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Authors
Selkowitz, S.E.
Papamichael, K.M.
Wilde, G.M.

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Lawrence Berkeley Laboratory

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S. E. Selkowitz, K. M. Papamichael, and G.M. Wilde

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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S. Selkowitz K. M. Papamichael M. Wilde

Abstract

A review of current daylighting design tools indicates that over 30 tools are now available, including nomographs, protractors, overlays, and programs for micro-, mini-, and mainframe computers. Computer-based tools allow testing and analyzing of more design alternatives under a wider variety of conditions than was previously practical with slower techniques, but they have not fundamentally changed the information available to the design professional. These tools are applicable to certain limited functions of the design process and do not address the varying information needs of the designer at various points in the design process. We describe a concept for a computer-based building envelope design tool that is structured to overcome many of the limitations of the existing tools. The tool would address daylighting design in the context of the overall building envelope design, covering a range of environmental quality issues in addition to quantitative aspects of lighting and energy use. It would be useful throughout the process of design, construction, and occupancy, and is intended to provide important feedback that is often missing between those stages of the building's life cycle. A cost-effective tool with these performance features is not technically feasible using today's hardware technology. However, examination of the development of the necessary technologies provides strong evidence for future feasibility; accordingly we are developing the tool to be used in a 1990+ time frame. To date we have studied the features and capabilities that such a tool should have, as well as several key areas, such as the design process, computer graphics, imaging systems, expert systems, and building science data bases.

Introduction

Architectural design is a process that involves many different activities from the initial decision to have a building designed and built through making the final detailed drawings and specifications for the actual building construction. Many tools have been developed over the years to assist building designers in effectively and efficiently carrying out design tasks. The most successful and prevalent tool in most design tasks is the combination of a pencil and tracing paper, driven by the skills, knowledge, and experience of the designer. One major limitation of this powerful tool is the lack of speed, which has become critical with the evolution of architectural practice. The rapid pace of building technology development and building-related research makes this limitation even more profound. The designer is left with little time or capacity to collect, organize, and apply the newly available knowledge. Moreover, as new building technology is applied to solve problems, and as researchers in building sciences develop a better understanding of the interactions between the environment, buildings, and building users, the number and depth of design considerations will continue to increase at a rapid rate.

This need for more memory and speed has led to increasing use of computers in architectural practice. However, most of the currently available computer applications for architectural practice are limited to routine and repetitive tasks like drafting, word processing, engineering calculations, and accounting. These tasks are not directly related to the design process, and do not require the designer's creative expertise. The memory and speed of computers have not yet been effectively applied to the conceptual and creative part of the design process to assist in the designer's difficult and important role, by increasing efficiency and reducing uncertainty.

Many design tools are currently available to the designer and several have been implemented as computer applications. However, these tools address specific tasks in the design process and are not integrated. Since design is not a linear process, the designer must constantly switch from one tool to another, investing time and effort to iteratively analyze the output of one tool and prepare appropriate input for another. Moreover, there are still many design tasks that are not addressed effectively or at all by the available tools. Variables that can not be easily or satisfactorily quantified, such as aesthetics, glare potential, and view access, may be ignored or omitted in the design process.

S. Selkowitz, Group Leader; K. M. Papamichael, Research Associate; and M. Wilde, Staff Scientist. All with the Windows and Daylighting Group, Center for Building Science, Applied Science Division, Lawrence Berkeley Laboratory.

Another important issue that is not adequately considered is the lack of continuity between the design of a building and the rest of its life-cycle stages, from construction and occupancy to probable retrofit, renovation, conversion, and finally demolition. Our experience with post-occupancy evaluation studies indicates that this lack of communication between the designers of a building and its occupants or managers leads to ineffective use and operation of buildings, since the occupants rarely understand the designer's intent. In addition, the designer rarely benefits from an improved understanding of the success or failure of a specific solution that would come from feedback from the occupants and managers of buildings.

During the last two years, we have been considering the design and development of an "ideal" building envelope design tool with attributes dictated by the needs of the building-design community and the nature of the design process. The driving forces in our efforts were the limitations of the existing tools and the opportunities offered by the development of expert systems software and imaging technologies. We have been following the development of new software and technologies and have been exploring the potential of their contribution towards the design and development of an advanced computer-based design tool that would address both quantitative and qualitative aspects of building design. We understand the magnitude of the time and effort required, and are considering a five-year tool-development period, planned to coincide with the anticipated availability of affordable powerful computing workstations that would make the tool widely accessible in the building-design community.

In this paper we describe our concepts of the tasks in the design process, and the associated needs of the designer, along with an overview of the available tools, theories, and technologies that would contribute to the design, development, and implementation of an advanced computer-based design tool. We also discuss our past and current activities aimed at the achievement of this ambitious, yet realistic, goal.

Limitations of Existing Tools

It may appear that existing design tools address all of the design-related activities. One can identify tools for economic analysis, site planning, structural analysis, or energy analysis. However, these tools are independent, each serving a particular task in the design process. The use of each tool requires particular knowledge and skills for preparation of the input and for effective interpretation of output, thus introducing a trade-off between prospective benefits and effort and time invested. Since the input/output of each tool follows specific data structures and formats, the use of several independent tools requires time-consuming specialized processes either for formatting the same data in different ways, or for converting the output format of one tool to serve as input for another. But even if the currently available tools were combined and implemented in an integrated package, there would still be major limitations. For building design criteria such as aesthetic appeal, glare potential, and view access, there is a lack of appropriate variables or performance indices for effective communication and evaluation. Also, there is lack of means for effective and efficient utilization of the knowledge of a designer, either for the development of design criteria or for determining and evaluating design alternatives.

In other areas, although the information provided by available tools may be adequate, it is usually not in the right format to be directly utilized. For example, the output of powerful tools for the evaluation of the interior luminous environment are often in the form of data tables and charts. Effective use of such information for the evaluation of the luminous environment requires specialized knowledge and experience. Moreover, even if an experienced lighting designer can interpret such output, communication of his/her understanding to the other interested parties involved in the design process is very difficult, if not impossible. It is crucial to recognize the visual nature of architectural design, suggesting more extensive use of images of the environments to be communicated or evaluated in the design process.

The design of buildings requires an enormous amount of knowledge, which is continuously increased by constant progress in research and technology development and, on an individual level, by the experience of the designer. Such knowledge includes successful and unsuccessful solutions to specific design problems, expert advice from specialized consultants in specific areas, and new technologies and research findings. There are no tools currently available to help the designer store, organize, evaluate and manipulate this knowledge comprehensively and efficiently. The designer has to rely primarily on his/her own strategies and mental abilities with limited help from publishers of handbooks, product files, and periodicals.

Advanced Envelope Design Tool Concept

There has been a rapid increase in the number of computer-based tools for designers over the last few years. Most of the widely used ones are based on microcomputers. While these tools can greatly increase the speed and productivity in solving specific problems, they do not begin to approach the required capabilities. The economics of survival in the software business dictate producing software for popular machines, which at the present time do not have the technical capability (e.g. speed and storage) to meet the needs of an "ideal tool" as we conceive it. Instead of building a tool around the available hardware, we choose to define an ideal tool and then find or develop the hardware/software to make it possible.

During the last two years, we have been identifying and exploring various design tasks and the resulting needs for information and processes. We focused on identifying the attributes of an ideal tool for the design of buildings and ignored the limitations of existing technologies, to avoid constraining our imaginations. The attributes that we identified are summarized below.

An "ideal tool" for the design of buildings should:

- be useful for all building and occupancy types as well as for all climates,
- be useful throughout the design process, from the initial design concept to the detailed drawings and specifications,
- be useful throughout the building life cycle, from design and construction to renovation and demolition,
- support design tasks at all levels, from site planning and form massing to furniture layout,
- address all critical design issues, from human comfort and energy/cost requirements to aesthetics,
- be interactive and encourage/reinforce interaction between design participants and interested parties,
- accommodate different users, such as architects, engineers, lighting designers, interior designers, etc.,
- accommodate different skill and experience levels, providing the necessary guidance,
- support the visually oriented nature of design and provide means for the evaluation of non-quantifiable design aspects,
- build on prior projects by storing and organizing the project and post-occupancy evaluation data, so that it "grows" along with its users,
- be cost effective with respect to time and hardware/software requirements.

Although we purposely avoided confining our list of ideal attributes to those we thought "realistic" or technically feasible, the technology to realize those ambitious capabilities is expected to become available in the next five years. This conclusion is based on the explosive growth in such fields as expert systems and imaging, accompanied by the revolution in the development of powerful microcomputers with greatly enhanced computational power and storage capabilities.

The magnitude of the information required by an ideal design tool introduces the issue of efficient data handling, especially to support visual information in the form of images. We intend to minimize data manipulation time by generating appropriate indices from multiple parametric analyses of standard building design cases (Sullivan and Selkowitz 1985; Kim, Papamichael, and Selkowitz 1986), use expert systems software to efficiently guide and control the computing processes, and take advantage of the continuous advances in computer graphics and imaging technologies to generate, store, retrieve, and manipulate images (Figure 1). Following are brief discussions of three key technology areas critical to the design and development of such a design tool: the design process, expert systems, and computer graphics/imaging.

The Design Process

The design process is aimed at producing a plan which, if executed, is expected to lead to a situation with specific intended properties but without unintended or unforseen undesirable side- and after-effects (Rittel 1973). Two major tasks can thus be identified in architectural design. The first task is the identification of the "ought-to-be environment." The second task is the prescription of the plan that would lead to the creation of the "ought-to-be environment." Each of these tasks requires availability and manipulation of specific kinds of knowledge.

During the task of identifying the "ought-to-be environment," the designer determines the design criteria and their relative importance for decision making. This is the process of creating a value system to be used later for the evaluation of alternative design solutions. It can be viewed as an argumentative process between the various parties that are interested in the development of 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" (Kunz and Rittel 1970; Dehlinger, Protzen 1972). These are text data bases that can help to explicitly organize the various 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 is to look for ways to create an environment that satisfies the developed design criteria. This can be considered as the "creative" phase of design and can be further subdivided into two parts: 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 his/her personal strategies for generating alternative design solutions. Several concepts have been formalized to assist the designer in generating ideas, such as the "morphological box" (Grant 1977) and the "morphological tree" (Grant 1977). 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 alternative building designs by providing information about the performance of the building with respect to one or more quantifiable design issues, such as thermal comfort, luminous comfort, energy requirements, or economics. The designer evaluates the performance according to the design criteria and makes a judgement on the appropriateness of the design alternatives.

Since design is not a linear process, design tasks are not independent. For example, the designer simultaneously generates ideas and evaluates them, constantly altering and reconstructing the image of the "ought-to-be" environment. What makes design complicated is that there are many criteria to be considered and there are often complex trade-offs between them. Design solutions can be considered as compromises between many individual solutions that are optimized with respect to limited criteria.

Expert Systems

Expert systems are computer programs that allow encoding of expertise in a field into rule statements (the knowledge base or rule base) and then mimick human reasoning, in order to make certain types of decisions. The reasoning is performed by the "rule interpreter" and is a process of plowing through the rules, testing assertions, checking data, and asking questions until either it knows enough to conclude something, or collapses trying (Park 1984).

We believe that there can be no single expert for determining the "ought-to-be environment." There are usually many different parties affected by the development of an environment, often with conflicting interests. The only expertise that can be identified is for guiding the process of dealing with a design problem, but not for the subject matter of the problem (Rittel 1972). However, once the design criteria have been established, expertise can be found for constructing an environment that satisfies specific requirements.

The concept of expert systems can be applied in many areas of the design process, especially for the task of determining the "ought-to-be environment." Once a set of design criteria has been identified and an evaluation system has been determined, expert knowledge can be applied to generate a set of potential design solutions and rank them according to their performance with respect to the design criteria considered. We understand that, although the necessary expertise may be available, the design and implementation of an expert system that would cover the design of a whole building is an extremely ambitious and longer-term endeavor. However, we believe that over a shorter time period expert systems can be created for many specific small-scale tasks in the design process, such as site planning, spatial relationships, structural design, mechanical design, window design, lighting design, or furniture layout, based on the available expertise in each area. These expert systems would play the role of "consultants," specialized in specific areas of the design process, in the form of a knowledge base that holds the appropriate rules, integrated with a data base that holds the necessary data for the variables to be considered.

The effectiveness of such expert systems would be limited by those design criteria for which performance variables cannot be easily or satisfactorily identified. Even so, the use of expert systems for the consideration of those design criteria with identified performance variables and quantitative indices would greatly contribute to the effectiveness and efficiency of the designer by significantly reducing the number of both the design criteria and the design solutions to be considered directly by the designer.

Computer Graphics and Imaging Systems

Architectural design is a visually oriented process. The generation of appropriate images of the predicted environment is critical for both communication and evaluation. The traditional hand drawing of such images (i.e. plans, sections, axonometrics, perspectives, etc.) is time consuming and requires significant effort. Moreover, hand drawings can not be easily altered or modified. Computer graphics technologies are already bringing a revolution to the design profession in the form of Computer Aided Drafting (CAD) hardware/software packages. However, most of the software currently used in architectural and engineering offices generates graphics by mimicking the hand-drawing process. Only a few computer graphics packages quantitatively account for the effect of the luminous environment, which is the most important factor for visual perception. However, the most sophisticated software (i.e. ray-tracing) can currently be implemented only in large computers since it requires significant computational time and data storage. However, increasingly powerful computer graphics packages are becoming available for engineering workstations, which are making rapid advances in computational power per unit cost.

Imaging systems are the technologies with the most promise of overcoming the limitations of computer graphics applications. Here we are considering hardware and software to capture, store, manipulate, transmit, and present detailed, realistic images from sources such as real environments, scale models, or documents, and from direct computation. While these may offer less flexibility than computer graphics, they are very efficient in image generation, storage, and retrieval, and can render a very realistic representation of the environment. So far, they have been used extensively in non-architectural fields, such as the military and aerospace, for robot vision and flight simulators. As the imaging technology becomes less expensive, its commercial applications, such as video systems, electronic cameras, and optical disks, are multiplying quickly. While these may not be directly relevant to our needs, they fuel the industrial research and development for the next generation of more sophisticated imaging technologies.

Imaging systems and optical-disk storage could be used to generate very large data bases of images for use with a design tool. Such data bases may cover a wide range of visual information. They may include images of pages from handbooks, product catalogues, and magazines, for efficient "on-line" reference, images of existing buildings, or images from scale models. These images might be combined in various ways: the images of an actual view through a window may be integrated with computer graphics capabilities to produce a realistic representation of interior spaces. Currently, the storage capacity of a single optical disk (CD ROM) is in the range of 50,000 images. Not only will capacity increase and costs fall, but these Read Only Memories (ROM) will also be replaced by Write Once Memories and ultimately by eraseable media, allowing the user to routinely modify the image data base. This capacity for image storage along with the very short retrieval time that is available will contribute significantly to the tool's efficiency as part of the overall concept.

Implementation: Past, Current and Future Activities

Our concept of an advanced tool for the design of buildings has emerged over many years of design tool development in our research program. Our research work has been oriented towards understanding the luminous and thermal performance of the building envelope with respect to building performance and occupants' health and comfort. This knowledge has been used to generate design guidelines and tools, primarily for energy-conscious design (Bryan and Clear 1981; Bryan and Carlberg 1984; Selkowitz and Gabel 1984; Lighting Systems Research Group 1985; Windows and Daylighting Group 1985, 1986; American Architectural Manufacturers Association 1986).

Our experience has indicated that unless such tools include integrated consideration of other than energy-related criteria, their usefulness to designers is limited. Most designers are not interested in considering one design criterion at a time, and the interest in energy as a design criterion has plummeted with the price of oil. The designer is interested in predicting the performance of alternative solutions with respect to all of the design criteria considered. For example, while the designer is exploring means for optimizing the energy performance of alternative solutions, he/she is interested in the concurrent effects on luminous or thermal comfort, view, economics, etc. The above realization has encouraged us to increase the number of design criteria considered in our research work. Currently, we are developing a methodology to generate fenestration performance indices from regression techniques applied to data derived from parametric building operation simulations. These indices will be used to efficiently provide fenestration-related performance data for any design criterion for which indices can be adequately quantified (energy, economics, glare, thermal comfort, etc.), primarily for comparative evaluation of alternative fenestration designs. Once the methodology is established, we intend to generate such indices for a large variety of commonly used fenestration systems. We have also been exploring the potential of expert systems applications in fenestration design.

Another issue that emerged from our studies of the performance of fenestration systems is the lack of means for effectively evaluating the quality of the luminous environment, view access, and aesthetic appeal, without the use of realistic images. During the last years we have been working on using our state-of-the-art illuminance and luminance computer models to generate realistic images of environments under different lighting conditions (Modest 1982, 1983; Ward 1986). We have also been working on the development of a luminance mapping SLR camera to be used for the evaluation and analysis of actual environments. Currently, we are exploring the potential of imaging technologies for generating, storing, and manipulating such images, as well as the hybrid approach of using computer graphics and imaging systems concurrently to increasing overall efficiency. We have continued to track the development of microcomputer technology and new high-resolution imaging systems and expect to use each in the near future to demonstrate the potential of the overall tool.

Conclusions

We have described the rationale and direction of a major project to produce an advanced building envelope design tool over the next five years. From our perspective and based on our contacts with the design profession over the last 10-15 years, the need for such a tool is clear. Although many technical details have yet to be settled, our ongoing review of the relevant technology base for such a tool has convinced us that in the next 5-10 years, the required technology will be both available and affordable. Planning a project around hardware capabilities that may be available in five years entails significant risk, which we acknowledge. However, the expert systems' knowledge bases and the building science data bases will take several years to develop, providing an opportunity to track the evolution of the new hardware. To complete the project as envisioned will therefore require significant time and financial resources. We began the development of this tool concept with support from the U.S. Department of Energy. In view of the broad range of potential beneficiaries we hope to ultimately support this effort from a number of private and public sources.

This paper is presented as a statement of intent rather than as a record of accomplishment. We hope it will stimulate critical review and help us to refine this vision and begin the implementation phase. We welcome comments on any of the issues raised herein.

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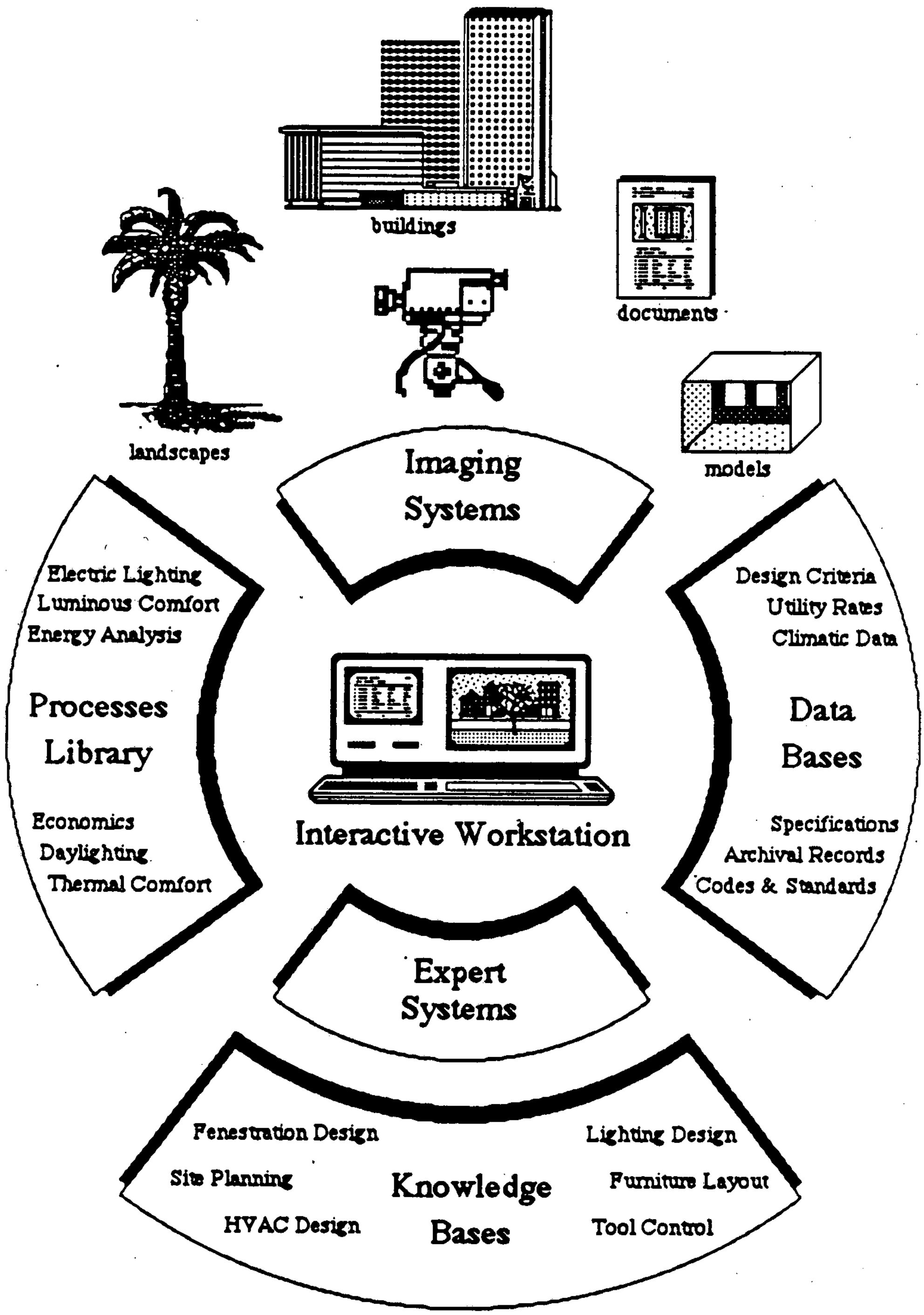

Figure 1 Schematic of the concept of an advanced computer-based building envelope design tool, showing the major tool elements and examples of their tentative contents.

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UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720