at the MIT Intelligent Engineering Systems Laboratory (IESL)(a). The objective of this system is to support cooperation between engineers involved in design and construction. The system consists of several knowledge based modules that communicate through a global database--the blackboard. CIDCIS is being implemented on a network of SUN computers, utilizing concepts from object-oriented programming, knowledge-based expert systems, and database management systems.

(a) N. Chandra and R. Logcher, "Steps Towards Automatic Interpretation of Project Data: a Knowledge-Based Systems Approach," working paper, Intelligent Engineering Systems Laboratory, Department of Civil Engineering, Massachusetts Institute of Technology.

Another major project at IESL involves the development of programs that are capable of generating innovative design concepts during the conceptual design stage.

CONTACT PERSON(S): D. Sriram, Dept. of Civil Engineering, MIT, Cambridge, Massachusetts (617) 253-6981.

RECENT CONCEPTUAL ADVANCES IN KNOWLEDGE-BASED BUILDING OPERATIONS MANAGEMENT SYSTEMS

The KBSs being developed for building operations-related applications are discussed in this section. These KBSs all involve either building diagnostics or monitoring applications. Four main classifications of building operations-related KBS activities were identified in the survey. They are

- HVAC diagnosis
- infiltration
- energy management and control systems (EMCS)
- auditing/monitoring.

A brief overview of KBS R&D activities within each of these classifications follows. The status of each is summarized in Table D.2.

HVAC Diagnostics

One of the more active energy-related KBS development areas involves the diagnosis of HVAC equipment. Most of the KBSs identified in the survey involve the diagnosis of a few very specific components within the overall HVAC system. Currently, only a few of these applications are fully developed. KBS applications for HVAC diagnosis are being developed at the following organizations:

- Honeywell (HCtrl)
- Princeton University (PRIN)
- University of Colorado (CU).

The research efforts at each of these organizations are briefly discussed below.

Honeywell (HCtrl)

A KBS was developed to provide field assistance to air-conditioning service technicians. The system is frame-based and runs on an IBM PC. Thirty of the KBSs have been extensively used in the field for the last year.

CONTACT PERSON(S): C. Culp, Honeywell, Arlington Heights, Illinois (312) 394-4000.

Princeton University (PRIN)

Several KBSs are under development at the Center for Energy and Environmental Studies at Princeton University (Haberl 1988). Some of the projects involve work that Haberl started earlier at the University of Colorado. The approach taken is to identify malfunctioning HVAC equipment and poor building operations practices through the analysis of metered utility data. These systems are model-based, knowledge-based systems that detect over-consumption by comparing actual energy consumption to normalized consumption. The knowledge base for these systems contains building characteristic information, engineering analysis (concerning the whole building and individual components), and heuristics for operation and maintenance. Early results on two federal office buildings (Haberl and Vajda 1988) indicate that 5 to 15% of the energy used in existing buildings can be saved simply by using advanced monitoring, feedback, and incentives.

CONTACT PERSON(S): J. Haberl, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey (609) 452-5677.

University of Colorado (CU)

Researchers at the Department of Civil, Environmental, and Architectural Engineering are involved in developing several expert systems directly related to building energy use (Haberl 1986; Haberl and Claridge 1985, 1987; Hildebrand 1986).

The Building Energy Analysis Consultant (BEACON) an expert system that performs daily diagnosis of HVAC system operations has been successfully developed for a large recreation center on the Colorado campus and has reduced

the center's energy consumption by 15%. The expert system was developed using the PC-based language M.1. (a modified version of PROLOG). Efforts are now under way to generalize the procedure in order to apply it in other building types.

CONTACT PERSON(S): J. Kreider, Dept of Civil, Environmental and Architectural Engineering, Boulder, Colorado (303) 492-3915.

Infiltration/Moisture

A few organizations have started to develop KBSs for diagnosing infiltration and moisture problems in buildings. This application area is being researched at

- New Jersey Institute of Technology (NJIT)
- National Institute of Standards and Technology (NIST)
- National Research Council of Canada (NRCC).

The research efforts at each of these organizations are briefly discussed below.

New Jersey Institute of Technology (NJIT)

Members of the Building Engineering & Architectural Research Center are actively developing an expert system for solving moisture problems in residential buildings. A team of experts has been assembled, and a demonstration system is under development. The demonstration system involves an off-the-shelf shell for the IBM PC. Future plans include generalizing the expert system to address moisture problems in other types of buildings.

CONTACT PERSON(S): I. Bales, Building Engineering and Architectural Research Center, NJIT, Newark, New Jersey (201) 596-3010.

National Institute of Standards and Technology (NIST)

Andrew Persily is in the initial stages of developing an expert system to be used in conjunction with NIST's Thermal Analysis Program (TARP). TARP is a computer simulation tool designed for analysis and diagnosis of air

infiltration rates and air leakage problems. Currently, the model is intended to be applied to residential buildings.

A working prototype of the expert system has been designed to diagnose moisture problems. The prototype was developed with a commercially available shell for PC-based systems.

Future plans include broadening the scope of the expert system to include other infiltration problems.

CONTACT PERSON(S): A. Persily, NIST, Gaithersburg, Maryland (301) 975-6418.

National Research Council of Canada (NRCC)

The WINDEKS expert system has been developed at the Institute for Research in Construction at NRCC. This expert system assists in diagnosing window problems. The first phase of the expert system, involving the condensation diagnostician, is completed. It was developed on the XEROX 1108 computer using Interlisp D. Modifications to generalize the expert system are ongoing.

CONTACT PERSON(S): K. Ruberg, Institute for Research in Construction, National Research Council, Ottawa, Ontario, Canada (613) 993-9580.

Energy Monitoring and Control Systems (EMCS)

KBSs that work with energy monitoring and control systems to maintain economical and comfortable space conditions in buildings are being developed at the following organizations:

- National Institute of Standards and Technology (NIST)
- National Research Council of Canada (NRCC)
- Princeton University (PRIN)
- HVAC controls companies.

The KBS activities at each of these organizations are briefly discussed below.

National Institute of Standards and Technology (NIST)

A KBS for evaluating real-time EMCS data is being developed at NIST. We have no details about this effort.

CONTACT PERSON(S): G. Kelly, NIST, National Institute of Standards and Technology, Gaithersburg, Maryland (301) 975-5870.

National Research Council of Canada (NRCC)

A KBS for EMCS is being developed at the Institute for Research in Construction (IRC). A primary focus in this work is to standardize the operator interface of EMCS. No further details about this effort have been received yet.

CONTACT PERSON(S): K. Ruberg, Institute for Research in Construction, National Research Council, Ottawa, Ontario, Canada (613) 993-9580.

Princeton University (PRIN)

Researchers at the Center for Energy Studies are developing a quasi-real-time expert system for analyzing data generated by Energy Management Systems (EMS). The work is being funded by the Prudential Insurance Company.

The data monitored by the EMS will be used to perform automated energy auditing and diagnostics. One of the key areas of effort in this work is the integration of the expert system with an existing data base and with a standard graphics package. The researchers are attempting to develop a user interface with easy-to-understand graphic presentations. The expert system is being developed for use on IBM PCs. It is expected that the fully developed expert system will be available to the public in about 1 year.

CONTACT PERSON(S): J. Haberl, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey (609) 452-5677.

HVAC Controls Companies

Several HVAC controls manufacturers (such as Andover, Honeywell, Johnson, Staefa Controls) are actively developing expert systems and KBSs that have application in specific domains such as real-time controls environments,

diagnostics, and training tools. Because these KBSs are proprietary in nature, these companies generally do not reveal information about the activities.

Auditing/Monitoring

Renewed interest in building energy consumption monitoring has led to increased activity in the development of KBSs for assisting in compiling and interpreting monitored data. KBSs that fall within this classification are being researched at the following organizations:

- Pacific Northwest Laboratory (PNL)
- Electric Power Research Institute (EPRI)
- University of Colorado (CU)
- Princeton University (PRIN)
- utilities.

The research efforts at each of these organizations are briefly discussed below.

Pacific Northwest Laboratory (PNL)

Researchers at PNL have developed the Logger Verification Assistant (LVA) to assist in the End-Use Load and Consumer Assessment Program (ELCAP), a large building metering program. The system assists in diagnosing mistakes in the installation of field data recorders. The problem of data verification can be characterized as time-consuming, data-intensive, repetitive, and based on experience. These properties lend the task well to a KBS solution. The LVA is a hybrid system that combines rule-based reasoning, a dynamic object-oriented database, procedural knowledge, and algorithmic programming to solve the problem. The knowledge-based portion of the system is implemented on a LISP processor and linked to a general-purpose computer that performs statistical analysis and database query functions.

For large-scale data collection efforts like ELCAP, which collects more than 16 million data values per month, automated data verification procedures are critical. At the peak of the verification effort, ELCAP employed 8 full time staff for data verification alone. The LVA system decreased the time

required to verify a typical site by 40%. The LVA system is fully integrated into the ELCAP data flow. Thanks to LVA and other improvements, the ELCAP verification staff level has dropped to 1.5 full-time staff. A more complete discussion of LVA and the ELCAP data verification process can be found in Lauffman and Crowder (1987).

CONTACT PERSON(S): R. S. Crowder, Pacific Northwest Laboratory, Richland, Washington.

Electric Power Research Institute (EPRI)

The Electric Power Research Institute is developing an expert system that will offer a different approach to conventional utility rate structures. This expert system involves a real-time price response to customer demand that is continuously broadcast to the utilities' major customers. The innovative aspect of this approach is that the customer is instantly and continuously rewarded with lower utility rates for maintaining peak demand at a relatively low level. The customer then has the added incentive to monitor peak demand in order to reduce utility costs.

CONTACT PERSON(S): L. Carmichael, EPRI, Palo Alto, California (415) 855-7982.

University of Colorado (CU)

Another expert system developed at CU involves the analysis of energy audit data (Brothers, Meadows, and Stern 1987). This expert system is still under development using the M.I. language.

CONTACT PERSON(S): J. Kreider, Dept. of Civil, Environmental and Architectural Engineering, Boulder, Colorado (303) 492-6069.

Princeton University (PRIN)

Another knowledge-based system under development at the Center for Energy and Environmental Studies implements a multilevel data-driven energy audit. The system, being developed and tested for New Jersey commercial customers, provides useful information about a customer's energy usage using constrained

data sets. The analysis is targeted for use by utilities, energy auditors, utility customers, and state agencies.

CONTACT PERSON(S): J. Haberl, Center for Energy and Environmental Studies,
Princeton University, Princeton, New Jersey, (609)
452-5677.

Utilities

Many utilities are actively involved in energy conservation programs to reduce customer demands on their plants, to avoid the tremendous cost of constructing new power generating facilities. A few of the utilities have become actively involved in developing expert systems that help their customers reduce their peak load demands. To accomplish this task, much effort has been focused on pattern recognition in monitored utility data.

OTHER DESIGN-ORIENTED KNOWLEDGE-BASED RESEARCH ACTIVITIES

A group of significant KBS development activities was identified in the survey that did not fall within the classifications of building design or building operations. These assorted KBS activities can be classified under the following headings:

- construction engineering and management
- general mechanical design
- CAD-based KBS.

A brief overview of these KBS R&D activities follows.

Construction Engineering and Management

An area receiving a great deal of attention by civil engineering researchers is construction engineering and management. Levitt (Maher 1987) identified 11 KBS programs, in various stages of development, related to construction engineering and management. Several of the KBS programs that are the farthest along have been developed at the following organizations:

- Carnegie-Mellon University (CMU)
- Purdue University

- Stanford University.

The research efforts at each of these organizations are briefly discussed below.

Carnegie-Mellon University (CMU)

A KBS development effort related to construction engineering and management is underway at CMU.^(a) The program MASON is a KBS for masonry construction duration estimation. This system is currently an operational prototype.

CONTACT PERSON(S): M. Maher, Dept. of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-3777.
S. Fenves, Dept. of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania (412) 268-2944.

Purdue University

Several KBSs for construction engineering and management are being developed at Purdue. Efforts are under way to provide design assistance with project scheduling, project risk analysis, and the simulation of construction site activities. No further details about these efforts have been received yet.

CONTACT PERSON(S): M. Skibniewski, Dept. of Civil Engineering, Purdue University, West Lafayette, Indiana (317) 494-2250.

Stanford University

A KBS called PLATFORM is being developed in the Civil Engineering Department (Levitt and Kunz 1985). The objective of PLATFORM is to show that an AI environment can represent and use construction task knowledge and, hence, improve the capabilities of project management systems. The ultimate goal is to develop real-time project "control" tools. PLATFORM is developed in the

(a) C. Hendrickson, D. Martinelli, and D. Rehak, "Heirarchical Rule-Based Activity Duration Estimation," working paper, Department of Civil Engineering, Carnegie-Mellon University.

KEE programming environment. PLATFORM is a fully operational KBS, although domain extensions are under way.

CONTACT PERSON(S): R. Levitt, Dept. of Civil Engineering, Stanford University, Stanford, California.

General Design-Oriented KBS

Most of the design-oriented KBS R&D currently under way is focussed on non-building related mechanical and electrical design problems such as circuit design and mechanical assembly design. Many different methods of solving these design problems have been used by the various researchers. To some degree, each new KBS builds on the methods used previously. One of the most powerful methods of solving complex design problems, identified in this survey, is hierarchical planning. Research efforts using some form of this problem-solving method are briefly identified below.

Hierarchical Problem Solving

Because several of the most recently developed KBSs use hierarchical planning, a general overview of this method is provided here. In simplest terms, this method allows the designer to solve a problem sequentially, with a backtracking capability to alter assumptions that may have been made prematurely.

This problem-solving approach usually begins by identifying the most important aspects of a problem. Initially, the systems focus only on the most important aspects of the problem. This usually involves subdividing the problem into many independent subproblems. The planning feature then determines the sequence in which the subproblems should be solved. If some subproblems cannot be solved because of a lack of information, methods for approximating a solution are identified (i.e., plausible guessing is used).

Once a plan of attack is completed for the important aspects of the problem, the system can begin to address the subproblems. Usually when this is attempted, the plans completed earlier for the more important sub-problems need to be revised.

A knowledge base for this problem-solving approach requires a significantly greater level of detail than would be required for some other approaches. For hierarchical planning, the knowledge base must include domain specific information about proposing solutions, constraining solutions, and revising solutions.

Four recent R&D efforts that use the hierarchical problem-solving approach are:

- AIR/CYL, a tool to assist in the design of air cylinders developed at Worcester Polytechnic Institute (Brown 1985).
 - CONTACT PERSON(S): D. Brown, Computer Science Department, Worcester Polytechnic Institute, Worcester, Massachusetts.
- ISIS, a factory job shop scheduling KBS developed at CMU (Fox, Allen, and Strohm 1982; Fox et al. 1983; Fox and Smith 1984; Smith, Fox, and Ow 1986).
 - CONTACT PERSON(S): M. Fox, Dept. of Computer Science, Carnegie Mellon University, Pittsburgh, Pennsylvania.
- MOLGEN, a tool to assist geneticists design molecular genetics experiments developed at Stanford University (Stefik 1981a, 1981b; Stefik et al. 1983).
 - CONTACT PERSON(S): M. Stefik, Stanford University, Stanford, California.
- VT, an elevator design program developed for Westinghouse (Marcus 1988; Marcus and McDermott 1986; Marcus, McDermott, and Wang 1985).
 - CONTACT PERSON(S): S. Marcus, Dept. of Computer Science, Carnegie-Mellon University, Pittsburgh, Pennsylvania.

J. McDermott, Dept. of Computer Science, Carnegie-Mellon University, Pittsburgh, Pennsylvania.

Other General Mechanical Design KBS Methods

The following list includes several miscellaneous KBSs for mechanical design that were identified in the survey. Because these KBSs do not directly apply to buildings, details of these systems are not provided here. They are

identified here because some of these recent efforts may provide helpful information in the conceptual planning of other applications. Detailed reports on these research efforts can be found in the indicated references.

- DCA, a technique for evaluating the overall compatibility of a candidate design with the required specifications for a design (Ishii and Barkan 1987) - The theory of fuzzy measure is used to compute the utility of a schematic design in terms of an index called the Match Index.
 - CONTACT PERSON(S): P. Barkan, Dept. of Mechanical Engineering, Stanford University, Stanford, California.
- DKBS, a KBS shell for general conceptual and preliminary design applications (Rosen, Erdman, and Riley 1987) - The approach is to decompose design domains into design issues, problem statements, design strategies, and technical solutions. The system is in the operational prototype phase of development.
 - CONTACT PERSON(S): A. Erdman, Dept. of Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota.

D. Riley, Dept. of Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota.
- VEXPERT, a tool to assist in the design of V-belts (Dixon and Simmons 1985) - The program is written in LISP and uses OPS5 production rules. The basic approach is to iteratively design and redesign a solution for the problem.
 - CONTACT PERSON(S): M. Simmons, KBSs Group, Corporate Research and Development, General Electric, Schenectady, New York.

SWEC is actively using several expert systems that were developed inhouse (Finn and Reinschmidt 1986). Some of the more successful KBSs are:

- PUMP PRO - a tool to assist in the diagnosis of centrifugal pump failures at operating locations
- Vibration Analysis - a tool to assist with the diagnosis of problems associated with rotating machinery
- Welding Defect Diagnosis - a tool to assist with the diagnosis of welding failures.

SWEC has also developed diagnostic expert systems, regulatory compliance expert systems, and an expert system to review a CADD database for consistency.

CONTACT PERSON(S): G. Finn, SWEC, Boston, Massachusetts (617) 589-1567.

CADD-based Knowledge Based Systems

Several KBS R&D efforts focus on bringing intelligent design decision capabilities into CADD environments. However, most efforts are in the early planning stages. A few of the more fully developed KBSs are being worked on at the following organizations:

- National Institute of Standards and Technology (NIST)
- Skidmore Owings and Merrill (SOM)
- U.S. Army Construction Engineering Research Laboratory (CERL)
- other private corporate R&D efforts.

The research and development efforts at each of these organizations are briefly discussed below.

National Institute of Standards and Technology (NIST)

NIST has started several research projects to help develop standards related to CADD, including the Standards Interface for Computer-Aided Design (SICAD). The objective of this work is to develop a standard for storing data related to compliance with building codes for use by CADD systems.

A standardized approach for storing this data is needed to efficiently use standards checking programs such as SASE. The approach that NIST is investigating is to have the CADD systems separate the data needed for standards checking from the rest of the CADD routines.

In a related effort, NIST is participating in a committee for updating the Initial Graphics Exchange Specification (IGES), the ANSI standard for data interchange between CADD systems.

CONTACT PERSON(S): Kent Reed, National Institute of Standards and Technology, Gaithersburg, Maryland (301) 975-5852.

Skidmore Owings and Merrill (SOM)

SOM has developed a powerful CAD design environment for IBM-RT computers. The system runs under IBM's version of UNIX known as AIX. The basic CAD package has several optional analysis packages such as structural, lighting, HVAC equipment, and piping. Currently, the system has knowledge based capabilities for structural design only. However, the KBS design is supposed to be readily adaptable for implementation in other building subsystems design applications.

CONTACT PERSON(S): K. Stebbins, Skidmore Owings and Merrill, Chicago, Illinois (312) 641-5959.

U.S. Army Construction Engineering Research Laboratory (CERL)

In addition to architectural design KBSs, CERL is involved in another effort: the Computer-Aided Engineering and Architectural Design System (CAEADS). The CAEADS project involves an attempt to link CADD with building layout tools, energy analysis tools (BLAST), and other large databases (CAPCES).

CONTACT PERSON(S): L. Lawrie, CERL, Champaign, Illinois (217) 373-7282.

Other Private Industry Efforts

KBSs for CAD systems are being developed by many vendors. About a dozen vendors dominate this market (e.g., Computervision, ICAD, Intergraph, Prime, Wisdom Systems). Multiple areas into which CADD manufacturers are expanding include:

- enhanced imaging systems
- enhanced building representation
- intelligent building design
- database acquisition systems
- interfacing with existing analysis tools.

Because all of these developments are important to the AEDOT research effort, the private-sector contribution is significant. However, each

manufacturer is currently dealing with interface issues individually. The interfacing between various KBSs, CAD systems, databases, analysis tools, and graphics systems has not been standardized. To implement all of these features into a single product, such as the proposed energy design advisor which will be publicly available, the standardization of these interfaces is necessary. These issues are currently being addressed in several forums.

Although intelligent design tools for many building features are being developed by some CAD vendors, the energy-related aspects of building design have not yet been addressed, and adequate integration has not been accomplished.

REFERENCES

- Brothers, P., K. Meadows and F. Stern. 1987. "An Expert System for the Building Energy Audit Process." Paper presented at the Seminar on Knowledge-Based Systems, ASHRAE 1987 Annual Meeting, June 28 - July 2, Nashville, Tennessee.
- Brown, D. 1985. "Failure Handling in a Design Expert System." Computer Aided Design 17:436-442.
- Burt Hill Kosar Rittelmann Associates. 1985. Small Office Building Handbook, Van Nostrand Reinhold Co., New York.
- Camacho, G. 1985. "LOW-RISE: An Expert System for Structural Planning and Design of Industrial Buildings." Master's thesis, Department of Civil Engineerings, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Dixon, J., and M. Simmons. 1985. "Expert Systems for Engineering Design: Standard V-Belt Drive Design as an Example of the Design-Evaluate-Redesign Architecture." In proceedings of the ASME Computers in Engineering Conference.
- Fenves, S., and M. Maher, 1981. "The Use of Artificial Intelligence Techniques in Preliminary Structural Design." Technical Report, Design Research Center Report DRC-12-04-81, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Finn, G., and K. Reinschmidt. 1986. "Expert Systems in an Engineering Construction Firm." Expert Systems in Civil Engineering, ASCE, New York.
- Fox, M., B. Allen, and G. Strohm. 1982. "Job-Shop Scheduling: An Investigation in Constraint-Directed Reasoning." Proceedings AAAI-82, pp. 155-158.

- Fox, M., S. F. Smith, B. P. Allen, G. A. Stohm, and F. C. Wimberly. 1983. ISIS: a constraint-directed reasoning approach to job-shop scheduling. Proceedings of the IEEE Conference on Trends and Applications.
- Fox, M. and M. Smith. 1984. "ISIS: A Knowledge-Based System for Factory Scheduling". Expert Systems 1(1).
- Garrett, J. 1986. "A Knowledge-Based Standards Processor for Structural Component Design." Ph.D. Dissertation, Dept. of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Gero, J., and R. Coyne. 1986. "Developments in Expert Systems, for Design Synthesis." Expert Systems in Civil Engineering, ASCE, New York.
- Haberl, J. 1986. An Expert System for the Analysis of Building Energy Consumption. Ph.D. Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado at Boulder.
- Haberl, J., and D. Claridge. 1985. "Retrofit Energy Studies of a Recreation Center." ASHRAE Transactions, Vol. 91, Part 2B, pp. 1421-1433.
- Haberl, J., and D. Claridge. 1987. "An Expert System for Building Energy Consumption Analysis: Prototype Results." ASHRAE Transactions, Vol. 93, Part 1, pp. 979-998.
- Haberl, J., and E. Vajda. 1988. "Use of Metered Data Analysis to Improve Building Operation and Maintenance: Early Results from Two Federal Complexes." In proceedings of the ACEEE 1988 Summer Study on Energy Efficiency in Buildings, Pacific Grove, California.
- Harmon, P., R. Maus, and W. Morrissey. 1988. Expert Systems - Tools and Applications. J. Wiley and Sons, New York, New York.
- Hart, G., J. Kurtz, and W. Whidden. 1980. Predesign Energy Analysis: A New Graphic Approach to Energy Conscious Design for Buildings. DOE/CS-0171, Prepared as Energy Graphics by Booze Allen and Hamilton, Inc. for the U.S. Department of Energy, Washington, D.C.
- Heidell, J., and J. Deringer. 1987. Developing an Energy Design Tool - Phase I Report. PNL-5709, Pacific Northwest Laboratory, Richland, Washington.
- Hildbrand, A. 1986. A Knowledge System for HVAC Diagnostics. Masters Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado at Boulder.
- Hutchinson, P. 1985. "An Expert System for the Selection of Earth Retaining Structures." Master's thesis, Department of Architectural Science, University of Sydney, Australia.

- Ishii, K., and P. Barkan. 1987. "Design Compatibility Analysis - A Framework for Expert Systems in Mechanical System Design." In Proceedings of the 1987 ASME International Computers in Engineering Conference and Exhibition, New York, New York.
- Kalay, Y. 1985. "Redefining the Role of Computers in Architecture: From Drafting/Modelling Tools to Knowledge Based Assistants." Computer-Aided Design 17(7):319-328.
- Kalay, Y. 1987. "A Knowledge-Based Computable Model of Design." IFIP Conference on Expert Systems in Computer-Aided Design, Sydney, Australia.
- Kalay, Y., A. Harfmann, and L. Swerdloff. 1985. ALEX: A Knowledge-Based Architectural Design System. Computer-Aided Design/Graphics Laboratory Report, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Kalay, Y., L. Swerdloff, and A. Harfmann. 1987. "A Knowledge-Based Approach to Dynamic Computer-Aided Design Task Allocation", Computer-Aided Design/Graphics Laboratory Report, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Karakatsanis, A. 1985. FLODER: An Expert System for Floor Plan Layout. Master's Thesis, Department of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Kim, M. K. 1987. "Development of Machine Intelligence for the Interface of Design Intent Implicit in Design Specifications." Computability of Design, ed. Y. E. Kalay, pp. 99-116. Wiley, New York.
- Laufmann, S. C., and R. S. Crowder, III. 1987. "LVA: A Knowledge-Based System for Diagnosing Faults in Digital Data Loggers." In Proceedings of the Third Conference on Artificial Intelligence Applications, February 23-27, 1987, Kissimmee, Florida, pp. 144-148. IEEE Computer Society, Washington, D. C.
- Levitt, R., and J. Kunz. 1985. "Using Knowledge of Construction and Project Management for Automated Schedule Updating." Project Management Journal 16(5).
- Maher, M. 1984. HI-RISE: A Knowledge-Based Expert System for the Preliminary Structural Design of High Rise Buildings. Ph.D. Dissertation, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Maher, M. 1987. Expert Systems for Civil Engineers. American Society of Civil Engineers.
- Marcus, S., J. McDermott, and T. Wang. 1985. "Knowledge Acquisition for Constructive Systems." In Proceedings of the Ninth International Joint Conference on Artificial Intelligence, pp. 637-639. Morgan Kauffmann, Los Altos, California.

- Marcus, S., and J. McDermott. 1986. SALT: A Knowledge Acquisition Tool for Propose-and-Revise Systems. Technical Report, CMU-CS-86-170, Dept. of Computer Science, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Marcus, S. 1988. "A Knowledge Representation Scheme for Acquiring Design Knowledge". In Artificial Intelligence Approaches to Engineering Design, eds. C. Tong and D. Sriram, Addison-Wesley, Reading, Massachusetts.
- Qadrel, R., and W. Kroner. 1985. "Intelligent Energy Graphics--An Expert System for Building Energy Analysis." In Research and Design. American Institute of Architects Foundation, Washington, D.C.
- Rehak, D., H. Howard, and D. Sriram. 1985. "Architecture of an Integrated Knowledge-Based Environment for Structural Engineering Applications." Knowledge Engineering in Computer Aided Design, pp. 89-113. North-Holland Publishing.
- Rosen, D., A. Erdman, and D. Riley. 1987. "A General Design Knowledge Based System Shell with Application to Dwell Mechanism Design." In Proceedings of the 1987 ASME International Computers in Engineering Conference and Exhibition, New York.
- Rosenman, M., and J. Gero. 1985. "Design Codes as Expert Systems." Computer-Aided Design, 17(9).
- Rosenman, M., J. Gero, and R. Oxman. 1986. "An Expert System for Design Codes and Design Rules." Applications of Artificial Intelligence to Engineering Problems.
- Rosenman, M., J. S. Gero, P. Hutchinson, and R. Oxman. 1986. "Expert Systems Applications in Computer-Aided Designs." Computer Aided Design, 18(10):546-551.
- Schmitt, G. 1985a. Microcomputer Based Energy Design Expert Systems. Research Report Series: DA85-09. Department of Architecture, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Schmitt, G. February, 1985b. "Microcomputer-Based Integrated Energy Design Expert Systems: A Powerful New Tool." In Proceedings of the First National Conference on Microcomputer Applications for Fenestration and Renewable Energy, pp. 289-294, NCMACRE, Tuscon, Arizona.
- Schmitt, G. 1986. "Project CAESAR: Towards Quality Decision in CAD." Research Report Series: DA86-13, Department of Architecture, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Schmitt, G. 1987a. "Expert Systems in Design Abstraction and Evaluation." Computability of Design, ed. Y. E. Kalay, pp. 213-244. J. Wiley and Sons, New York.

- Schmitt, G. 1987b. ARCHPLAN - An Architectural Front End to Engineering Design Expert Systems. Report EDRC-48-04-87, Engineering Design Research Center, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Selkowitz, S., K. M. Papamichael, and M. Wilde. 1986. "A Concept for an Advanced Computer-Based Building Envelope Design Tool." In Proceedings of the 1986 International Daylighting Conference, November 4-7, Long Beach, California, pp. 496-502.
- Smith, S., M. Fox, and P. Ow. 1986. "Constructing and Maintaining Detailed Production Plans: Investigations into the Development of Knowledge-Based Factory Scheduling Systems." AI Magazine 7(4):45-60.
- Sriram, D., M. Maher, and S. Fenves. 1984. Knowledge-Based Expert Systems in Structural Design. Carnegie Mellon University, Pittsburgh, Pennsylvania.
- Sriram, D. 1986. Knowledge-Based Approaches for Structural Design. Ph.D. Thesis, Carnegie-Mellon University, Pittsburgh, Pennsylvania.
- Stefik, M. 1981a. "Planning and Meta-Planning (MOLGEN: Part 2)." Artificial Intelligence 16:141-170.
- Stefik, M. 1981b. "Planning and Meta-Planning (MOLGEN: Part 2)." Artificial Intelligence 16:111-140.
- Stefik, M., J. Aikins, R. Balzer, J. Benoit, L. Birnbaum, F. Hayes-Roth, and E. Sacerdoti. 1983. "The Architecture of Expert Systems." In Building Expert Systems, eds. F. Hayes-Roth, D. Waterman and D. Lenat, pp. 89-126. Addison-Wesley, Reading, Massachusetts.
- Swerdloff, L. M., and Y. E. Kalay. 1987. "A Partnership Approach to CAD." Computability of Design, ed. Y. E. Kalay, pp. 315-336. Wiley, New York.

BIBLIOGRAPHY

- Barr, A. and E. A. Feigenbaum (Eds.). 1981. The Handbook of Artificial Intelligence, volume 1.
- Cohen, P. R. and E. A. Feighenbaum. 1983. The Handbook of Artificial Intelligence, volume 3.
- Forsyth, R. and C. Naylor. 1985. The Hitch Hiker's Guide to Artificial Intelligence. Chapman and Hall/Methuen.
- Hart, A. 1986. Knowledge Acquisition for Expert Systems, McGraw-Hill.
- Hayes-Roth, F., D. A. Waterman, and D. Lenat (Eds.). 1983. Building Expert Systems, Addison-Wesley.

- Keller, R. 1987. Expert System Technology: Development and Application. Jourdon Press, Englewood Cliffs, New Jersey.
- Plahr, P. and D. Waterman (Eds.). 1986. Expert Systems: Techniques, Tools, and Applications. Addison-Wesley, Reading, Massachusetts.
- Negoita, C. V. 1985. Expert Systems and Fuzzy Systems. The Benjamin/Cummings Publishing Co. Inc.
- Nilsson, N. 1980. Principles of Artificial Intelligence. Tioga Pub. Co., Palo Alto, California.
- Rolston, D. W. 1988. Principles of Artificial Intelligence and Expert System Development. McGraw-Hill.
- Waterman, D. A. 1986. A Guide to Expert Systems. Addison-Wesley Publishing Co.
- Weiss, S. and C. Kulikowski. 1984. A Practical Guide to Designing Expert Systems. Towman and Allanhead, Totowa, New Jersey.

APPENDIX E

POTENTIAL APPLICATIONS FOR INTELLIGENT COMPUTER-BASED DESIGN AND OPERATION TECHNOLOGIES

APPENDIX E

POTENTIAL APPLICATIONS FOR INTELLIGENT COMPUTER-BASED DESIGN AND OPERATION TECHNOLOGIES

The technologies proposed for development by this research would apply to decisions about all major building energy systems. Also, they would provide knowledge and decision assistance for all phases of the building life cycle. To indicate the scope of the intended products, application areas are identified in this appendix.

APPLICATION CATEGORIES

The technologies would have two main application areas: new and existing buildings. Within these, the numerous building design, construction, and operation decisions over the building life cycle have been grouped into nine major application areas: building programming, design, construction, commissioning, monitoring, diagnosis, rehabilitation, operation, and controls. The major application areas are depicted in Figure E.1. The AEDOT research project would concern design of new buildings as well as operation and maintenance of both new and existing buildings. Applications of the technologies to retrofit and rehabilitation would be natural extensions of this project, but are not currently part of the recommendations.

The decisions within each of the application areas involve many distinct technical issues. The complexity of each application area is discussed in the sections that follow. The overall importance of these applications is summarized in the final section of this appendix.

NEW BUILDINGS

As Figure E.1 shows, the major applications for new buildings are

- programming
- design

FIGURE E.1. Application Areas for the Proposed Design and Operation Technologies

- construction
- commissioning.

The potential for improving building energy conservation for these four areas is discussed below.

Programming

Building programming involves identifying and defining the design needs of a facility and communicating the client's needs to the designer (Heidel and Deringer 1987). Programming activities determine goals, objectives, criteria, requirements, and constraints for the building or for specific building systems. Building programming occurs at several phases of every building project, before each phase of design synthesis. This can range from notes on a napkin at dinner to verbal goals, to requirements and constraints given by telephone, to lengthy reports supported by rigorous analysis. The information that is generated provides a rich source for the designer to use in making design decisions in general and energy decisions in particular.

Current building programming methodologies provide a strong base for building energy design decision models and systems. Current programming methodologies only partially address energy issues. In the proposed research, methods and tools would be developed to greatly enhance and extend building programming products to improve the information basis for energy-related design decisions.

Design

This is potentially a major application area, but several obstacles must be overcome. As indicated above, current design methods are unstructured and largely intuitive, and present many obstacles to good energy decision making. Much research needs to be done in this area before satisfactory knowledge-based methods and systems can be developed to provide direct assistance in this area. (Much of the proposed research for new buildings would likely also apply to building retrofit and to major building rehabilitation.) Research on design applications can focus on specific physical parts of a building or on whole-building system interactions. This includes interactions among the major energy subsystems that affect both the energy consumption and the economics of the building.

Building Subsystems

Design decisions for each building subsystem or material component are important topics for energy design process research. The intent is to provide

decision assistance for the detailed design of the major building energy subsystems, components, and materials. An overview of the building subsystems that should be of interest in this project and the relative priorities assigned to each by Heidel and Deringer (1987) are given in Table E.1.

Given the energy end-use mix of commercial buildings, the areas assigned the highest priority for decision research are system selection for lighting, HVAC, and envelope systems. While not shown in Table E.1, envelope analyses should also be categorized into separate aspects of system selection and detailed system design. For certain commercial building types and functions, daylighting,^(a) water heating,^(b) cooking,^(c) and refrigeration^(d) are also of high priority.

Whole-Building Interactions

The highest expected benefits would be from application of AEDOT research to the interactions among major building energy-related subsystems. These are shown in Figure E.2.

This domain is more complex than the individual building subsystems because of its breadth. Energy-related design process research in this area should address the core of the building design decision process in the early design stages. This is when tradeoffs among major alternative strategies and subsystems are considered and made. Such decisions and tradeoffs cannot be made for each subsystem in isolation from the other subsystems because decisions for each impact the others.

-
- (a) Especially for such building types and functions as offices, schools, and storage.
 - (b) Especially for hotels, but also for apartments, hospitals, and nursing homes.
 - (c) Especially for restaurants.
 - (d) Especially for grocery stores.

TABLE E.1. Building Subsystems: Areas for Design Process Research with Priorities Assigned by Heidel and Deringer (1987)

SUBSYSTEM	SELECTED DESIGN PROCESS RESEARCH AREAS	PRIORITY ^(a)
HVAC	System selection System design Component Efficiency Controls Zoning Thermal Comfort	1 2 3 1 2 1
Lighting	System selection System design Component Efficiency Controls Illumination criteria and productivity	1 2 3 1 1
Envelope	Fenestration Opaque elements (roof, wall, etc.) Conduction, including: Thermal breaks Moisture impacts Solar effects Thermal mass Infiltration	1 2 3 3 2
Daylighting	Systems Controls Window management Interface with other subsystems	2 2 2 1
Water Heating	Systems O&M Losses	2 2 2
(a) Lower numbers indicate higher priority.

FIGURE E.2. Whole Building Framework

Energy and Economic Analysis Activities

Several AEDOT applications could significantly improve both the capability and usability of existing energy and economic analysis activities and tools. For example, specialized energy design decision methods and related KBSs could be used to reduce the often sizable amount of expertise now required to competently use energy and economic analysis tools. For example, knowledgeable DOE-2 users estimate that it takes about 2 months of full-time effort to become competent (not expert) in using DOE-2 because of its complexity. Some sample applications for the proposed AEDOT technologies are

- diagnostics for energy analysis tool inputs
- diagnostics for energy analysis tool outputs

- diagnostics for economic analysis tools
- real-time interactive energy and economics modeling.

Building Construction

Research into decisions made during construction should focus on the energy impacts of change orders and of quality control procedures. One important result of this research would be intelligent computer-based systems to assist in assessing change orders and in monitoring quality control during building construction.

Building Commissioning

Research and development activities in this area should address computer-based systems that provide guidance in checking and diagnosing all of the factors involved in building turnover from contractor to owner.

EXISTING BUILDINGS

The first step in attempting to improve the energy efficiency of existing buildings is to survey and analyze the condition of the building systems, the building operation practices, and the building's energy consumption profile. This way, specific characteristics that need to be modified can be identified. Only then can the proper design of modifications or improvements to the building begin. The actual design procedure for retrofits is very similar, in principle, to that for new buildings: identify energy opportunities, select energy conservation options, design strategies, install or construct improvements, and turn over the building to users. However, priorities are significantly different from those for new building design because the existing building imposes additional constraints.

Potential applications of the technologies planned for development in the AEDOT project to existing buildings are

- operation and maintenance
- survey and analysis
- retrofit of some building features

- major rehabilitation of buildings.

Only building operation and maintenance, which apply to both new and existing buildings, are now part of the proposed AEDOT project. However, the technologies that would be developed in this project would likely show great promise for adaptation, with some modifications, to the other areas.

Survey, Monitoring, and Analysis Applications

Existing buildings have characteristics that an expert may recognize as significant to energy demand and consumption. Existing buildings often contain peculiarities or unexpected features or operations. Understanding how an existing building works often requires considerable skill and expertise. Important features are often not obvious to the untrained. Numerous examples can be given of audits that collected detailed data on building features that have little or no impact on energy consumption but ignored collecting data on important energy features.

Matching actual building consumption to estimates from analysis tools is the technique currently used to evaluate existing building operation conditions. Identifying possible causes of discrepancies between energy audit data and energy analysis estimates is another valuable type of expert assistance that is needed. Even seasoned energy analysts can have difficulty with this task.

Potential areas for application of intelligent computer-based assistance in operation and maintenance are monitoring, diagnosis, and control. A great deal of knowledge about the details of building operations would likely come from the extensive building field data acquisition projects now being conducted (for example, from the BPA's ELCAP project) and from building operators themselves.

The operation systems resulting from the AEDOT project should ultimately provide energy-decision assistance for complete facilities management. Such systems for new buildings might use a single building database to provide continuity of decision making and recording of physical changes to a building over its entire life span from initial concept through its design, construction, operation, and renovation, to its ultimate demolition. Data on

performance would be fed back to designers (and the design assistance machine) for evaluation and updating of design knowledge bases with the objective of ultimately improving energy design.

The proposed research program would focus first on the impacts that decisions during design potentially have on building operations, and then later on building operations issues from a facilities management point of view. Part of the initial activity would focus on the transfer or need for transfer of information (data) between stages of the building life cycle.

Considerable activity is already occurring for building operations and control. Work on "intelligent" or "smart" buildings and "smart" building subsystems, which operate using a knowledge base to exercise control and which can "learn" from experience in the sense of anticipating desired performance based on earlier patterns observed, is already in progress. For example, the National Electrical Manufacturers Association (NEMA) has formed a task force to examine the potential for smart buildings, and the AIA has held a symposium. Also, building control manufacturers will most likely adopt KBS technologies to incorporate increasing amounts of "expertise" into their control devices. As mentioned earlier, several controls manufacturers are active in this area. In some sense, this is an expansion of existing control systems for both individual systems and overall building EMCS. This work is needed because building managers and operators (even professional managers) often misunderstand how buildings are actually operating.

SUMMARY OF APPLICATIONS

Once completed, the proposed intelligent computer-based systems would be capable of providing assistance for all stages of design for new buildings and for operation and maintenance of both new and existing buildings. However, during the development stages of this project, a priority may need to be assigned to each application. The priority should be based on

- level of impact on building energy efficiency
- degree of complexity/amount of time required
- relationship to other application areas

- level of ongoing activity in the application area.

The greatest level of effort would be required for developing decision models for new building design. As a result, early project work (approximately the first 4.5 years) should focus on design. One of the greatest impacts on the energy efficiency of new buildings is determined by the programming activities, and this would be given special consideration in AEDOT research.

Most ongoing knowledge-based work by other researchers is in the areas of energy audit and HVAC diagnosis for existing buildings. These activities both are relatively narrow in focus, but the understanding and experience gained by these researchers would be most beneficial to developing decision models for operation and maintenance of new and existing buildings. These sources of knowledge should be carefully integrated into the project at appropriate times.

REFERENCE

Heidel, J. A., and J. J. Deringer. 1987. Developing an Energy Design Tool--Phase I Report. PNL-5709, Pacific Northwest Laboratory, Richland, Washington.

APPENDIX F

PRINCIPAL AREAS FOR KNOWLEDGE ACQUISITION

APPENDIX F

PRINCIPAL AREAS FOR KNOWLEDGE ACQUISITION

BUILDING DESIGN

Building Design Process

Design, in general, is largely a process of integrating technology and the designer's skills with constraints imposed by the problem, the technology, the designer, and the designer's client to satisfy a set of requirements. The purpose of design is to construct a structural description of an object that

- meets both qualitative and quantitative requirements (i.e., what characteristics the object must possess)
- conforms to constraints, limitations, and restrictions (i.e., what properties the object must not have)
- satisfies functional specifications.

In addition to the design, which is the primary product of the design process, additional products can result that ordinarily might not be made explicit.

Examples include

- documentation specifying how to use the structure
- justification that the structure is correct and complete
- justification of the design decisions and rationale.

The knowledge acquisition activity associated with the building design process must determine the knowledge, the data, and the transformations that lead to the primary and secondary products of design. Also, the stages of design must be thoroughly understood and a model of the design process constructed. The stages of design include activities like development of bubble charts, architect's drawings, and architect's plans (Zachman 1987), or project planning, predesign, schematic design, and detailed design development

(Heidell and Deringer 1987). According to Mostow (1987), a comprehensive model of design should include

- design states and history
- design/problem goal structure
- design decision options and rationale
- design process control
- learning process.

This list illustrates the complexity of information that must be gathered and modeled as both data and processes in order for a design system to be built. The specific information that results from study of the building design process is what distinguishes building design from other types of design, but that information can be classified into broad categories that are more universally applicable.

Energy Design

The general types of knowledge that must be acquired on energy-efficient building design are largely the same as those for building design. However, additional areas for knowledge acquisition must be pursued. These areas include methods for energy analysis and how and when they are integrated into the building design process.

Building Life Cycle

The building life cycle includes design, construction, commissioning, operation/maintenance, and modification. Each stage has both unique knowledge requirements and requirements common to other stages of the building life cycle. Also, each stage can impact others. For example, a building design is transformed to the as-built structure, which, because of construction requirements and constraints, may differ in some ways from the original design. In some cases, this will affect the energy efficiency of the building during operation. Each stage of the life cycle must be characterized during the Requirements Analysis so that interactions between stages are understood and systems that adequately account for these interactions can be developed.

COMPUTER AUTOMATION

Hardware and Software Requirements

A final product of the Requirements Analysis would be a set of requirements that specifies hardware and software properties anticipated to be necessary to implement an automated system for energy-efficient building design. The Requirements Analysis task would provide the initial set of requirements, which would be refined, modified and developed further as part of System Development.

Hardware requirements pertain to disk storage, memory, execution speed, processing architecture, screen attributes, output devices, networking, and software and graphics capabilities. Software requirements concern operating systems, languages, windowing systems, editors, database systems, networking, software tools/products such as existing and anticipated CABD and CADD systems, and the design modules that would be developed as part of the AEDOT project.

System Integration

For a computer system to implement the AEDOT concept, it would require, as a minimum, hardware components consisting of a computer, input devices (e.g., a mouse and electronic sketch pad), and output devices (e.g., printers and plotters). The system must also have the capability to network with a number of other computers. The components must be integrated so that they perform as a whole. To users, the component makeup must be transparent, and the system must appear to be a single unit.

The system must provide for control of and communication between several components. This includes physical connection of hardware and inter-process communication for software. The communication system must provide connections (handshake) between components of the integrated system, regulate connection, break connection, and manage other connection requests while engaged in a communication session. Control in this context concerns managing component communication, i.e., the control system must determine system priorities, allow communication, and synchronize the use of data, files, and computation.

Networking should be reviewed as part of the Requirements Analysis so that appropriate associated requirements can be established. These requirements would be refined and updated as additional details are developed in the System and Component Development tasks of the AEDOT project.

Artificial Intelligence (AI) and Knowledge Representation

Issues concerning artificial intelligence and knowledge representation include the storage, manipulation, and presentation of knowledge. Manipulation includes retrieval, transformation (if necessary), and execution (including inferencing) using knowledge. Presentation issues involve graphics, logical representation of information, and intelligent interfaces. One potential capability of intelligent interfaces might be to develop models of individual users based on past interactions with each user. These models would account for the users' expectations and perspectives.

Areas of AI that would require exploration during the Requirements Analysis are intelligent interfaces, database technology, object-oriented programming (smart data), inference mechanisms, and knowledge representation schemes.

Computer Graphics, Imaging, Visualization and Information Input/Output

Building designers tend to think in visual terms, and many building design decisions are based on evaluation of visual information. Therefore, sophisticated capabilities for visualizing interior and exterior building environments should be incorporated into the AEDOT design systems to enhance the designer's ability to assess design states and make decisions.

The interface between the designer and the AEDOT tools would rely heavily on visual representations of information and data. Figures would be developed as solid figures or wire frames, possibly with shading and surface texture. The method used would depend on the particular application and stage of design. Non-text graphics may require capabilities in real time and non-real time for rotation, pan, zoom, and animation. It is therefore crucial to the success of the proposed AEDOT project that it utilize the best technologies available to create, store, manipulate, and present visual information to designers.

The goals of the Imaging/Visualization component of the AEDOT project would be to identify, evaluate, and develop technologies for generation, manipulation, and display of visual information. The visualization needs of the various members of a design team would be assessed in the Requirements Analysis as functions of the design task and the stage of the design process. The result would be a specification of the needs of the designer (i.e., a set of requirements on the computer-based design system), an evaluation of the ability to meet those needs economically using available technology, and a specification of developments required to fulfill needs that current technology cannot satisfy.

Initial work is now under way at Lawrence Berkeley Laboratory under the direction of Steve Selkowitz. This work includes 1) performing a needs assessment, 2) surveying imaging technologies and visualization tools, and 3) testing and evaluating alternative imaging technologies. These tasks would be necessary components of the AEDOT Requirements Analysis and should be classified as part of it. Because these activities are already in progress, specification of the graphics and visualization requirements should be completed earlier than other parts of the Requirements Analysis. Upon completion, actual research and development of the AEDOT visualization capabilities should begin as part of Component Development. Specific activities are yet to be identified as part of the tasks in progress.

MAN-MACHINE INTEGRATION

Task Allocation

Responsibility for the performance of tasks must be allocated between human designers and the machine. This allocation must be clearly defined in the requirements specification. The allocation of tasks implicitly specifies the working relationship between humans and the machine and must be psychologically and cognitively acceptable to the user. Adequate treatment of human factors issues helps ensure an optimal allocation of tasks and an acceptable working relationship.

Human Factors

If an automated system requires interaction with a human user but the man-machine integration is inadequate, then the automated system (regardless of the capability of the machine to perform its required tasks) will be unacceptable to the user and thus a failure. In general, the frequently observed lack of user acceptance of intelligent systems is attributed to unfamiliarity with computer technology, difficulty in adjusting to the interface, fear of replacement, and a feeling that the user can perform the task better than the machine (Rohm 1987). Some examples of specific human factor issues are ease of learning the system, ease of system use, and degree of belief in the system output (i.e., results and assessments provided by the machine).

Areas related to human factors that would require examination are

- task analysis
- task information requirements
- interface design.

Task analysis consists of describing the psychological and physical tasks and subtasks which must be completed by the machine or the human in order to satisfy requirements on system operation and performance.

Information required for each task must be determined, whether the task is completed by the human or the machine. Allocation of responsibility for providing this information and the proper form for that information are important issues having a direct effect on the user. The user must also be provided sufficient information so that conclusions drawn by the machine can be evaluated, then accepted and believed (or rejected).

Interface design must consider the effects on, and capabilities of, the user working with the system. A good interface takes optimal advantage of the user's sensory-motor and cognitive abilities. Every user has in mind some overall goal as well as subgoals in interacting with a system; the system must satisfy these. In addition, automated systems should be both psychologically and physically easy to use (Norman 1986). Users also often want to

understand what the system is doing. This understanding can be facilitated by models of how the system works depicted in system displays (Gordon 1987).

These and other human-factor issues that might be identified during the investigation of the building design process should be addressed in the Requirements Analysis.

REFERENCES

- Gordon, S. E. 1987. "Focusing on the Human Factor in Expert Systems." Paper presented at the Topical Meeting on Artificial Intelligence and Other Innovative Applications in the Nuclear Industry: Present and Future, An American Nuclear Society Topical Meeting, September 1987, Snowbird, Utah.
- Heidel, J. A., and J. J. Deringer. 1987. Developing an Energy Design Tool--Phase I Report. PNL-5709, Pacific Northwest Laboratory, Richland, Washington.
- Mostow, J. 1985. "Towards Better Models of the Design Process." AI Magazine 6(1):44-57.
- Norman, D. A. 1986. "Cognitive Engineering." In User Centered System Design, D. A. Norman and S. W. Draper, eds., Lawrence Erlbaum Associates, Hillsdale, New Jersey.
- Rohm, H. H. 1988. "Advanced Technology for Nuclear Power Plants." Paper presented at the Topical Meeting on Artificial Intelligence and Other Innovative Applications in the Nuclear Industry: Present and Future, An American Nuclear Society Topical Meeting, September 1987, Snowbird, Utah.
- Zachman, J. A. 1987. "Framework for Information System Architecture." IBM Systems J. 26(3):276-292.

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>	
10	DOE/Office of Scientific and Technical Information F. Abel U.S. Department of Energy 1000 Independence Ave., SW Forrestal Building, CE-13 5E-098 Washington, DC 20585		L. Abernethy IBM P.O. Box 10501 Stamford, CT 06904-2501
		3	M. Addison 701 S. Roosevelt, Apartment 109 Tempe, AZ 85281
10	M. Bailey U.S. Department of Energy 1000 Independence Ave., SW Forrestal Building, CE-131 5E-098 Washington, DC 20585		O. Ahmed Beling Consultants 7620 N. University St. Suite 2200 Peoria, IL 61614
10	J. Boulin U.S. Department of Energy 1000 Independence Ave., SW Forrestal Building, CE-131 5E-098 Washington, DC 20585		H. Akbari Lawrence Berkeley Laboratory Building 90 Berkeley, CA 94720
	T. Kurkowski U.S. Department of Energy 1000 Independence Ave., SW Forrestal Building, CE-30.1 6C-026 Washington, DC 20585		J. Amber Amber Associates 716 S. Elm Boulevard Champaign, IL 61820-5806
	J. Millhone U.S. Department of Energy 1000 Independence Ave., SW Forrestal Building, CE-13 5E-098 Washington, DC 20585		H. Amistadi Cornerstones-Wright, Inc. P.O. Box 4904 Portland, ME 04112
	J. Smith U.S. Department of Energy 1000 Independence Ave., SW Forrestal Building, CE-131 5E-098 Washington, DC 20585		B. Anderson Lawrence Berkeley Laboratory Building 90 Berkeley, CA 94720
			T. Armstrong IBM Corporation 472 Wheelers Farm Road Milford, CT 06460

No. of
Copies

E. Bales
NJ Institute of Technology
Building Engineering and
Architecture Research Center
Newark, NJ 07102

J. Barron
NYSEDA
Two Rockefeller Plaza
Albany, NY 12223

D. Beranek
Headquarters, USACE
20 Massachusetts Ave., NW
Washington, DC 20314

C. Bovill
University of Tennessee
1715 Volunteer Blvd.
Knoxville, TN 37996

D. Branson
Fanning, Fanning and Associates
2555 74th St.
Lubbock, TX 79423

M. Bray
EG&G Idaho, Incorporated
P.O. Box 1625
Idaho Falls, ID 83415

P. Brothers
Johnson Controls
P.O. Box 423
Milwaukee, WI 53201

G. Brown
University of Oregon
Department of Architecture
Eugene, OR 97403

J. Bruce
Bureau of Buildings Management
1603 City Hall
900 E. Broad St.
Richmond, VA 23219

No. of
Copies

S. Byrne
Lawrence Berkeley Laboratory
Building 90-3125
Berkeley, CA 94720

G. Caan
Washington State Energy Office
809 Legion Way SE FA-11
Olympia, WA 98504

K. Capps
Johnson Controls, Inc.
P.O. Box 423
Milwaukee, WI 53201

L. Carmichael
Electric Power Research
Institute
P.O. Box 10412
Palo Alto, CA 94303

S. Chandra
Florida Solar Energy Center
300 State Road 401
Cape Canaveral, FL 32920

J. Chang
FlexiCad
3508 Market Street
Suite 210
Philadelphia, PA 19104

D. Claridge
Texas A&M University
Department of Architecture
College Station, TX 77843

C. Cleary
Seattle City Light
1015 Third Avenue
Seattle, WA 98104

M. Cohen
Cornell University
120 Rand Hall
Ithaca, NY 14853

No. of
Copies

3 C. Culp
Honeywell Inc.
1500 West Dundee Road
Arlington Heights, IL 60004

J. Deringer
The Deringer Group
1349 Addison Street
Berkeley, CA 94702

M. Digiovanni
Albert Kahn
700 New Center Building
Detroit, MI 48202

L. Downing
Stueven Associates
924 Westwood Blvd., Suite 330
Los Angeles, CA 90024

J. Eberhard
Building Research Board
2101 Constitution Avenue
Washington, DC 20418

T. Edmann
Honeywell Incorporated
Honeywell Plaza, MN27-4156
Minneapolis, MN 55408

N. Fedoruk
Energy Conservation Coalition
1525 New Hampshire Ave., NW
Washington, DC 20036

S. Fenves
Carnegie Mellon University
Department of Civil Engineering
Pittsburgh, PA 15213

F. Ferreira
Ferreira and Kalasinsky
Associates
13 Welby Road
New Bedford, MA 02745

No. of
Copies

G. Finn
Stone & Webster Engineering
Corporation
P.O. Box 2325
Boston, MA 02107

T. Fischer
Honeywell Incorporated
Honeywell Plaza
Minneapolis, MN 55408

B. Flake
Air Force Institute of
Technology
AFIT/DEE
Wright Patterson, OH 45433

U. Flemming
Carnegie Mellon University
Department of Architecture
Pittsburgh, PA 15213

C. Gardner
Puget Energy Systems
1750 112th NE, Suite E175
Bellevue, WA 98004

H. Gordon
Burt Hill Stinson Cappelli
1056 Thomas Jefferson St.
Washington, DC 20007

G. Gupton
Gupton Engineering
3109 Maple Drive, NE
Atlanta, GA 30305

J. Haberl
Princeton University
Engineering Quadrangle
Princeton, NJ 08544

3 J. Hall
The Deringer Group
Box 299
Riva, MD 21140

No. of
Copies

J. Heidell
Synergic Resources Corporation
1511 Third Ave., Suite 1016
Seattle, WA 98101

D. Herron
U.S. Army Corps of Engineers
P.O. Box 4005
Champaign, IL 61820

J. Hill
National Institute of Standards
and Technology
Building 226, Room B306
Gaithersburg, MD 20899

D. Hittle
Ray W. Herrick Laboratory
State St., Purdue University
West Lafayette, IN 47907

J. Huang
Lawrence Berkeley Laboratory
Building 90
Berkeley, CA 94720

R. Johnson
University of Michigan
2000 Bonisteel Blvd.
Ann Arbor, MI 48109

J. Jones
University of Texas at Austin
Engineering Teaching Center
Austin, TX 78712

R. Jones
Hussmann Corporation
12999 St. Charles Rock Road
Bridgeton, MO 63044

Y. Kalay
University of New York at
Buffalo
235 Hayes Hall
Buffalo, NY 14214

No. of
Copies

J. Kim
Lawrence Berkeley Laboratory
Building 90
Berkeley, CA 94720

M. Kim
University of Illinois
608 Taft Drive
Champaign, IL 61820

J. Klems
Lawrence Berkeley Laboratory
Building 90-3111
Berkeley, CA 94720

E. Knipe
Brown and Caldwell
P.O. Box 7103
Pasadena, CA 91109

L. Lawrie
U.S. Army Corps of Engineers
P.O. Box 4005
Champaign, IL 61820

M. Ledbetter
ACEEE
1001 Connecticut Ave., NW
Suite 535
Washington, DC 20036

V. Loftness
Carnegie Mellon University
Department of Architecture
Pittsburgh, PA 15213

P. McIntosh
College of Architecture and
Engineering
Arizona State University
Tempe, AZ 85287

J. McIntosh
College of Architecture and
Engineering
Arizona State University
Tempe, AZ 85287

No. of
Copies

H. Mileaf
McGraw Hill
1221 Avenue of the Americas
New York, NY 10020

R. Miller
Johnson Controls, Incorporated
P.O. Box 423
Milwaukee, WI 53201

H. Misuriello
W.S. Fleming & Associates, Inc.
1511 K St. NW, Suite 331
Washington, DC 20005

J. Nation
CAER Engineers, Incorporated
814 Eleventh St.
Golden, CO 80401

L. Norford
Massachusetts Institute of
Technology
77 Massachusetts Ave.
Building 3/#434
Cambridge, MA 02139

R. Norton
City of San Jose, California
801 N. First St., Room 500
San Jose, CA 95110

B. Novell
Intergraph Corporation
1 Madison Industrial Park
Huntsville, AL 35807

H. Pakravan
Control Data Corporation
8100 34th Avenue South
Minneapolis, MN 55440

K. Papamichael
Lawrence Berkeley Laboratory
Building 90
Berkeley, CA 94720

No. of
Copies

N. Patterson
The Trane Company
3600 Pammel Creek Road
La Crosse, WI 54601

C. Pedersen
University of Illinois
1206 W. Green St.
Urbana, IL 61801

A. Persily
National Institute of Standards
and Technology
Building 226, Room B114
Gaithersburg, MD 20899

W. Place
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

A. Rabl
Princeton University
CEES
Princeton, NJ 08544

V. Rabl
Electric Power Research
Institute
P.O. Box 10412
Palo Alto, CA 94303

K. Reed
National Institute of Standards
and Technology
Building 226, Room B306
Gaithersburg, MD 20899

K. Reinschmidt
Stone & Webster Engineering
P.O. Box 2325
Boston, MA 02107

No. of
Copies

No. of
Copies

	R. Renz IBM Corporation 472 Wheelers Farm Road Milford, CT 06460		C. Sherman Energy Simulation Specialists 64 E. Broadway Road, Suite 230 Tempe, AZ 85282
	R. Ritchard Lawrence Berkeley Laboratory Building 90 Berkeley, CA 94720		C. Sloup Energroup Incorporated 1815 Capitol Avenue Omaha, NB 68102
	R. Rittelmann Burt Hill Kosar Rittelmann Associates 400 Morgan Center Butler, PA 16001		P. Smeallie Building Research Board 2101 Constitution Ave., NW Washington, DC 20418
5	J. Rivera D&R International 962 Wayne Avenue Silver Spring, MD 20910		R. Socolow Princeton University CEES Princeton, NJ 08544
	A. Rosenfeld Lawrence Berkeley Laboratory 1 Cyclotron Road, Building 90 Berkeley, CA 94720		R. Sonderegger Morgan Systems Corporation 1654 Solano Avenue Berkeley, CA 94707
	F. Rubinstein Lawrence Berkeley Laboratory Building 90 Berkeley, CA 94720		D. Spethmann Honeywell, Incorporated 1500 W. Dundee Road Arlington Heights, IL 60004
	P. Scarponcini McDonnell Douglas 325 McDonnell Blvd., C994/305/4W Hazelwood, MO 63042		R. Sullivan Lawrence Berkeley Laboratory Building 90 Berkeley, CA 94720
	G. Schmitt Carnegie Mellon University Department of Architecture Pittsburgh, PA 15213		S. Treado National Institute of Standards and Technology Room A-313, Building 226 Gaithersburg, MD 20899
5	S. Selkowitz Lawrence Berkeley Laboratory 1 Cyclotron Road, Building 90-3111 Berkeley, CA 94720		P. Tseng Montgomery County Government 110 N Washington St. Rockville, MD 20850

No. of
Copies

P. Tuft
City of San Jose
801 North First St., Room 4
San Jose, CA 95110

T. Usibelli
Washington State Energy Office
809 Legion Way SE FA-11
Olympia, WA 98504

C. Van Wyk
School of Architecture
190 West 17th Ave.
189 Brown Hall
Columbus, OH 43210

G. Ward
Lawrence Berkeley Laboratory
Building 90
Berkeley, CA 94720

J. Warner
ACEC
1015 15th Street NW
Suite 802
Washington, DC 20005

J. Westburg
Arizona Energy Office
Capitol Tower, 5th Floor
1700 W. Washington St.
Phoenix, AZ 85007

M. Wilde
Lawrence Berkeley Laboratory
Building 90-3111
Berkeley, CA 94720

J. Williams
Third Party Applications
Autodesk, Inc.
2320 Marinship Way
Sausalito, CA 94965

No. of
Copies

W. Wood
Honeywell, Incorporated
Honeywell Plaza
Minneapolis, MN 55408

J. Woods
Honeywell, Incorporated
1985 Douglas Drive North
Golden Valley, MN 55422-3992

FOREIGN

G. Biviano
Division of Building Research
P.O. Box 56, Graham Road
Highett, Victoria
AUSTRALIA

J. Clarke
University of Strathclyde
131 Rottenrow
Glasgow, G4 ONG
SCOTLAND, UNITED KINGDOM

V. Crisp
Building Research Establishment
Building Research Station
Garston, Watford WD2 7JR
UNITED KINGDOM

K. James
Knowledge Transfer
P.O. Box 314/Station "A"
Ottawa, Ontario K1N 6A0
CANADA

R. Kohonen
Technical Research Centre of
Finland
Laboratory of Heating and
Ventilation
Lampomiehenuja 3
SF-02150 ESP00
FINLAND

No. of
Copies

P. Lund
Helsinki University of
Technology
Department of Technical Physics
SF-02150 S2EP00 Helsinki
FINLAND

M. Mason
Mechanical Building Services
Group
ACADS
576 St. Kilda Road
Melbourne
AUSTRALIA 3004

G. Mitalas
IRC
Building Services Section
Ottawa, Ontario K1A 0R6
CANADA

B. Puppa
BC Hydro
1265 Howe St.
Vancouver, BC V6Z 2C8
CANADA

A. Radford
Department of Architectural
Science
The University of Sydney
NSW 20006
AUSTRALIA

K. Rao
Department of Building Science
National University of Singapore
Kent Ridge, Singapore 0511
SINGAPORE

K. Ruberg
IRC
Building M-20
Ottawa, Ontario A1A 0R6
CANADA

No. of
Copies

J. Saarimaa
Technical Research Centre of
Finland
Laboratory of Structural
Engineering
Betonimiehenkuja 3
SF-02150 ESP00
FINLAND

R. Sinha
Scanada Consultants
436 MacLaren
Ottawa, Ontario K2P 0M8
CANADA

F. Vaculik
Public Works Canada
Riverside Drive, Room A430
Ottawa, Ontario K1A 0M2
CANADA

D. Vanier
National Research Council Canada
Building Services Section
Ottawa, Ontario K1A 0R6
CANADA

B. Wanggren
Monitoring Center for Energy
Research
Royal Institute of Technology
Brinellvagen 34
S-100 44 Stockholm
SWEDEN

No. of
Copies

ONSITE

3 DOE Richland Operations Office

R. F. Christensen, A5-90
D. R. Segna, A5-90
J. J. Sutey, A5-90

2 Kaiser Engineers Hanford

D. W. Dean
M. S. Rees

56 Pacific Northwest Laboratory

J. F. Bagley, K1-45
M. R. Brambley (15), K5-20
R. L. Cheatham, K1-82
D. B. Crawley (15), K5-20
R. S. Crowder, K1-86
J. W. Currie, K6-66
D. D. Hostetler (3), K1-86
B. M. Johnson, K5-12
R. B. Melton, K2-26
R. W. Reilly, K6-61
R. G. Rivera, K6-69
T. J. Secrest (5), K5-20
G. M. Stokes, K2-51
R. C. Stratton (3), K1-86
R. O. Weijs, K6-54
Publishing Coordination
Technical Report Files (5)