ADVANCES IN BUILDING SIMULATION

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In recent years. researchers, designers and contractors have begun to investigate the use of new technologies in building construction and operation.The search for more efficient designs has led to complex and difficult to analyze components, systems, and whole building structures. Existing building energy simulation programs were initially conceived in an era when design questions were simpler than they are today. As a result, there are fundamental limitations in the analysis capabilities of these programs. In particular, techniques have not been developed that allow realistic simulation of the interactions between building envelope, architectural components and mechanical equipment and their controls in a generalized, integrated and easily extendible manner. Analysis of complex designs and advanced technologies requires superior capabilities of the next generation of building performance simulation programs.

In five to ten years, the use of computer-aided design (CAD) systems for buildings will be commonplace; expert systems will be developed to improve decision making in architectural and engineering design and operational problems; and energy management systems will increasingly be used for building control, monitoring and diagnostics.

The advanced building simulation programs will greatly facilitate the integration of performance simulation with design simulation, thus ensuring that energy efficiency and comfort evaluation issues receive proper emphasis in building design and control. Furthermore the integrated building systems will facilitate the creation of modularized, user-friendly and easy to operate programs for analysis of building components and their interactions. The author explores opportunities in building simulation advances and suggest ways to extend them into next generation of software programs for the A&E Service industry.

INTRODUCTION

The science of providing appropriate environmental conditions in buildings has undergone significant advancement in recent years. Early computer simulations used in the analysis and design of building systems were typically large scale emulations of hand-calculation type algorithms. The computer made it possible to perform repetitive calculations quickly. Today, high-speed computers can be accessed through interactive and graphic modes; as well, they can monitor building conditions and control mechanical and electrical systems in response to anticipated exterior and interior changes. This paper reviews this evolution and develops an hypothesis for the future of whole building simulation.

An historical review of building and computer science developments is presented. Current trends in computational capability are discussed and means to overcome development obstacles are proposed.

A Master Building Simulation (MBS) system is proposed to analyze a building as a whole. The MBS is a logical extension and natural assemblage of the current software attributes found in building simulation packages. It embodies the principal aspects of building design and operation.

The current focus on reducing the operating costs of buildings has emphasized energy conservation. The complexity of dealing with the issues involved is evident through the number of energy analysis approaches that are currently available to the building design and operation professional. The complexity arises from the difficulty in responding to the needs of each of the players involved. Several authors have indicated a trend toward whole building simulation in a generalized, integrated and easily extendible manner.

The proposed Master Building Simulation (MBS) system will facilitate the integration of performance simulation with design simulation. The next generation of programs, that the MBS heralds, will respond to the enhanced degree of sophistication and energy performance that is demanded in the designs of buildings by Architecture and Engineering (A&E) system industry professionals.

HISTORICAL REVIEW OF BUILDING SCIENCE

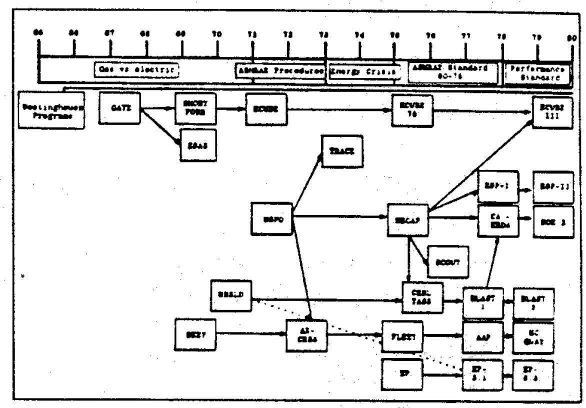
The first use of computers in building design was for duct sizing and layout, artificial lighting systems, and structural design. This was followed by energy simulation for engineering analysis and architectural considerations.

Computer simulation of building energy use was introduced into the Architectural and Engineering design and analysis communities in 1965. In 1969, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) published procedures of determining heating and cooling loads for computerized energy calculations. Using these procedures, the first generation of loads/energy programs were developed by the National Bureau of Standards (NBS) and the U.S. Post Office and were placed in the public domain. Throughout the same period, a number of computer energy calculation programs were being developed in the private sector with proprietary data that did not always follow ASHRAE procedures.

Figure 1 illustrates the history of development of energy analysis computer programs up to 1980. Virtually all of the computer programs referenced in the figure use a multi-step approach to perform their analysis.

FIGURE 1

HISTORY OF ENERGY ANALYSIS COMPUTER PROGRAMS



Initially, this type of program was seen as a powerful computational aid to the building energy analyst and designer. However, as analysis techniques became more sophisticated (for example, by the addition of routines to calculate solar load effects, thermal mass considerations, interzone heat transfer, dynamic thermal characteristics, and others) the programs became more complex. It became increasingly difficult to keep track of the intention of the internal assumptions in the computer codes and to interpret the results.

The ASHRAE bibliography of computer simulations of buildings lists more that 200 programs; many of which produce different results with the same algorithms.One reason for this is the difference in simplifying assumptions inherent in these programs. The analyses typically use either hourly or bin data in their approaches. Table 1 lists 23 of the more commonly used simulations. A PWC survey in 1987 indicated that the top 11 programs comprise 92.5% of reported total program sales.

Computer Aided Design (CAD) techniques are rapidly entering the A&E design communities. Initially, these were simply drafting tools for repetitive work. In addition, CAD systems became useful for preparing lists of materials. Current developments include computational capability and enhanced user/machine interfacing. CAD is also being integrated with energy system analysis procedures. Table 2 lists the 12 most commonly used CAD systems.

TABLE 1

LIST OF PROGRAM AUTHOR/VENDORS
1. SASEAP/Sud Associates Computer Programmers
2. ENERGY/Elite Software Development Inc.
3. EN4M/MC2 Engineering Software
4. EFACT/Johnson Controls, Inc.
5. TRAKLOAD 3.0/Morgan Systems Corp.
6. ENERGY/520/Timeshare Systems, Inc.
7. SYRSOL/Syrsol
8. ENERGY/PC/Engineering Applications Specialists
9. BESA/Candaplan Resources Inc.
10. ENERGY/Tempmaster Corporation
11. SEA/Ferreira & Kalasinsky Associates
12. ESAS/Ross F. Meriwether & Associates
13. ACCESS/Southern Company Services
14. PC-BEACON/Energy Systems Engineers
15. MEDSI ENERGY/MEDSI
16. BLAST/BLAST Support Office
17. LE6/Engineering Software Systems
18. TRACE & TRACE II/The Trane Company
19. ESP-11/APEC, Inc.
20. ADM-2/ADM Associates
21. MICRO-DOE/Acrosoft International
22. E20-II HAP/Carrier Corporation
23. AXCESS-Micro/Syska and Hennessy

TABLE 2

TWELVE MOST COMMONLY USED CAD SYSTEMS
AUTOCAD
AUTOCAD AEC
C-CADD
CADKEY
CAD-SOLUTIONS
CADVANCE
DATACAD
DESIGN BOARD PROFESSIONAL
DRAWBASE
PERSONAL DESIGNER
VERSACAD
VERSACAD 3D

Source: reference 15

REVIEW OF COMPUTER SCIENCE

Computers have been used increasingly in building simulation for more than 20 years. Early programs were available to mainframe owners and batch users. Progressive hardware developments have enabled the development of micro-based building simulations which have made powerful analysis and design tools accessible to all architectural and engineering offices.

Initially, computer simulations were simply complications of the common energy use algorithms. These rigorous and comprehensive models have evolved into more flexible and interactive treatments of building energy use. This evolution has resulted from microprocessor-based strategies that monitor and control building functions related to energy use and human comfort and health issues. This interactive capability is evident in the machine/user interface as well as with the software as seen in the recent development of adaptive and predictive control strategy programs.

The principal developments in computer technology generally fall into the following categories:

- algorithm developments and analytical methods;
- knowledge based expert systems;
- database management;
- heuristic approaches;
- artificial intelligence; and
- parallel processing, graphics and windowing.

Each of these developments is discussed briefly in the following paragraphs and their contribution to the Master Building Simulation (MBS) system is demonstrated in the following sections.

Analytical Methods and Algorithm Development

Building simulation programs have traditionally been developed by assembling algorithms which model fundamental static and dynamic energy flow characteristics. In many cases these algorithms are either analytically or empirically derived steady-state representations of assumed linear behaviour. Unfortunately, the processes in buildings generally exhibit non-linear response to a variety of external and internal loads.

Finite differences and even finite element approaches have been used in some energy analysis programs. These methods tend to be excessively accurate chainings of steady-state modelled nodes and their development has not been enthusiastically pursued.

Expert Systems

The Expert System methodology has proven to be successful in several scientific areas for more than 20 years. Recently, this approach has been applied to buildings (1,2). The basic principle is that there is a relationship between cause and effect. The approach is to prepare a multi-dimensional series of 'if-then' rules which the computer can use to deduce the probable cause of an observed effect (backward chaining), or the probable effect of certain causes (forward chaining). The rules are not very rigid and generally allow for some uncertainty. This exercise is generally done interactively with a human operator.

Expert systems are not implicitly creative. They can, however, simplify the solution process by guiding the user through a matrix of cause/effect statements. The path by which the computer traverses the matrix is within the logical framework established by human experts. The expert system is set up in a way to emulate the human-judgement process. Its value lies in the capability to retain accumulated knowledge and to traverse the decision process indefatigably. Additional advantages are that the computer can bring to mind ideas that were forgotten or overlooked, explore a large number of possible paths and give explanations of its "reasoning" process.

Database Management

Early databases consisted of rigidly formatted groups of numbers or information connected by input/output paths to structured computer codes. Formatting differences made it cumbersome to use the same database interchangeably with several codes. Databases has evolved in recent years to include internal computational capability. The data may not only be manipulated internally but may also be updated through the input paths. These developments are significant contributions to the advancement of integrated systems.

Heuristic Approaches

The most common heuristic approach developments in building simulation are based in 'predictive' or 'adaptive' control strategies. These computer programs are generally within the mechanical/electrical system control loop. They continuously monitor building performance and adjust the controls in response to load varying set points in real time. A sophisticated predictive control strategy is capable of updating the as-built parameters and directing the controller to make adjustments in response to previously-recorded behaviour patterns in view of anticipated loads.

Artificial Intelligence

The field of artificial intelligence (AI) is particularly appropriate to building simulation. This is because control in the form of 'intelligence' is required to track and respond to the constantly varying behaviour of buildings (i.e., heuristic approach). Advances are being made in programming computers to follow a series of commands that would follow a pattern regarding the appropriate response needed to optimize building function and operation (e.g., expert systems). The value of this field of endeavour is that AI systems facilitate the human-decision process. Developments such as natural language processing and computer vision will enhance this facility. For example, computers can respond to voice commands and can be interrogated verbally rather than in codewords. Visually, a computer could 'see' and 'understand' a pipe leak and 'know' what to do about it.

Parallel Processing, Graphics and Windowing

Computer graphics and windowing provide effective user/machine interfacing capability. These techniques result in a reduction of the time required for user inputs. Project organization and coherence are enhanced by the visual displays which embody a great deal of information in a small space.

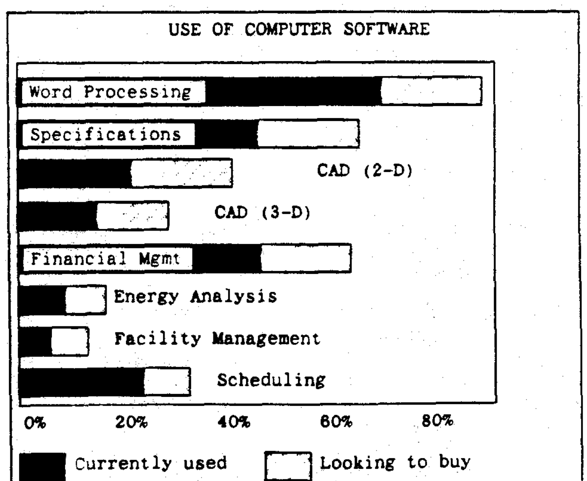
TRENDS DEVELOPING

Advances in microcomputer technology and the availability of a variety of software packages has resulted in a notable increase in the use of desktop personal computers during the past few years. Significant improvements in the automated control of buildings started about 1970 when centralized systems for larger buildings were combined with computer technology to facilitate more sophisticated central control algorithms. Microprocessor technology is now accepted as a key element in the introduction and management of energy conservation strategies in commercial and industrial buildings.

Consulting engineers and architects are making increasing use of microcomputers in their offices in order to stay competitive. Three-hundred respondents in a survey of nearly four-hundred participants at a one-day symposia conducted by Public Works Canada in 1984 indicated that 73% of all firms represented own a computer, of which 43% use energy analysis programs and 36% plan to use them in the future (3).

A report published by the American Institute of Architects (AIA) in 1987 presents the results of a survey of 1,800 U.S. design firms (4). Figure 2 illustrates the percentage of these firms that use or plan to purchase computer software. The results indicate the already widespread use of computer software for word processing and specification writing. What is most interesting in the anticipated near doubling, short-term growth rate for CAD, energy analysis and facility management programs.

FIGURE 2



Source: Building Design & Construction
November 1987, p. 20

There are now more than 300,00 installations of CAD systems in North America, of which AUTOCAD controls about 50% of the market. According to the Marketing Advisory Committee for all CAD vendors, the worldwide market for CAD systems is projected to be 1.1 million units by the year 1990.

Universities are producing engineers and architects who are fluently experienced with the use of computers and available software programs. The art of energy analysis and design with 'back of the envelope' calculations has given way to the computer-aided science of building energy analysis. The complexity of functions and control with which buildings are operated today requires the enhanced sophistication which can be provided by computers. Whereas the first software developments were simply high-speed emulations of hand calculation procedures, current programs consider the interactions among various building components and functions which were previously too cumbersome to carry out manually.

The integration of specific domain software into comprehensive design packages is providing design professionals with valuable tools. More and more mechanical, electrical, structural and civil engineering programs are being integrated with CAD systems. This advance reduces user effort and enables the introduction of optimization techniques which can improve the quality of whole building simulation.

MacRandal has pointed out that the incremental approach to the development of simulation programs has produced codes which are increasingly complex and hence difficult to modify (1). The trend now is to develop "object-oriented" programming methods. This modular concept embodies an anthropomorphic process which focusses on manipulating data within the database rather than in a separately defined procedure. This approach has great potential to facilitate the integration of building simulation with automatic control strategies.

A further trend is to integrate the experience of professionals into the overall control strategy through knowledge-based expert systems. The expert system approach has been successful for guiding the user in making more effective and comprehensive decisions (2,5). Continued development of this approach will involve the expert system in modifying predetermined control strategies in response to a problem. Only when the expert system "realizes" that it cannot solve the problem will it alert the operator.

In addition, voice activation and enhanced user/machine interfacing are contributing to improved communication (5).

Central control systems have followed a natural evolution of using the data collected by the microprocessor to manage the building controls to providing comfort conditions at minimum energy consumption. This combining of different types of software purposes is sometimes referred to as "artificial intelligence". A further advance along this path is to then merge the qualities of the building energy analysis and design programs with the automatic control system.

The more sophisticated building energy control strategies in use or being developed today have the ability to make at least a limited number of calculations to predict the future indoor environmental conditions based on the anticipated climatic conditions. Recent control systems have a certain degree of ability to not only control the building functions with preprogrammed instructions, but also to modify the particular instructions through input of variable parameters derived from collected data on specific monitored information. This method of 'adaptive' or 'predictive' control is marking the way toward whole building system simulation programs (6).

Developments by various government and private-sector organizations around the world point to increased use and appropriateness of building simulation programs. Some of these international activities are discussed in the following sections.

DEVELOPMENT ACTIVITIES

Government and private-sector organizations around the world are actively pursuing a variety of approaches to building simulation. Each of these developments is in response to a particular perception of the needs of the professional design communities.

The Solar Energy Research Institute (SERI) in the U.S. has focussed considerable effort on the validation of building energy analysis simulation programs during the past few years (7). Significant contributions by SERI researchers to the advancement of building simulation include the development of a validation methodology and monitoring techniques used for empirical studies, documentation of the results of intermodel comparisons as well as the results of analytical verification and empirical validation studies.

In Scotland and the U.S., a new approach to model building design and operation is being developed (8). The Energy Kernel System (EKS), as it is called, is a modular concept intended to improve the quality of energy analysis by facilitating the integration of the fundamental heat transfer algorithms, computer-aided design techniques and knowledge-based expert systems.

A development project in Finland is using geometric data from a CAD system as input to an energy calculation program for early design stage analysis (9,10). An advantage of this approach is a reduction of the time and effort normally required to prepare an input file for the analysis and design programs. The development is being done with the use of standard off-the-shelf programs. This approach limits the flexibility of the simulation package; however, the focus of the work is on improving program/user interfaces and CAD system database capabilities.

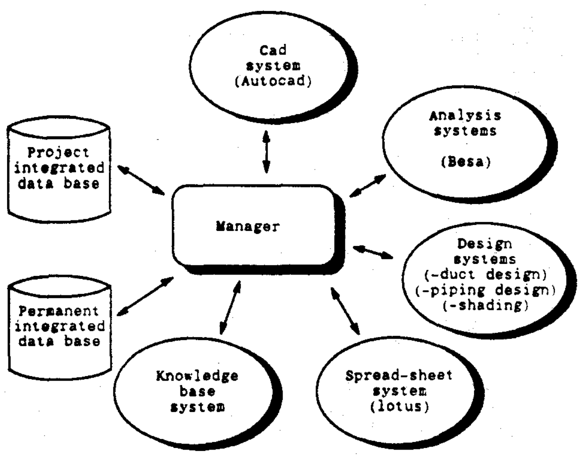
The U.S. National Bureau of Standards is developing HVACSIM+, a hierarchical, variable-timestep simulation which models the dynamics the building envelopes, the HVAC system and controls. The program solves non-linear algebraic and differential equations in response to a user-assembled model of the building components to be modelled. The IBM Los Angeles Scientific Center has developed ENET, a new approach which simplifies the iterative solution procedure required by programs such as HVACSIM+ (11).

A significant contribution toward the integrated analysis and design of buildings has been made by the Construction Engineering Research Laboratory (CERL) of the U.S. Army Corps of Engineers. During the past decade the CERL has been designing and implementing the Computer-Aided Engineering and Architectural Design System (CAEADS). The CAEADS building model organizes the description of a building as a collection of interdependent subsystems (i.e., architectural, structural, mechanical, electrical and civil). This approach leads to a more coherent design because the same databases are available to each of the design professionals involved.

Public Works Canada (PWC) is working on similar developments with the Societe d'Informatique et de Recherche pour l'Industrie de la Construction (SIRICON) to produce a simulation model with integrated systems capability. Figure 3 illustrates a conceptual flowchart of the anticipated integrated system. All of the circumferential packages represented exist in a multitude of forms. A first generation 'manager' is in operation. The focus of the development is a protocol for the interfaces between the manager and the standard design/analysis systems and the databases. A prototype of the BESA/AUTOCAD relationship is presently functional.

FIGURE 3

GENERAL FLOWCHART
FOR AN INTEGRATED SYSTEM



Two examples illustrate the value of this activity. First, input to the analysis systems can be made graphically through a CAD package. In addition, the effect of architectural changes in the CAD graphics would be reflected immediately through the analysis systems, be they energy, cost, structural, or other characteristics. Second, there would be diagnostic operational capability. For example, a knowledge-based expert system may determine that an increased infiltration load is due to a faulty duct damper motor. The integrated system report may then propose a realistic repair procedure and schedule complete with cost, anticipated energy savings and payback.

Public Works Canada (PWC) has actively supported department of building simulation programs for the past 15 years. In response to surveys of design professionals and building operators in North America, PWC contracted with Candaplan Resources Inc. to develop a comprehensive Building Energy Systems Analysis (BESA) program. The package, when completed, will consist of 'concept design', 'detailed design' and 'retrofit' modules which address the requirements of various stages of the design process.

Another significant research effort supported by PWC is the instrumentation and monitoring of a commercial building by R&D CDA Inc. of Montreal. A microprocessor-based predictive control strategy is being tested as a means of maintaining superior comfort conditions with significant energy-use reduction. The method uses "as built" thermal resistance and capacitance characteristics in addition to current climatic data to control the building mechanical and electrical systems.

Organizations such as the International Building Performance Simulation Association (IBPSA) and the Building Research Establishment (BRE) are valuable forums within which standardization and advancement of building simulation procedures are taking place. These non-profit groups are active in promoting research and bringing new developments into the public domain.

DEVELOPMENT OBSTACLES

There is a general lack of coordination among competing software and hardware developers. For example, a consortium headed by IBM is currently challenging licensing restrictions on the UNIX operating system which have been imposed by its developer AT&T (12). The issue of proprietary rights related to developments is one that is continually being challenged in the courts (13).

Government inaction in promulgating strict standards for energy compliance and comfort levels is another obstacle to coordinated research and development. If not through legislation, it is certainly a responsibility of government to disseminate information and recommend procedures for energy conservation which reflect a broad-based resource management policy.

Another barrier to the department of appropriate simulation tools is the low cost of energy. Rosenfeld and Hafemeister (14) have made a strong case illustrating the value to the U.S. economy of improving the efficiency of energy use in buildings, despite its current low costs.

The current fast-paced development of easily accessible hardware and software is geared toward market demands. While many new products are released continuously, there is a lack of coherent direction because both the users and the developers tend to be dispersed among small enterprises.

The lack of building simulation and operation protocol is evidenced by the fact that the design community and the controls industry are not linked at a fundamental level. Typically, a building owner will hire a design team to produce the desired product. Once constructed, the owner engages another group to control the building functions. The obvious disadvantage of this approach is that the operator may not perceive the designers' intention of certain features. In addition, the designers may never know if their intentions were realized with sound results.

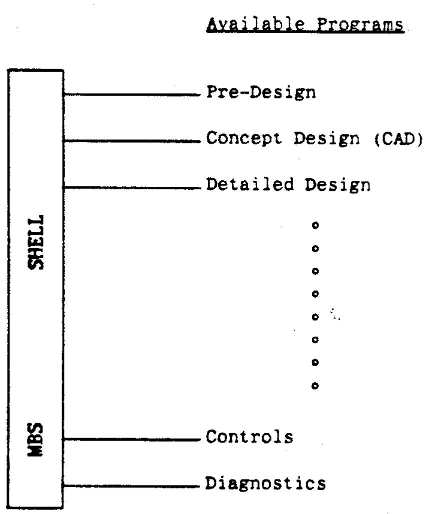
THE MBS SYSTEM - A VISION FOR THE FUTURE

There has been accelerated development of both computer software and hardware during the past decade. The products available today offer significant potential for improving the way in which buildings are designed, constructed, monitored and operated. Hundreds of programs exist for performing a variety of building simulations. Current efforts focus on developing whole building system packages.

The Master Building Simulation (MBS) is a shell which has the capability to guide the user through a series of available simulation programs. Upon entering the MBS system, the user receives information regarding the current status of the whole building analysis and design. This is followed by the principal menu which contains a list of the available programs. The user can then interactively input or modify the data in the appropriate program; upon running the program, all other programs will be updated through the protocol established by the MBS shell. Figure 4 illustrates the MBS system configuration.

FIGURE 4

MBS CONFIGURATION



The MBS protocol provides a system approach to whole building simulation. By "grafting" each program to the MBS shell an integrated system is created which is capable of performing whole building optimization techniques while transferring data between the appropriate programs.

The principal contributions of the MBS shell protocol to the advancement of building simulation are to standardize input methods, and to provide a systematic guide into the MBS core. The MBS provides a target for future programmers to direct their creations toward an industry standard, with the knowledge and confidence that their program will be compatible with other independently developed programs.

The following statement summarize the current trend of building simulation programs. The MBS will satisfy the requirements.

> The objectives of building simulation programs are to provide superior functional design and operation at competitive first cost and minimal operating cost. In order to achieve these objectives, programs of the future will operate quickly through a series of iterative optimization procedures in a interactive mode with the designer and building operator.
>
> The current development of software packages which integrate analysis and CAD capabilities can greatly reduce the design time and provide a more coherent and elegant design. This process can allow the design professional immediate feedback regarding the appropriateness and effectiveness of design options.
>
> The introduction of expert systems into the development of whole building software packages can add a valuable subjective element to the computational approach. By preprogramming the expert response in the software package, the decision process becomes somewhat more objective while retaining an underlying subjectivity.
>
> Furthermore, an expert system can serve as a directional guide within the software to systematically modify initial design characteristics and test them against optimization criteria. This process is commonly applied in 'predictive/adaptive' building monitoring and control strategies.
>
> Design decisions are generally based on the use of steady-state algorithms, either derived from fundamental physics or based on empirical correlations. A computational step in the right direction is to use the building monitoring system to continuously update the algorithms with "as-built" data. In this way the design program (which would be part of the building control strategy) would be perpetually available to suggest appropriate control and retrofit modifications.
>
> This heuristic approach can lead to a completely empirically derived simulation. By modelling performance, the computer can "create" an operation system based on historical data and experience. The combination computational ability, CAD integration and expert system guiding principals available today make it feasible to develop an hierarchical calculation procedure which can 'back-calculate' the reasons for energy use with great precision.

The Master Building Simulation is a comprehensive procedure which absorbs the uncertainties in current programs. After 20 years of modelling experience, certain heat flow mechanisms are still largely unsolved by way of computer simulation. Most notably, these are air infiltration and thermal mass issues. By monitoring building energy flows, the designer/operator will have access to information which will allow for more effective building operation.

REFERENCES

1. D. MacRandal, "Some Trends in Computing: The Implications for Simulation", Energy and Buildings, Vol. 10, No. 3, 1988.

2. P.W. Brothers, "Knowledge Engineering for HVAC Expert Systems", ASHRAE Transactions, V. 94, Pt. 1, 1988.

3. D. Seth, "The BESA Approach", ...

4. "AIA Firm Study Profiles U.S. Design Market", Building Design and Construction, November 1987, pp. 19-20.

5. J.D. Petze and D.R. Reed, "Artificial Intelligence in Building Control Systems", ASHRAE Transactions, V. 94, Pt. 1, 1988.

6. M.M. Shapiro, A.J. Yager and T.H. Ngan, "Test Hut Validation of a Microcomputer Predictive HVAC Control", ASHRAE Transactions, V. 94, Pt. 1, 1988.

7. R.D. Judkoff, "Validation of Building Energy Analysis Simulation Programs at the Solar Energy Research Institute", Energy and Buildings, Vol. 10, No. 3, 1988.

8. J.A. Clarke, "The Energy Kernel System", Energy and Buildings, Vol. 10, No. 3, 1988.

9. L.K. Heikkinen, "Energy Calculation Program for Early Design Stages Utilizing Geometric Data from a CAD System", CIB 5th International Symposium, Bath, ...

10. L. Heikkinen et al., "Transferring Geometric Data from a CAD-System to a Building Energy Calculation Program", BSRIA Computer Newsletter, Oxford, England, No. 16, November 1985 and No. 17, February 1986.

11. F. Winkelmann, "Advances in Building Energy Simulation in North America", Energy and Buildings, Vol. 10, No. 3, 1988.

12. The Gazette, Montreal, May 17, 1988, p. C-4.

13. Anne W. Branscomb, "Who Owns Creativity?", Technology Review, May/June 1988.

14. Arthur H. Rosenfeld and Dave Hafemeister, "Energy-efficient Buildings", Scientific American, April 1988.

15. SIRICON, The First MicroCAD Ratings Guide, 1987. (Available from SIRICON, 1455 de Maisonneuve boul. west, Montreal, Québec, H3G 1M8).

BIBLIOGRAPHY

The Global Network, Reshaping Our Future, Washington, D.C., 1987.

J.A. Clarke and A.D. Irving, "Building Energy Simulation: an Introduction", Energy and Buildings, Vol. 10, No. 3, 1988.

T.J. Wiltshire and A.J. Wright, "Advances in Building Energy Simulation in the U.K. - The Science and Engineering Research Council's Programme", Energy and Buildings, Vol. 10, No. 3, 1988.

D. Newton et al., "Building Energy Simulation - a User's Perspective", Energy and Buildings, Vol. 10, No. 3, 1988.

D. Seth, "Building Energy Systems Analysis", ...

Charles M. Eastman, "A Prototype Integrated Building Model", Institute of Building Sciences Research Report No. 3, Carnegie-Mellon University, January 1980.

Charles M. Eastman, "System Facilities for CAD Databases", Institute of Building Sciences Research Report No. 5, Carnegie-Mellon University, April 1980.

D. Seth, "Master Environmental Control System", APEC Journal, Fall 1982.

D. Seth, "A Novel Approach to Operating Smart Buildings of the Future", ...

V.A. Williams, "Intelligent Buildings - Smarter with DDC", ASHRAE Transactions, V. 94, Pt. 1, 1988.

P.P. Payne, "What Distributed Microcontrollers Bring to the Building ManagementSystem, ASHRAE Transactions, V. 94, Pt. 1, 1988.

G.E. Kelly, "Control System Simulation in North America", Energy and Buildings,Vol. 10., No. 3, 1988.