LBNL-41765
Preprint

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Application of Information Technologies in Building Design Decisions

Konstantinos Papamichael

Environmental Energy Technologies Division

May 1998

Published in
Building Research & Information

DISCLAIMER

LBNL-41765
DR-391
Reprint from *Building Research & Information, V.27(1):20-34, January/February 1999 ISSN 0961-3218*

Application of information technologies in building design decisions

Konstantinos Papamichael, Ph.D.

Building Technologies Department
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
1Cyclotron Road
Berkeley, CA 94720
USA

May 1998

The research reported here was funded in part by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Systems and Office of Building Equipment of the U.S. Department of Energy, as well as by the Laboratory Directed Research and Development (LDRD) Funds of Lawrence Berkeley National Laboratory, under Contract No. DE-AC03-76SF00098.

Abstract

This paper is about research and development efforts on the use of information technologies to assist in building design decisions. Theoretical models of the design and decision-making processes are described along with their implementation for the development of the Building Design Advisor (BDA), a software environment designed to facilitate informed decisions from the early schematic phases of building design to the detailed specification of building components and systems. To do that, the BDA supports the integrated, concurrent use of multiple simulation tools and databases, and makes their output available in forms that support multi-criterion judgement. The BDA data structures and algorithms for data management and process control are presented along with its graphical user interface and the simulation processes linked to its initial version. Finally, plans for future work are described, aimed at the expansion of the BDA software to link to additional tools and databases, and address the data needs of the whole building life cycle, from design, through construction and commissioning, to operation and demolition.

Introduction

The continuous demand for better buildings has resulted in an increasing number of new strategies and technologies aimed at improving buildings with respect to a variety of performance considerations, such as comfort, cost, aesthetics, environmental impact, etc. As the number of technological options increases, so does the complexity and associated cost of choosing among them, that is, deciding which combination of available options is the most appropriate for a given application. Informed decisions require the management of vast amounts of information about the combinations of available options and the simulation of their performance. Manual methods are almost impossible to implement at a comprehensive level. As a result, most building decisions are only partially informed, resulting in missed opportunities and often unaccounted, undesired effects.

The rapid advances in information technologies and the continuously decreasing cost of computing power present promising opportunities for the development of computer-based tools that may significantly improve decision-making and facilitate the building design process. Such tools capitalize on the main advantages that computers have over the human brain: memory capacity and computational speed. Successful implementation, however, requires comprehensive understanding of the design process for the formulation of appropriate data and process control schemata.

This paper is about the design theories and modeling techniques used for the development of the Building Design Advisor (BDA), a software environment aimed at facilitating the integrated use of multiple simulation tools and databases, to support informed decisions from the initial, schematic phases of building design to the detailed specification of building components and systems.

Design decisions

Design decisions are based on the comparison of alternative courses of action with respect to a variety of performance considerations, such as comfort, aesthetics, economics, environmental impact, etc. Building design can be seen as the iterative generation of alternative courses of actions in the form of technological combinations and the prediction and evaluation of their performance (Fig 1).

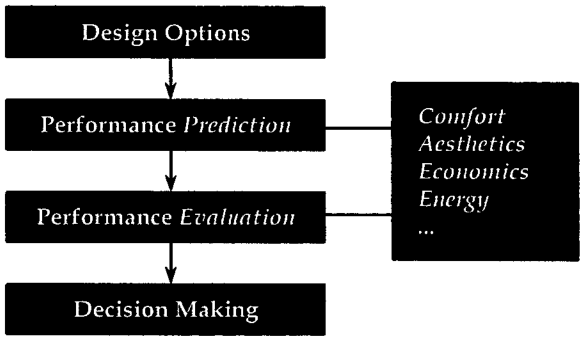

Figure 1. Building design decisions require performance prediction and evaluation with respect to multiple performance considerations.

Building performance is considered and communicated through the use of performance indices, or parameters, based on the values of which designers judge appropriateness. Performance indices may vary drastically with respect to the type of their value. Economic considerations, for example, involve mostly quantitative indices, such as initial, operational and lifecycle cost, rate of return, payback period, etc., all of which are real numbers that are measured on continuous scales. Aesthetic considerations, however, involve mostly qualitative indices, such as images of elevations, perspectives, etc., which operate on nominal scales, formed by the options themselves.

Performance prediction

Designers use various types of modeling techniques to predict performance, that is, to determine the values of performance indices. Traditionally, these techniques have been limited to sketches and drawings of building plans, sections, elevations, perspectives, etc., scale models and computations performed by hand or hand-held calculators. As the need for additional and more accurate performance information is increasing, new simulation techniques are becoming available, especially in the form of computer programs.

Computer-aided drafting (CAD) applications have been so far the most successful, mainly because they improve the efficiency of traditional building design methods, focusing on the production of drawings and specifications. Analytical applications, however, such as those used for lighting, energy and environmental impact analyses, have not seen the same acceptance, mainly because they were not part of the traditional design process. As such performance issues become increasingly important, various analytical applications, such as DOE-2, for building energy analyses (Winkelmann et al 1993), Radiance, for daylighting, lighting and visualization (Ward 1992), COMIS, for airflow and indoor air quality (Feustel 1992), are increasingly in demand to provide information for decision-making during the building design process.

Unfortunately, most of the available simulation programs were originally developed by researchers, for research purposes, and are not easy to use. They require significant amounts of detailed information about the building and its context, usually in the form of input files that consists of keywords and data, following particular syntax and structures. Moreover, the output is usually generated in the form of alphanumeric tables that are hard to review and interpret. As a result, such programs are very expensive to use, because they require significant knowledge and time for the preparation of their input and the interpretation of their output.

Different simulation programs use different representations of the building and its context, depending on the performance aspect that they address. A thermal analysis program, for example, uses a representation in terms of thermal barriers that are characterized by thermal transmission and capacity properties, while a lighting analysis program uses a representation in terms of polygons, cones and spheres, characterized by light reflectance and texture. As a result, the use of multiple programs requires repetitive descriptions of the building and its context in different formats, which makes the use of such programs even more costly and unattractive.

Performance evaluation

Performance prediction is mandatory but not adequate for decision-making. Once performance has been predicted, it has to be evaluated with respect to its goodness or appropriateness. Since "good" and "bad" make sense only when there are at least two of a kind, evaluation requires comparison of multiple alternative design schemes, as well as comparison with the performance of existing buildings. Moreover, evaluation requires concurrent and integrated consideration of all performance.

While performance prediction can be highly automated through the use of computers, performance evaluation cannot, unless it is with respect to a single criterion. The multi-criterion nature of most design decisions requires the direct involvement of humans. However, computers can still facilitate the evaluation process though appropriate user interface schemata that provide graphical presentation of data and allow for direct comparison of multiple solutions with respect to multiple performance considerations (Papamichael and Protzen, 1993).

Design information

Performance indices are functions of the descriptive characteristics of the building and its context. Simulation programs use algorithmic models of such functions and may vary widely with respect to modeling capabilities and prediction accuracy. Increased modeling capabilities and accuracy usually require significant amounts of input information, as well as computing power.

The descriptive characteristics of the building and its context are represented either by design or context parameters. Design parameters describe the characteristics that are directly controlled by designers, such as the height of a window, the color of a wall, etc. Context parameters describe the characteristics that designers do not have control over, such as the height of people, weather data, etc. Designers generate options for the values of design parameters and assume values for context parameters to determine and evaluate the values of performance indices.

The differentiation between design and context parameters is controlled by the decision-makers. Moreover, it varies throughout the design process, as the designer explores combinations of descriptive characteristics. The site, for example, usually a context parameter in building design, can be a design parameter when decision-makers consider more than one option for the location of the building. While the orientation of a building may be considered as a design parameter during the initial, schematic phases of building design, it can then serve as a context parameter for further decisions.

The values of design and context parameters serve as input to simulation models for the computation of the values of performance indices. Some of them, such as the height of the window, or the distance from the neighboring building, are used directly by simulation programs. Others are used as "names," which refer to sets of variables whose values are used in the actual computations. For example, a glass type name refers to a specific combination of luminous and thermal properties, a location name refers to specific hourly weather information, etc. In the case of design parameters that affect the values of sets of input variables, designers are limited to selecting among the available combinatorial options, with indirect and limited control on the values of the actual input parameters.

Information overload

The complexity in building design decisions arises from the fact that the effects of each decision depend on a large number of other decisions. The effects of the decision on glazing selection, for example, depends on decisions about the size and location of the window, its orientation, the selection of the lighting system and its controls, thermostat settings, etc. While building strategies and technologies are usually aimed at improving performance with respect to specific performance criteria, they usually affect most performance aspects, resulting in tradeoffs that need to be understood, quantified and evaluated. The use of light shelves, for example, is aimed at better utilization of daylight for increased luminous comfort and potential energy and cost savings through reduction of electric lighting requirements and HVAC loads. However, light shelves may also increase the initial cost of the building, they have a significant impact on aesthetic appeal, and may increase operating and maintenance costs. To decide on their "overall appropriateness" designers need to quantify all such effects and compare them with those of other options.

As the number of performance parameters is increasing, designers are faced with data overload even with the use of the simplest simulation tools. A simplified energy computation algorithm requires knowledge of the values of more than two hundred characteristics of the building and its context. Sophisticated models may require twice as much. Consider the large number of available options for each building component and system and add to it the knowledge of organizing and preparing data so that they are effectively supplied as input to the appropriate simulation routines. Finally, consider the need for knowledge of the performance of existing buildings, as well as the organization and the management of the performance of multiple alternatives for decision making, and you get the picture of design information overload. Fortunately, a significant part of the required data management can be automated using information technologies.

Information technologies

Let's consider the decision on glazing selection for a single window in a single space, assuming everything else is context information and that we are only concerned with one performance parameter, e.g., energy requirements. The design decision is now reduced to *finding a glazing, which will reduce energy requirements to the extent possible*. All of the information seeking and manipulating required for this search could be delegated and even automated. In fact, if minimization of energy requirements were the only criterion for glazing selection, the designer would not really be needed at all! Following up on our example, a glazing database can satisfy the need for information about existing glazings and their characteristics. While CAD modeling and weather databases can take care of contextual information, simulation algorithms can be employed to determine energy performance quantities. Moreover, the whole process of preparing the input to and manipulating the output from the simulation routines can be automated. Add an optimization algorithm and the selection of the glazing becomes the equivalent of executing a computer program that draws information from several databases.

That would indeed be the case for these types of decisions on selecting a member from a set of known alternatives. The main reason that this is not truly the case is that usually there is more than one performance aspect to be considered. Glazing selection often involves more than energy considerations. The need to also address performance aspects such as comfort, cost, aesthetics, etc., require a multi-criterion judgement, which cannot be specified and delegated to others, let alone machines. Decision-making is the main non-delegable design task and can only be addressed by the designers themselves. Moreover, it can only be addressed through direct, side-by-side comparison of multiple design alternatives (Papamichael and Protzen 1993).

With the exception of this type of multi-criterion optimization, the rest of the design tasks *can* be specified and delegated to others, especially to computers, which can perform them fast and, in principle, without errors. This recognition has been the basis for the development of the Building Design Advisor (BDA) software, in an attempt to automate as much as possible and assist decision-makers with the parts of the design process that require human judgement.

The Building Design Advisor

The goal of the Building Design Advisor (BDA) research and development efforts is to create a software environment that will facilitate building design by allowing designers to quickly and easily specify the characteristics of potential designs and get information about their performance. A major objective is to make use of available databases and computer simulation programs, like DOE-2, Radiance, COMIS, etc., automating the preparation of their input and facilitating the review and interpretation of their output. Another major objective is to create an environment that can grow through incremental development of links to more simulation tools and databases in the future and for the whole building lifecycle.

The BDA is composed of a central, common database that stores information about the building and its context in terms of "real world objects," such as walls, windows, etc. This central database, or building model, is linked to a graphical user interface, a set of external databases and a set of external processes (Fig 2). Some of the processes and databases are used for the creation and assignment of values to design and context variables, while others are used to compute the values of performance indices. The BDA automatically extracts information from databases, activates processes by supplying them with the information they need, in the form that they expect it, and stores their output in the central building model. Data structures and libraries

The BDA development is based on extensive use of object-oriented programming, which supports modeling in terms of "objects" that are linked to each other through "relations" and are characterized by "attributes" and "methods" (Fig 3). Following this paradigm, the BDA building representation is based on real objects, such as spaces, walls, windows, etc. as objects. However, the representation of the parameters that characterize them is not in the form of attributes. Rather it is in the form of software objects as well (Fig 4). The same is true for the relations among building objects. In this way, the BDA building model can be expanded through the creation of new building objects, as well as new relations and parameter objects for new and existing objects. Another advantage of this representation is the use of attributes to store information about the parameters themselves, like the simulation tools that use them as input or output, the different units used by each for automatic value

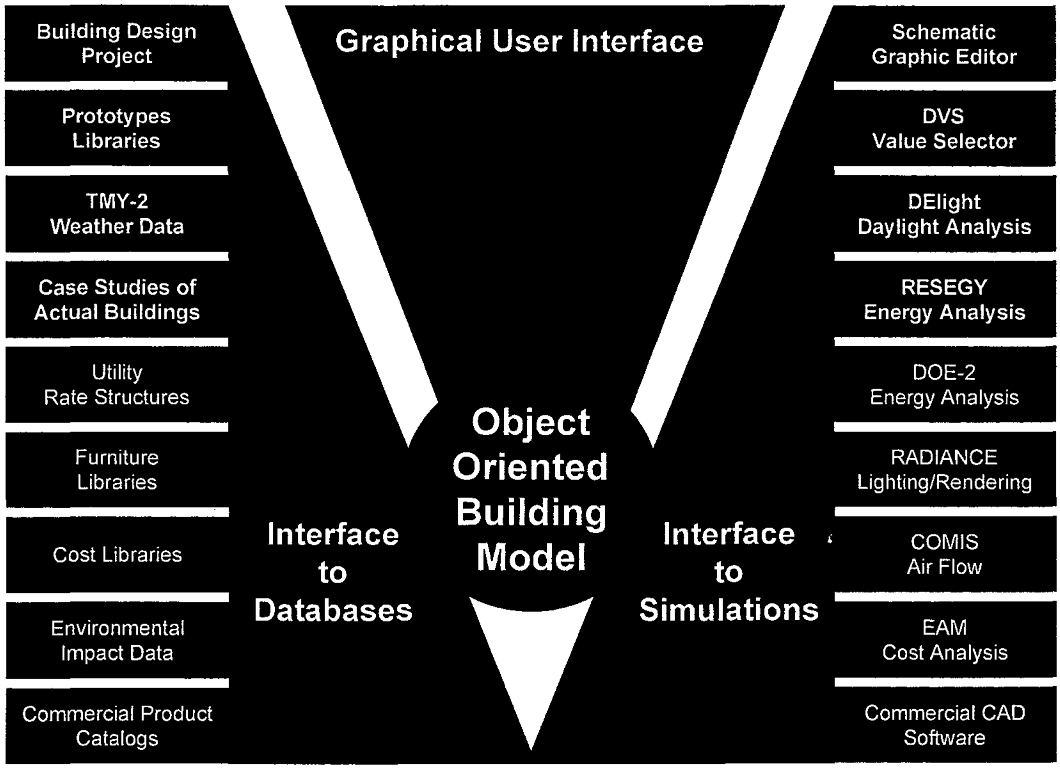

Figure 2. The Building Design Advisor is composed of a central data model that is linked to a graphical user interface and multiple simulation tools and databases.

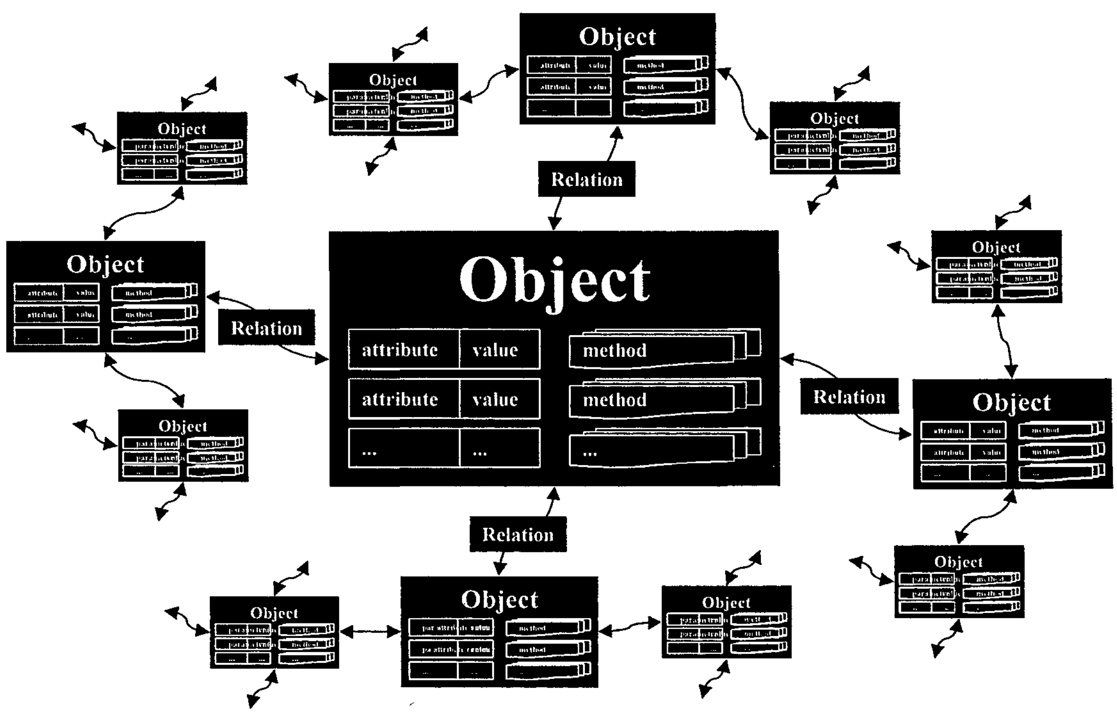

Figure 3. Object-oriented programming supports representation in terms of objects that may be related to each other and are characterized by attributes and methods.

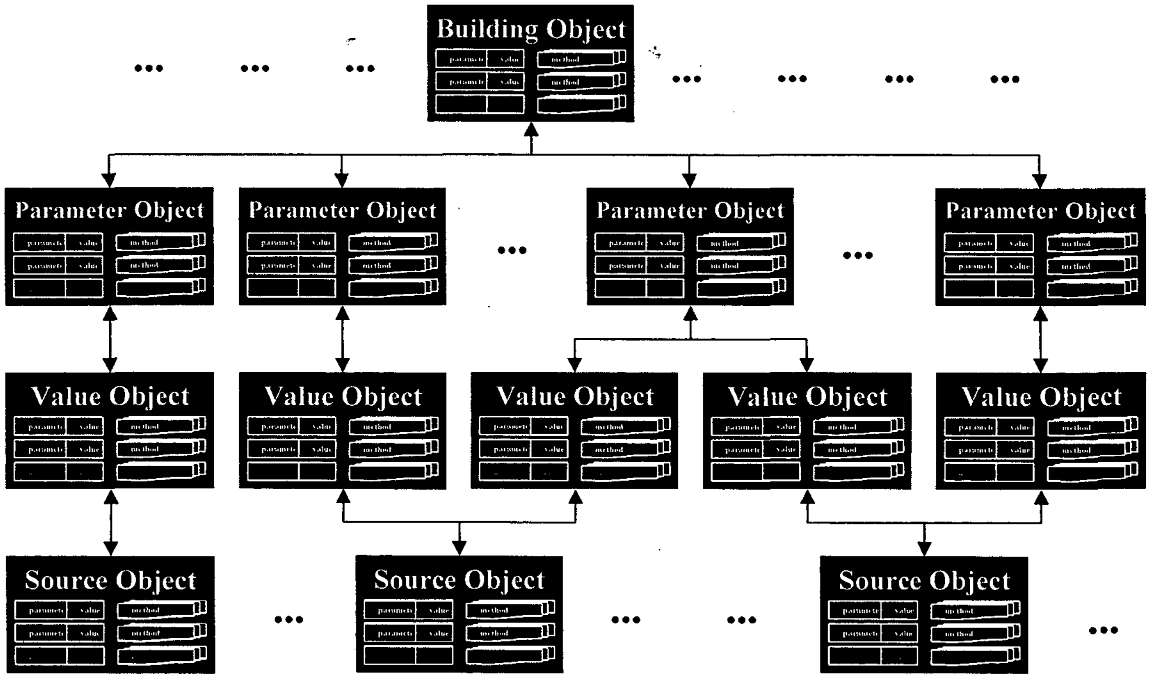

Figure 4. The BDA uses software objects to represent not only building objects, but their parameters and values as well.

conversion, etc. This representation, referred to as "meta-schema," is at the heart of the BDA environment and allows the treatment of the building model and the processes that operate on it to grow as data in a database (Fig 5). A separate application has been developed to define building objects, relations, parameters, units, simulation tools, etc., as the actual building data schema.

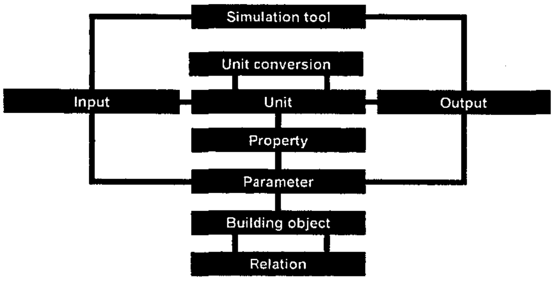

Figure 5. The BDA data meta-schema allows expansion of the BDA building model and the analysis tools that operate on it, as if they were data entered in a database.

To support links to multiple simulation tools and address the data needs of the whole building lifecycle for future expansion, even the values of parameters are modeled as software objects. In this way, one parameter may have multiple values, which may come from different sources and at different times during the building lifecycle (Fig 4). Acknowledging the fact that performance evaluation requires comparison among alternative options, the BDA also supports the concurrent representation of multiple design solutions as part of a "design project."

For every building object defined for the representation of the building and its context, such as "location," "space," "glazing," etc., the BDA maintains a library of alternatives, such as "San Francisco," "Conference," "Double low-e," etc., respectively. These libraries address the assignment of values to group of variables through the selection of names, reflecting the limited control that designers have on the values of the input variables to processes. The "San Francisco" location, for example, is translated into hourly weather data used for thermal and daylighting calculations, utility rates for the cost of energy, etc. The "Conference" room holds information about space activities that hold information about potential occupancy patterns, recommended thermostat settings and illumination levels, etc. The "Double low-e glazing" holds information about the transmittance and reflectance of the glazing, its thermal properties, etc. To create the BDA libraries of building components and systems, a separate application has been developed, which reads the data schema definitions and allows the assignment of values to their attributes for the creation of specific instances.

Process control

When the value or a parameter requested by the user is not available in the database, a recursive logic scheme is activated to identify the process or processes that need to be activated. If the value of an object or a parameter requested by the user is not available, the BDA checks to see which processes can compute it as part of their output. It then checks to see if all of the input parameters to those processes have values. If they do, then the BDA activates the process to compute the requested value. If one or more of the required input parameters do not have values, then the BDA follows the same approach of looking for processes that can generate them as output, stacking processes for sequential execution. If the search for processes fails, then the BDA asks the user for required values and then executes all stacked processes to compute the value that was initially requested (Fig 6).

One of the challenges in the design of the BDA has been the need to use sophisticated simulation tools from the early, schematic phases of building design, when the required details of building components and systems are not yet specified. To resolve this issue, the BDA uses a "Default Value Selection" process to assign default values to the parameters of building components and systems, based on three premises: building type, building location and space type. The selection of default values is based on building codes, standards and recommended practice, such as those provided by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE 1993), the Illuminating Engineering Society of North America (IESNA 1993), etc.

Acknowledging the fact that default values are the equivalent of design decisions, the BDA clearly differentiates between them and the values assigned by the designers. The default values can be reviewed and edited by the user at any point during the design process. The default value mechanism can be further expanded to include any number and type of premises. Moreover, it can be implemented as a set of processes that can include execution of simulation routines for additional information that may be needed for proper selection of defaults. The same mechanism can be the basis for processes that can provide design advise towards performance improvement.

User interface

The BDA uses a graphical user interface that allows designers to review and edit all objects and parameters in a "generic way." The graphical user interface is composed of two elements: the Building Browser and the Decision Desktop.

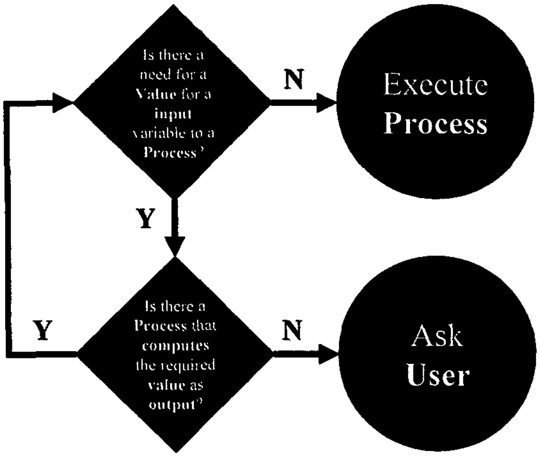

Figure 6. The BDA main process control logic supports automatic activation of processes, as needed.

The Building Browser supports navigation through the building model and editing of all values of building objects and parameters (Fig 7). In the left window of the Building Browser, the user can review all building objects in a hierarchical way. When the user selects an object in the left window of the Building Browser, its "children" objects and parameters appear on the right window, along with their values, units and value sources. An icon to the left of each parameter differentiates between default values and values assigned by users, while a check box allows the selection of any number of parameters for detailed display in the Design Desktop.

The values of building objects and parameters are changed though the Object and Parameter Information dialog boxes. The values of objects are changed by selecting the name of another object instance form the corresponding BDA object libraries (Fig 8). The values of parameters are assigned directly by the designer (Fig 9). Only certain parameters of object can be edited by the user, following the corresponding choices in the real world. For example, the user can change the thermostat setting of a space, but not the transmittance of a glazing. To directly control such inter-related parameters, the user has to define them in sets as new library entries.

The Decision Desktop is a matrix that facilitates the comparison of multiple design solutions with respect to multiple parameters. The rows of the matrix correspond to the parameters selected by the user in the Building Browser, while the columns correspond to alternative design solutions that have been defined by the designers (Fig 10). The BDA parameters can hold a variety of value types, ranging from single numbers, through two- and three-dimensional distributions, to images and even video. These values are displayed in the Decision Desktop cells in a variety of ways, which can be specified by the user by opening cells into their own windows for further manipulation of the data and the way they are displayed (Fig 11).

The Schematic Graphic Editor

The Schematic Graphic Editor (SGE) is an integral part of the BDA user interface. Following the general BDA software design, it was developed as a separate application that continuously communicates with the BDA, passing the geometric information about building components and systems drawn in it (Fig 12).

Unlike traditional CAD packages, the SGE supports the drawing of specific building components and systems, such as "spaces" and "windows," as opposed to "lines" that represent spaces and walls in one's mind. In this way, when the BDA receives the information about a particular object being drawn, it can generate all of the relevant objects and assign default values to them.

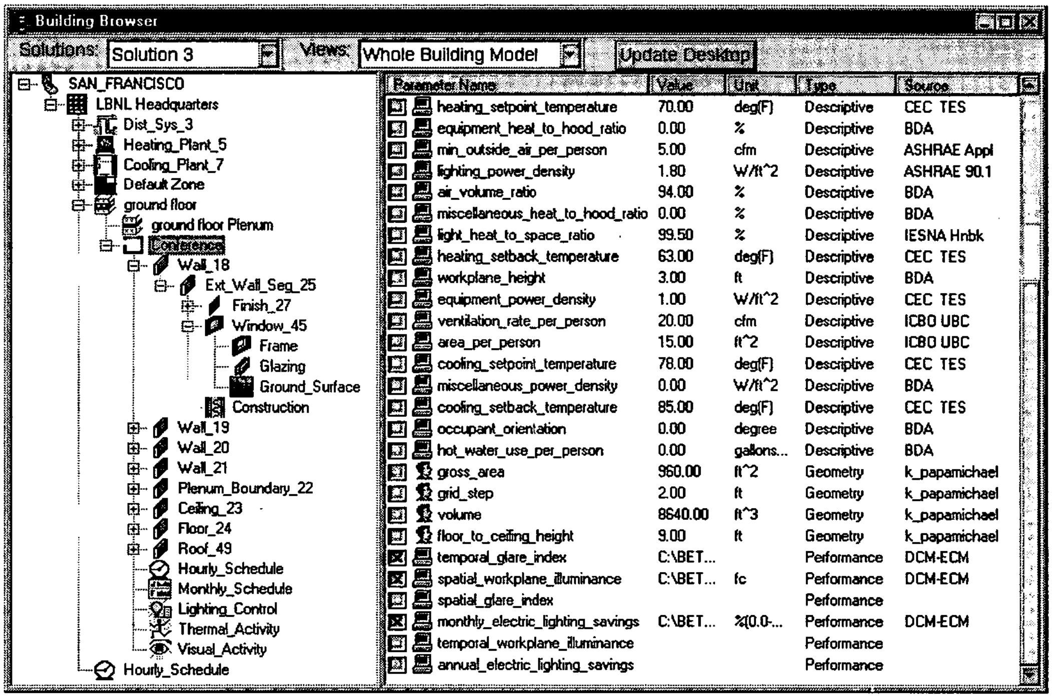

Figure 7. The Building Browser allows designers to quickly review and edit the whole building model.

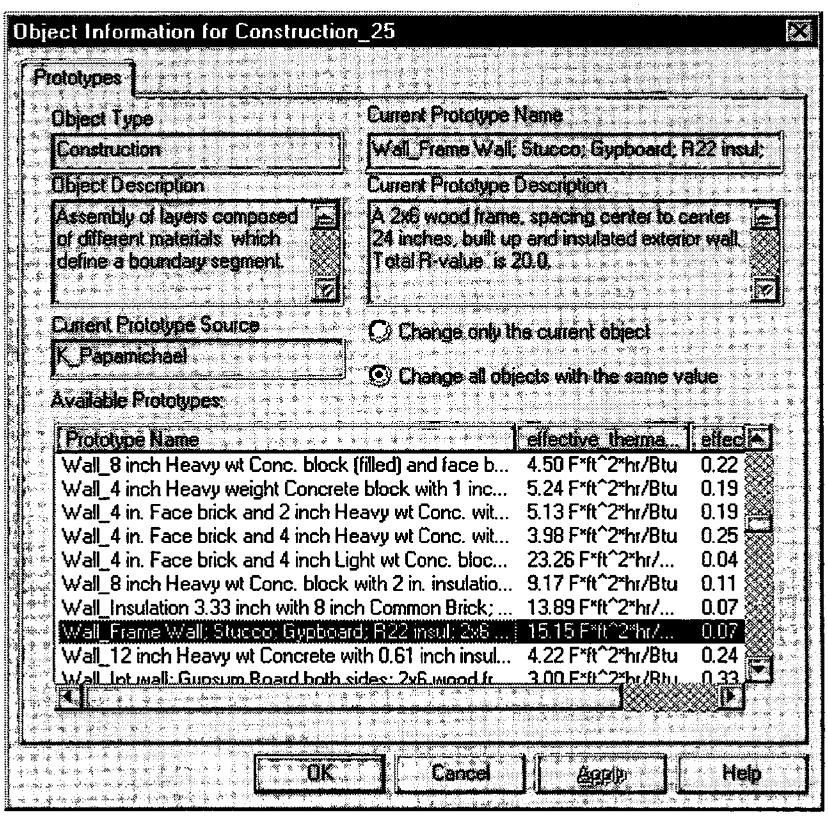

Figure 8. The Object Information dialog box allows designers to select alternative options for building objects from the BDA libraries of building components and systems.

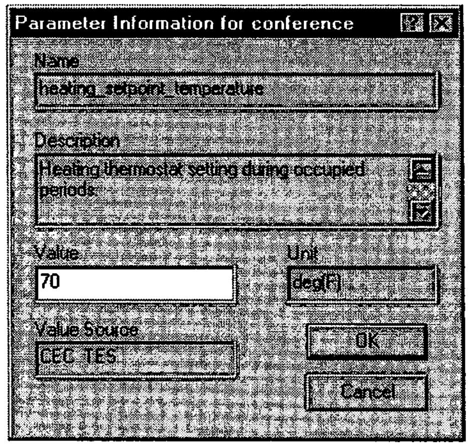

Figure 9. The Parameter Information dialog box allows designers to change the values of individual parameters.

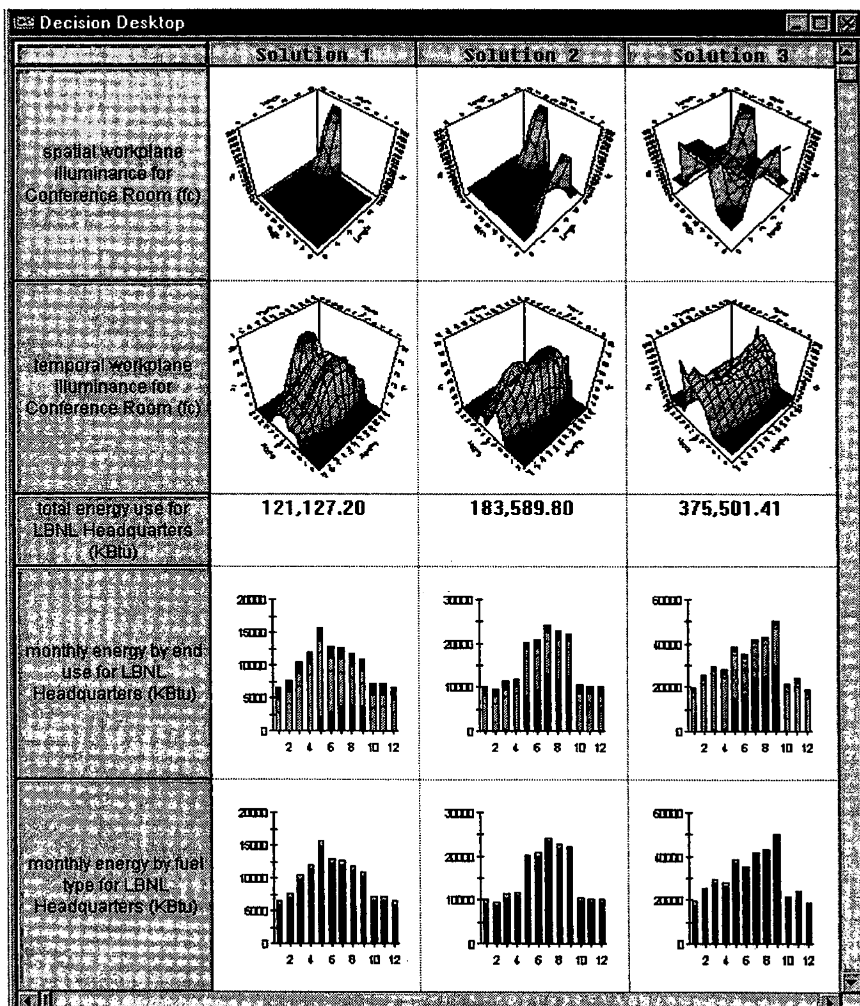

Figure 10. The Decision Desktop allows designers to compare multiple design solutions with respect to multiple descriptive and performance characteristics.

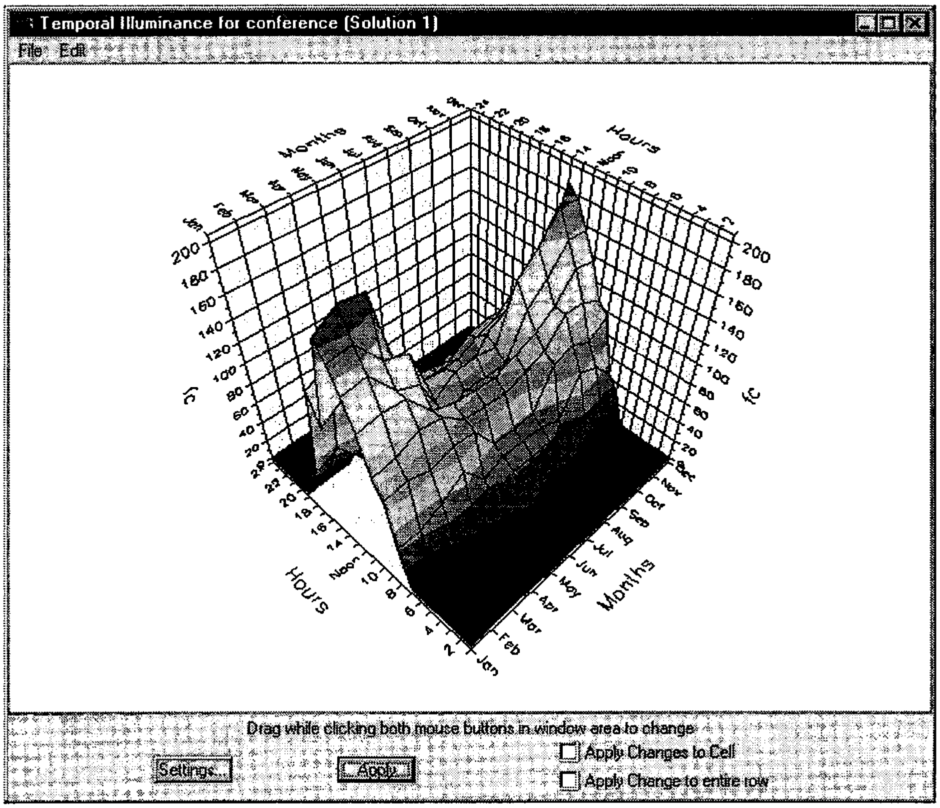

Figure 11. The display of information in the Decision Desktop can be customized by the designer.

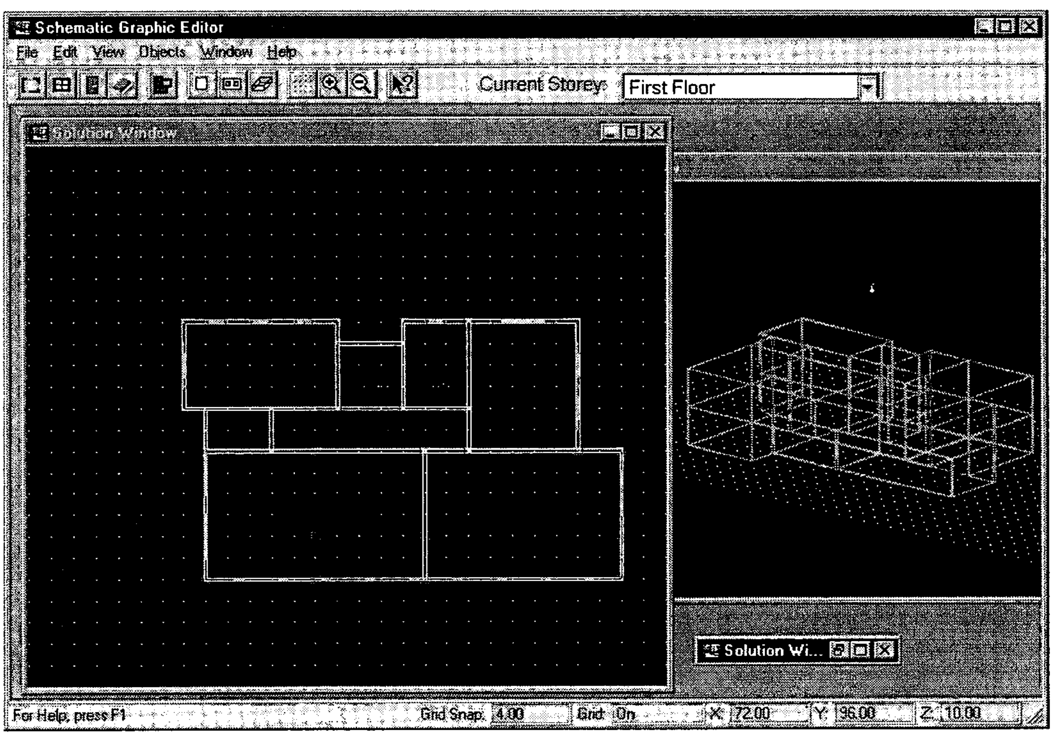

Figure 12. The Schematic Graphic Editor (SGE) is a stand-alone application that is linked to the BDA and allows designers to specify geometric attributes of building components.

One of the features in the design of the BDA and SGE data schemata is the concurrent representation of real world objects, such as "walls" and "windows," as well as related conceptual objects, such as "spaces." This type of combined representation allows designers to move whole spaces around, while the SGE automatically differentiates between exterior and interior wall segments for the assignment of appropriate values for wall construction.

Current status

The development of the BDA building model has been based on a "bottom-up" approach, covering only the data needs of the simulation processes that are linked to it. In its initial version, currently at Beta testing, the BDA supports the data needs of two simulation programs: DElight (Hitchcock 1995) and RESEGY (Carroll et al 1989). These programs were selected because they were complex enough to raise the necessary issues during the development of the BDA main program, and simple enough to allow focus on the development of the database management and the process control algorithms.

DElight computes spatial and temporal distributions of daylight work-plane illuminance and glare index, as well as the potential for electric lighting savings through the employment of electric lighting controls schemes. The spatial distributions are computed for a single point in time that can be changed by the user. The temporal distributions are computed for a single point in space that can also be changed by the user. The DElight version linked to the initial version of the BDA is limited to modeling only rectangular spaces. If a non-rectangular space is drawn, then the DElight output does not appear in the space's list of parameters in the Building Browser.

RESEGY uses a simplified method to calculate thermal and energy loads. It operates in two modes, thus being the equivalent of two processes. One mode is used with "design day" data to compute required sizes for the heating, cooling and ventilation equipment of the HVAC system. The other mode is used with annual weather data distributions to compute monthly totals for energy requirements by end use and energy source. Following the general BDA process control schema, if the user requests energy information provided by RESEGY without having specified sizes for the HVAC equipment, then the BDA automatically activates RESEGY in HVAC auto-sizing mode and uses that output as input to reactivate RESEGY in energy computation mode for the computation of the energy quantities requested.

The Beta version of the BDA has been made available through the World Wide Web and is being reviewed by a large number of building professional and academics. The reviewers' comments are most helpful in shaping the BDA with features and capabilities that will make it most useful to building designers. In the meantime, work is already underway for the next version of the software that will include links to the DOE-2 and, possibly, the Radiance programs.

Future directions

The BDA environment has been designed for expansion. The initial version has served as a test-bed for alternative ways of communicating with external processes and databases, which are now considered for the development of an "Application Programming Interface" (API), which will greatly facilitate expansion. Future work is expected to include both research and development efforts by the BDA developers, as well as other collaborators from academia and industry.

There are several ways in which the BDA environment can be expanded and enhanced. These include the development of links to additional simulation tools and databases, specialized user interface elements, and design advice modules. The simulation tools that are currently linked to the BDA are focusing on energy and lighting issues, while there is wide range of other performance aspects considered for building decision-making, such as comfort, economics, safety, environmental impact, etc. Links to such simulation tools will provide additional information to further enhance the decision-making process.

A wide variety of contextual databases will eventually be necessary to satisfy the input data needs of simulation tools. These databases will provide information about economics, such as utility rates, construction costs, etc., environmental impact, such as emissions, embodied energy of materials, etc. Moreover, the current BDA libraries of building components and systems can be expanded to include not only additional "generic" options, but actual products from manufacturers of building components and systems, as well.

The user interface of the BDA has been designed to allow basic and general access to all information for review and editing. In addition to the development of links to commercial CAD systems, a variety of specialized user interface elements can be developed for specific building components, such as an HVAC editor, with diagrams, icons, pop-up lists with direct lists to libraries, etc. Many user interface elements can also be developed for different building professionals, or areas of specialization, such as a daylighting editor, where all daylighting-related parameters from various building objects, are organized together to facilitate the generation and testing of alternative strategies.

The default value selector of the initial version of the BDA is in fact the equivalent of an "advice module," that operates as a simple "expert system." It considers only three premises (building type, location and space type) to assign default values to most non-geometric parameters. This approach can be expanded and specialized, so that more sophisticated inference is applied to default value selection, as well as advice modules that will recommend alternative options for design parameters towards specific performance improvements.

Finally, there are several ways that the BDA core program can be expanded. The current version of the BDA is a single-user, single-CPU program. Future versions will capitalize on the capabilities of the BDA database management system to support multi-user distributed computing over local and wide-area networks. An integrated Issue-Based Information System (Kunz and Rittel 1970; Noble and Rittel 1989) would greatly enhance collaboration through the identification, management and resolution of issues. The same approach could be used when the BDA will be linked to construction, commissioning and operation tools, for the identification and the resolution of issues raised through changes during construction, unexpected performance during operation, etc.

Conclusions

The research and development efforts described in this paper serve two main objectives:

The formulation of a software environment that will facilitate the exploration of ideas for the use of information technologies in the building life cycle.

The development of tools that will facilitate the consideration of important performance issues, such as those related to energy and environmental impact, which are now mostly ignored.

The initial version of the BDA is intended primarily for academic use, both as a research tool and teaching aid. To a lesser degree it is intended for professional use, especially during the early, schematic phases of building design. The latter use is expected to increase in future versions of the BDA, when it will be linked to more sophisticated simulation tools, like DOE-2 and Radiance, which have been extensively validated and are already in limited use by the building industry.

Over the next several years, collaborative efforts across various building-related disciplines will be needed to realize the overall vision of a computerized building industry. Appropriate licensing and distribution of the BDA executable and source code to academia and industry is expected to:

Encourage and facilitate further research and development efforts using the core BDA technology towards expanded applications.

Introduce these tools to the next generations of building designers, facilitating the understanding and consideration of multiple design issues, including energy and environmental impact, which are now mostly ignored.

Through expanded use of the tool by the building design community, create a large enough market to support business opportunities for the software and building industries to provide commercial distribution and support.

Common use of BDA-like tools will transform the way buildings are designed, constructed and operated. The overall vision includes multiple simulation tools and multiple databases that are all interoperable in a distributed, networked environment. The information generated during the design process will be immediately available during construction and commissioning to facilitate last-minute changes and assure expected performance. Actual building performance information will also be used to further guide and improve future design decisions, continuously improving the environments we live in.

Acknowledgments

The research reported here was funded in part by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Systems and Office of Building Equipment of the U.S. Department of Energy, as well as by the Laboratory Directed Research and Development (LDRD) Funds of Lawrence Berkeley National Laboratory, under Contract No. DE-AC03-76SF00098.

References

ASHRAE. 1993. *ASHRAE Fundamentals Handbook.* American Society of Heating, Refrigerating and Air-conditioning Engineers.

Carroll, W.L., B.E. Birdsall, R.J. Hitchcock and R.C. Kammerud. 1989. "RESEM: An evaluation tool for energy retrofits in institutional buildings." *Proceedings of Building Simulation '89*, pp. 107-112. International Building Performance Simulation Association.

Feustel, H.E. 1992. "Annex 23 multizone airflow modeling – an international effort." *Proceedings of the International Symposium on Air Flow in Multizone Structures*, Budapest, Hungary, 1992.

Hitchcock, R.J. 1995. "Advancing lighting and daylighting simulation: the transition from analysis to design aid tools." *Proceedings of Building Simulation '95*, pp. 308-315, International Building Performance Simulation Association.

IESNA. 1993. *IESNA Handbook.* Illuminating Engineering Society of North America.

Kunz, W., and H. Rittel. 1970. "Issues as elements of information systems (IBIS)" Working paper 131, Institute of Urban and Regional Development, CED, UC Berkeley.

Noble, D. and H. Rittel. "Issue-Based Information Systems for Design." Working Paper No. 492, Institute of Urban and Regional Development, University of California at Berkeley, 1989.

Papamichael, K., and J.P. Protzen. 1993. "The Limits of Intelligence in Design," *Proceedings of the Focus Symposium on Computer-Assisted Building Design Systems, of the Fourth International Symposium on System Research, Informatics and Cybernetics*, Baden-Baden, Germany.

Ward, G. 1992. "Visualization." *Lighting Design and Application*, Vol. 20, No. 6, pp. 4-20.

Winkelmann, F.C., B.E. Birdsall, W.F. Buhl, K.L. Ellington, A.E. Erdem, J.J. Hirsch, and S.D. Gates. 1993. "DOE-2 Supplement: Version 2.1E" Lawrence Berkeley Laboratory report no. LBL-34947.

Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road | Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098