AN INTERACTIVE GRAPHICS ENVIRONMENT FOR ARCHITECTURAL ENERGY SIMULATION

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ABSTRACT

An interactive computer graphics system has been developed for the architecture profession which provides a "design environment" for the evaluation of building energy consumption. The system includes an integrated set of graphic input tools which generate the geometric and attribute data necessary for the determination of thermal load in buildings. In addition, a comprehensive set of graphical output routines has been created to allow the designer to visually interpret the results of alternative design strategies.

INTRODUCTION

It is necessary that the architectural profession seek new ways to make buildings efficient in their use of energy. The evaluation of a building's energy performance requires the determination of heat loss / heat gain for each component of the structure and is dependent on the thermal envelope, the orientation, the external climate, and the internal operation conditions. The tools currently available for analysis of building energy performance do not lend themselves to use in the architectural design process. Furthermore, although architects work and think in visual and spatial terms, the current energy analysis programs are all numerically oriented. Computer graphics can be used to help bridge the gap between the visual, synthesis-oriented world of the architect and the necessity for numerically-oriented analysis.

The ENERGY design environment is designed to be a highly interactive, visual means for architects to easily create and manipulate large complex building descriptions. It consists of graphic input tools which allow the architect to create a volumetric description of the building geometry; create libraries of material, wall section, operating schedule, and window data; and assign specific elements of these libraries to geometric entities in the building description. This information is stored in a database which relates geometric data, attribute data, and thermal performance data for a particular design problem.

The design environment also provides output tools which the architect may use to graphically study the thermal performance of a building and its components. These include two and three-dimensional graphs of thermal performance, color-coded representations of heat loss and gain, and tools to allow the architect to study the relationship of solar orientation to shading patterns using shadow algorithms. These tools are structured to permit the architect to interactively view the relationships between various components and their effect on the building's energy performance.

LITERATURE SURVEY

Several thermal load determination programs have been in use for a number of years. These programs calculate the heat loss and heat gain for a building based on climate and operating conditions. The most advanced of these programs are ESP-2 [2], DOE-2 [11,16], and BLAST [15]. All currently depend on numerical input data making their usage cumbersome, expensive, and error-prone. Graphic preprocessors would substantially improve the use of such programs by eliminating these problems.

The development of graphic energy analysis pre- and post-processors is analagous to the development of graphic finite element pre- and post-processors in structural engineering. The algorithms to perform finite element analyses were well-established, but the difficulties in data input and interpretation led to the development of interactive graphics programs to improve human-machine communication [7,8,14,23]. These programs used a variety of graphics techniques to prepare input data and display the output of finite element analysis programs.

There have been several programs which address the problem of preprocessing thermal load data using interactive graphics. These include [1,18,21]. There is no precedent, however, for a complete design environment which includes both pre- and post-processing as well as a set of design tools for building energy load analysis.

The concept of a management program which controls and coordinates the activities of a number of applications has been previously explored in [5,17,22]. However, graphics versions of such programs have not been published.

For post processing, as well as establishing a symbiotic design environment between the designer and the computer, it is necessary to rely on sophisticated raster graphics algorithms for color displays. Shadowing algorithms such as those used in the ENERGY design environment are described in [4,10]. Methods for the color display of parametric data on two and three dimensional surfaces are described in [12,23].

OVERVIEW

The ENERGY design environment acts as an interface between the architect and energy analysis tools. It allows the architect to deal with the energy implications of a design problem using a familiar graphical vocabulary. It manages information on building geometry, thermal performance, orientation, weather data, and scheduling data; all of which is necessary to perform a building energy analysis. Included in the ENERGY design environment are aids to design decision making, a preprocessor for energy analysis data, and a postprocessor and display system for the results of an energy analysis. Visual cues are used whenever possible to facilitate interaction with the computer. Attempts have been made to adapt to the architect's mode of working rather than forcing the architect to conform to the computer (or programmer's) mode of working.

Structure of the system. The ENERGY design environment consists of four components: the ENERGY program, the project database, the generic database, and one or more analysis programs (Fig. 1). Each of these components is described below. The primary component is the ENERGY program which forms the interface between the architect and the computer and coordinates the activities of the other components. The architect communicates with the ENERGY program via menus using graphic input techniques. The menu pages are organized into a hierarchical tree structure containing five major subsystems: design tools which provide design decision-making tools for the architect. a library manager to deal with the generic database, an attribute editor to assign project attributes in the project database, a preprocessor to prepare data for analysis and control execution of the analysis, and a postprocessor to interpret the results of the analysis (Fig. 2). In addition, a view page (Fig. 3) is provided to allow the architect to display and manipulate images of the building geometry.

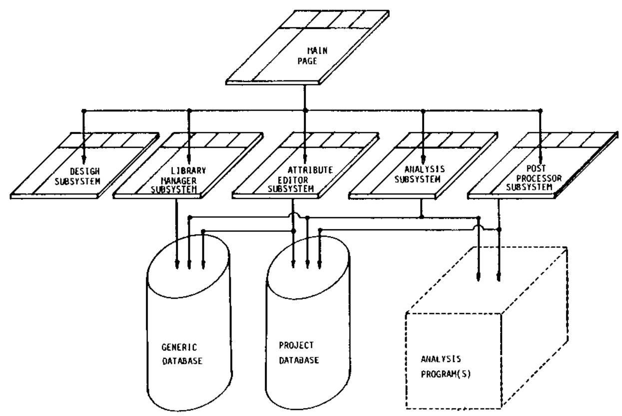

Figure 1. Components of the ENERGY design environment.

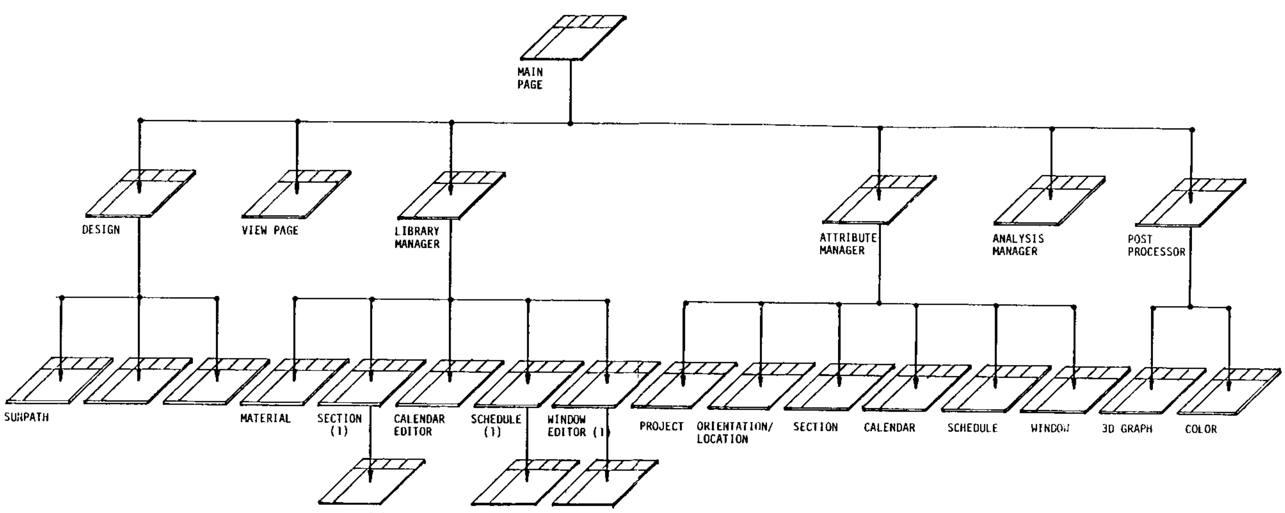

Figure 2. The menu tree of the ENERGY design environment.

Database. Information about each project is contained in a project data file. This file contains all of the information specific to the project and describes the building in sufficient detail for the ENERGY environment to perform the tasks required of it.

Each project file contains a complete description of project-specific data including building geometry, building location and orientation, project name, analysis results, and a historical record of work done on the project. In addition, the project file contains pointers to the generic database (described in the section on the library manager below). These pointers do not directly reference elements in the generic data libraries but reference a map in the project file which, in turn, points to specific generic data elements. This method of indirect referencing allows the designer to change the reference to an entire class of elements without changing each instance of the pointer.

The project file is structured as a tree and is implemented using a hierarchical polygonal database [9,13]. This database allows the grouping of geometric entities and the assignment of attributes to these groups.

DESIGN TOOLS

In many cases, the architect does not need to perform a complete energy analysis to determine the energy implications of a design decision. During the design process, it is often more useful for the architect to get a rough idea of thermal performance using quick, approximate methods. For this reason, the ENERGY environment provides tools which allow the architect to interactively evaluate a design without the time and expense involved in completing a full thermal analysis of the building. The design tools currently provided by the ENERGY environment include solar path diagrams and shadowing algorithms which are described below.

Solar path diagrams. Solar path diagrams provide the architect with the means to quickly observe the implications of building form and orientation on solar load. A solar path diagram shows the arc of the sun's position relative to the building for a given latitude, longitude, and date [3,6,19] (Fig. 4).

The solar path design tool provides several functions to aid the designer in the evaluation of solar load. These functions include rotation of the diagram to view the sun path and rotation of the building to study the effects of varying orientation. Perhaps most important, by selecting a time of day from the diagram, the architect can generate a "sun's eye" view of the building (Fig. 5). Hidden surfaces may be removed from this image leaving only those surfaces visible to the sun (Fig. 6). These visible surfaces will be in the sun at the specified time of day. All other surfaces will be in shadow and will, consequently, have no solar load. This capability is extremely useful in the design of "brise soleil" and other shading devices.

In addition to generating a static sun's eye view for a given time of day, the architect may choose to generate a sequence of sun's eye views for a given day. The sequence begins with sunrise and ends with sunset. The architect can very quickly see the changes in solar load as the day progresses. An auxiliary display of sun's path shows the architect the time of day as the sun moves through the sequence.

By allowing the architect to view the form and orientation of the building at the conceptual design phase and to visually determine its

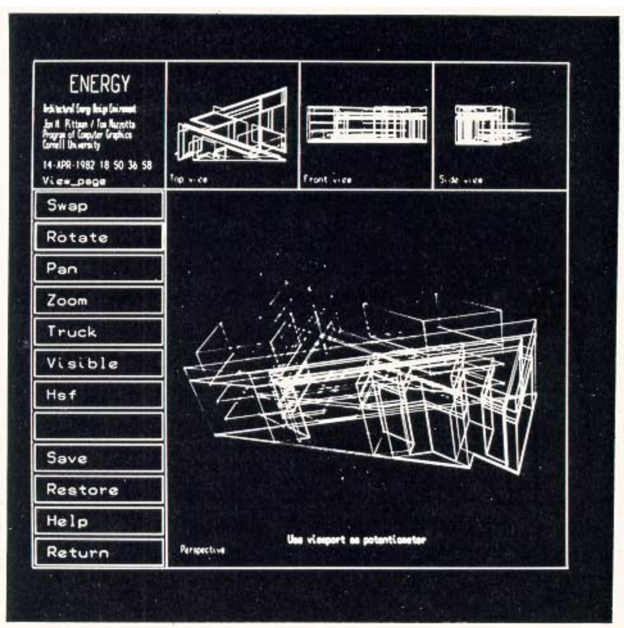

Figure 3. View Page allows the architect to view and manipulate building geometry.

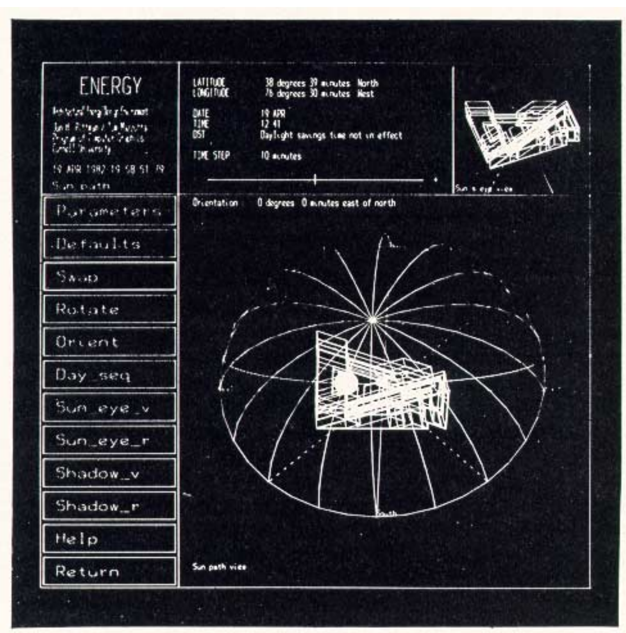

Figure 4. Solar path diagram showing arc of sun position and sun's eye view.

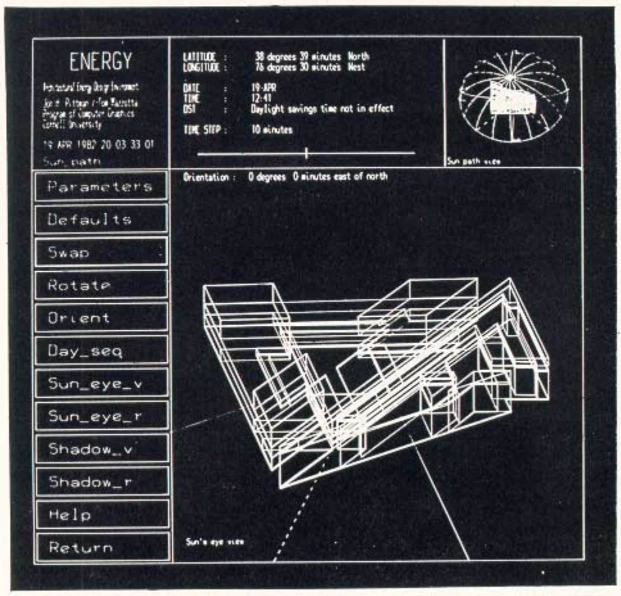

Figure 5. Sun's eye view of the building.

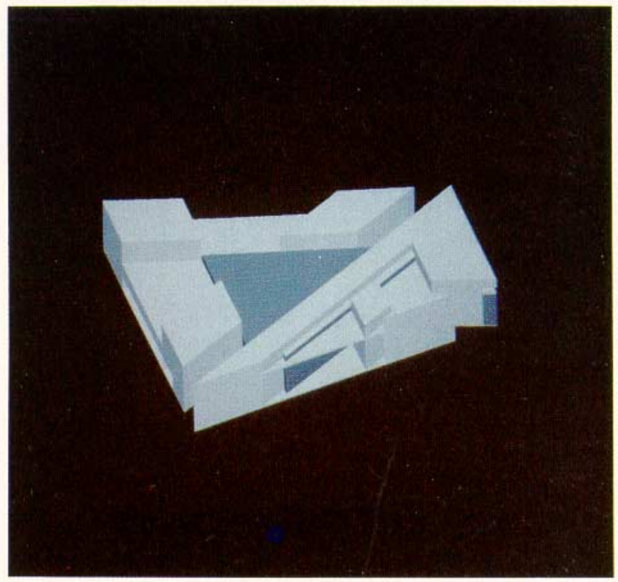

Figure 6. Sun's eye view of the building with hidden surfaces removed.

performance due to solar loads, design alternatives can quickly be evaluated in terms of solar performance.

Shadowing algorithms. Through the use of the shadowing facility, the architect can display the shadow patterns cast by the building (or a group of buildings) at a particular location and time. The shadowing facility uses well-known shadowing algorithms [4] to generate this display. As with the sun-path diagrams, the shadowed image of the building can aid the architect by providing a quick, visual evaluation of solar load and the shading effects of various building forms and architectural elements.

The design tools provided by the ENERGY environment supplement, but do not replace, a complete thermal load analysis. However, they do allow the architect to iterate through a design cycle with a minimum amount of effort and a maximum amount of aid in the evaluation of various design alternatives.

LIBRARY MANAGER

To perform an accurate and comprehensive building energy analysis, it is necessary to describe geometric data, thermal performance data, and operating conditions in the building. Some of this data is specific to a given building; other data, however, is generic. The ENERGY design environment maintains this generic data in a set of libraries. These libraries are maintained by the library manager which consists of a set of graphic library editors, a set of library access routines, and a set of direct access disk files which contain the library data (Fig. 7). Each type of generic data is contained in a separate library and managed by its own editor and access routines. The editors, access packages, and library files are described below.

Generic data may be applicable to many different buildings and may be described and maintained independently of a specific building project. This generic data includes building material information, building envelope section data, calendar data, schedule data, and window data. Users may add or modify library entries. As the usage of the ENERGY design environment increases, the libraries of generic data will become more complete and accurate. The generic data libraries, therefore, are an evolutionary part of the ENERGY design environment. They provide a shared pool of data which is accessible to everyone using the environment and may be applied to a number of specific building projects.

Each library of generic information is maintained by a graphic editor which provides a quick, convenient means of manipulating generic data.The editor allows the designer to interactively add, delete, or modify the information contained in its

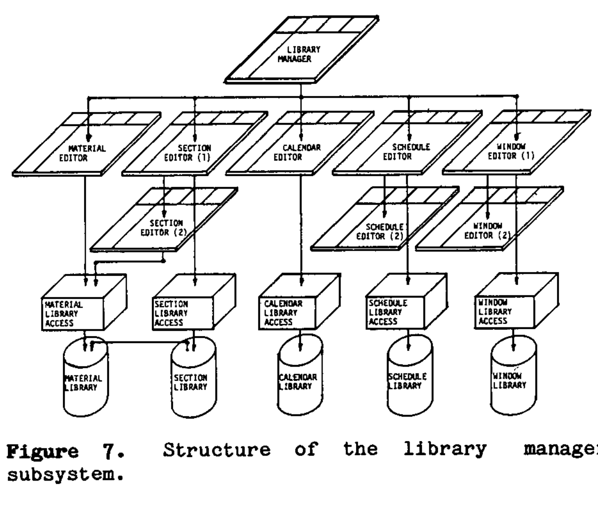

Figure 7. Structure of the library manager subsystem.

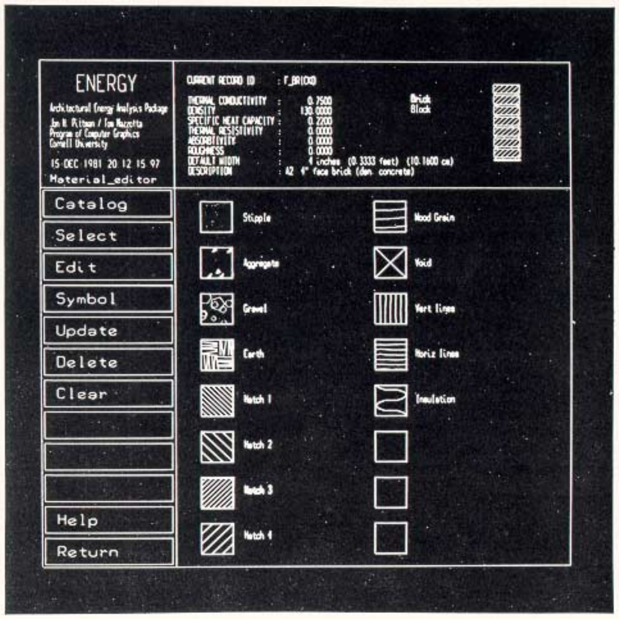

Figure 8. Material library editor with symbols.

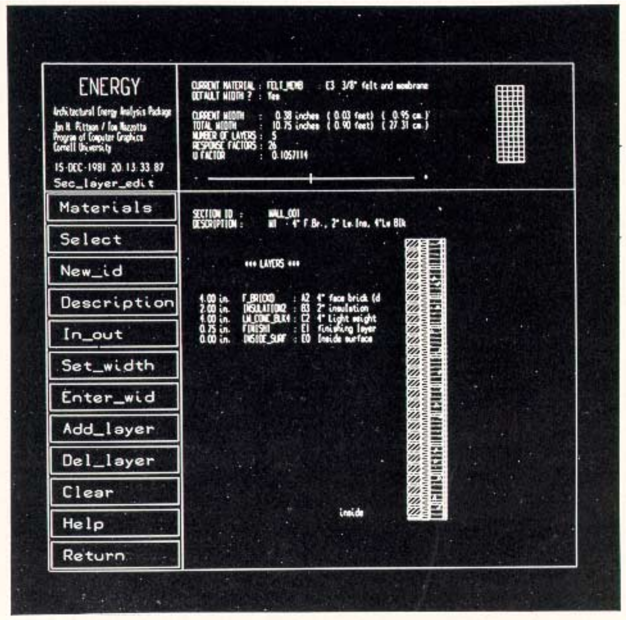

Figure 9. Section layer editor.

library. Functions are provided by each editor to display a catalog of entries in the library and to select one of the entries for editing. Since the graphic editors provide immediate visual feedback to the designer, the integrity and accuracy of the database is easily and efficiently maintained.

Material library. The material library contains information about commonly used building materials. Each entry in the material library provides a comprehensive description of that material's properties, including its thermal conductivity, specific heat, density, thermal resistivity, surface absorbtivity, and surface roughness. In addition, each material library entry contains the information necessary to construct a graphic display of the material (Fig. 8). This display uses standard architectural symbol conventions [20,25] and may be unique for each building material. It provides a familiar visual cue for the designer to identify the material.

Section library. Since the walls, floors, and roofs of a building consist of one or more layers of building materials, the section library contains a collection of building envelope sections. The thermal behavior of a given set of layers (i.e. building envelope section) is dependent on the thermal properties of the materials. Each entry in the building envelope section library contains a list of the materials which comprise the layers in the section (Fig. 9). Using this information, as well as the information associated with each material from the materials library, it is possible to compute measures of the thermal performance of the section. Each entry in the section library may contain these pre-computed values. Since many buildings use the same or similar building envelopes, it is clear that the use of this generic data library will help reduce the time and cost of describing the building for analysis purposes.

Schedule library. Heating and cooling requirements for a building may vary over a typical day. In addition, the energy necessary to heat and cool a building is partially dependent on daily fluctuations of internal loads; including people, lighting, and equipment. The schedule library contains a collection of building operating schedules that specify the percentage of internal load and heating or cooling required at each hour of the day (Fig. 10).

Calendar library. The operating conditions of the building are dependent not only on time of day, but also on the day of the week and the season. In addition, holidays, Saturdays, and Sundays will generally involve different internal loading conditions than those occurring on a normal work day. Internal loading and operating conditions may also vary from season to season. For example, summer lighting loads may differ from winter lighting loads. The calendar library contains a set of calendars defining days of the week, holidays, and seasons (Fig. 11). The generic calendars contained in the calendar library may be assigned to a particular building to specify its pattern of daily operating conditions.

Window library. Although window placement is unique from one building to the next, window fixtures are relatively standard. Windows can have a significant effect on the thermal performance of a building because of direct solar gain, shading factors, and infiltration around cracks. Each entry in the window library specifies the geometry of the window, data on solar gain, data on infiltration through cracks in the window and frame, shading data, and information on overhangs and fins which might shade the window. The geometric and shading device information contained in each library entry allows the editor to construct a graphic display of the window according to standard architectural drafting conventions. The window library allows the designer to select standard windows from the

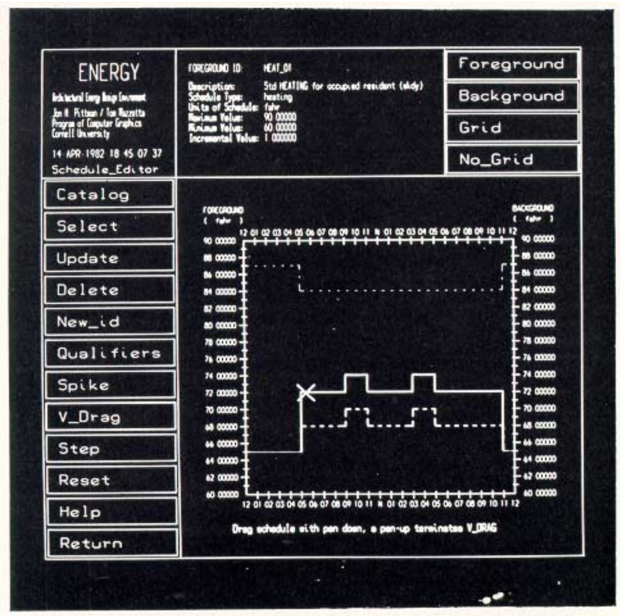

Figure 10. Schedule editor showing a typical building operating schedule.

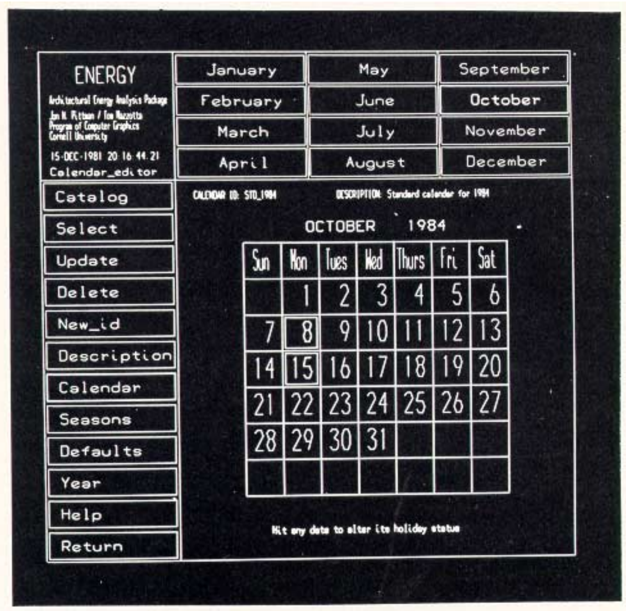

Figure 11. Calendar editor with a typical month.

catalog in a fashion similar to the actual design process of selecting a window from a product catalog of available windows.

ATTRIBUTE ASSIGNMENT

The project file described above contains a representation of the building geometry and other project-specific data. The building geometry representation is generated by a geometric modeling program which is external to the ENERGY environment [13,24]. To make the project file useful to the ENERGY environment, a large amount of additional information must be stored in the project database. The architect may store and manipulate this information by using the attribute assignment subsystem of the ENERGY environment. This subsystem consists of a set of editors which the architect may use to associate project specific information and generic data with the appropriate group in the project database.

The attribute assignment subsystem consists of six attribute editors: the project attribute editor, the orientation and location editor, the section attribute editor, the calendar attribute editor, the schedule attribute editor, and the window attribute editor (Fig. 12). Each editor allows the architect to graphically assign attribute information to the appropriate group in the project database.

ANALYSIS

To perform an energy analysis of a building, it is necessary to preprocess the data in the project database and execute an analysis program. After the analysis is complete, it is necessary to interpret the results and store them in the project data base for future use. The analysis subsystem of the ENERGY environment performs these three functions. It allows the architect to interactively specify which analysis package should be used, prepare input to the analysis, control the execution of the analysis, and automatically interpret the results of the analysis.

Many types of analysis packages could potentially be used with the ENERGY environment. Packages exist to deal with thermal loads, mechanical system simulation, solar energy concerns, costs of energy use, etc. The ENERGY design environment is currently concerned only with thermal load determination analysis. This type of analysis calculates the thermal loads imposed on the building and determines the amount of energy necessary to maintain a specified temperature in the building. These thermal loads are imposed by weather patterns, solar impact, and heat generated by the occupants, lighting, and equipment in the building. The thermal loads calculated by the analysis can then be used to determine mechanical equipment requirements and operating costs for the

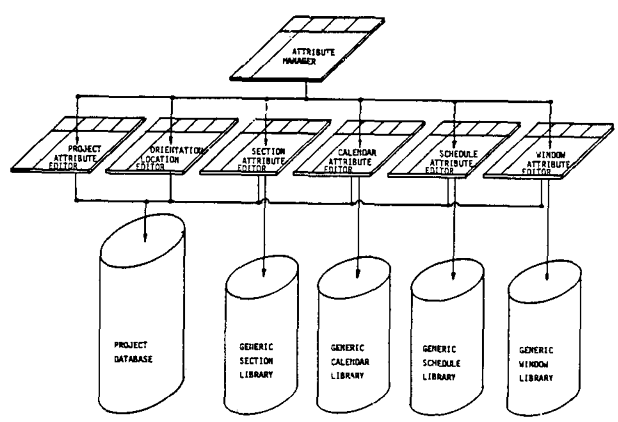

Figure 12. Structure of the attribute assignment subsystem.

building. Although the ENERGY environment now deals only with thermal loads, it has the capability to deal with other types of energy analyses in the future.

POSTPROCESSING

After an analysis has been performed, it is necessary to display the analysis results and do so in a form which is meaningful to the the architect. The postprocessor subsystem of the ENERGY program performs this function. Analysis results are displayed in graphic form, thus facilitating the study of the relationships between the thermal performance of various building components.

Two means of graphically displaying analysis results currently exist in the ENERGY design environment: 3-dimensional graphing of results and color representation.

It is frequently valuable to observe the thermal behavior of a building or its components over time. The 3-D graphing facility allows the architect to select a building component at any level of the building group structure and display the analysis results (or a summary of results) associated with it. This package displays the average heat loss/gain for each hour of an average day for each month of the year (Fig. 13). The graph may be rotated or scaled to exaggerate or minimize the variation in the heat loss/gain display.

Color representation of thermal loads is another means of displaying the results of thermal analysis data. Each building element is given a color code based on its thermal performance. The color coding indicating thermal performance results in a pseudo-color for each polygon in the display of the building. Since the pseudo-color may result in a loss of three-dimensional perception of the building geometry, two displays are generated, one to indicate diffuse shading of the building, and another to represent thermal performance parameters. These displays may be viewed on a color raster display device (Figs. 14,15). This capability allows the architect to observe heat flow patterns and identify, at a glance, building components with high levels of heat flow.

The postprocessor allows architects to deal effectively with the results of energy analysis. It allows them to evaluate these results using the visual vocabulary of the designer. It also provides a convenient, graphic means to relate thermal performance to building geometry. The primary goal of the ENERGY environment is to provide a set of tools for the architect to deal with thermal performance of buildings. The postprocessor subsystem meets this goal by providing the architect with the means to clearly and conveniently evaluate the results of an energy analysis.

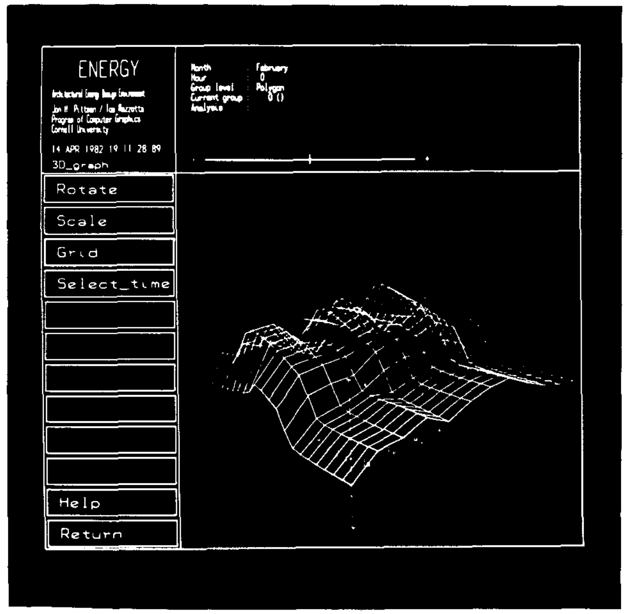

Figure 13. Three dimensional graph of thermal load summaries for the 15th of each month.

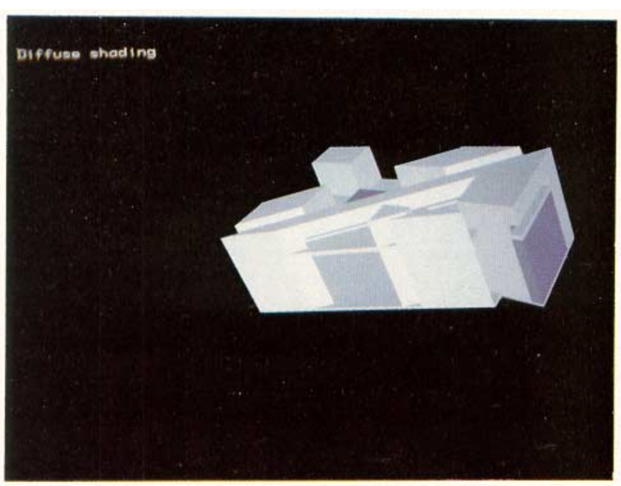

Figure 14. Color representation of a building showing diffuse shading.

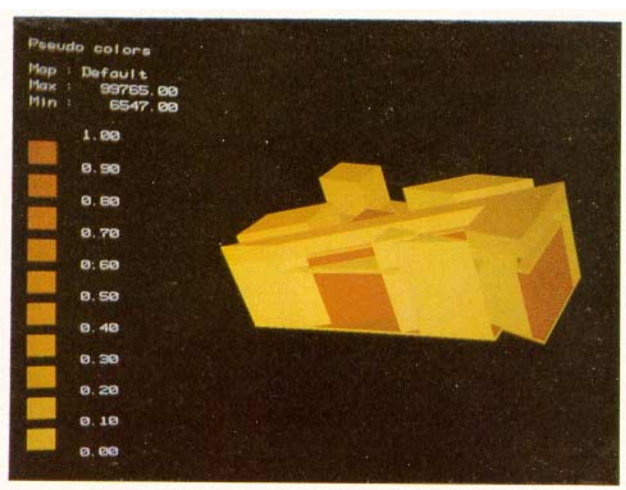

Figure 15. Color representation of a building using pseudo-colors to show thermal performance.

CONCLUSION

The ENERGY design environment described above provides a design tool which closely matches the needs of the architectural design process. Because of the graphic communication, the architect can work with the computer using a familiar graphic vocabulary. It thus allows architects to use the computer as a design tool without having to adapt their methods to the computer. Furthermore, the immediate feedback allows its use in the preliminary design phases since it can easily be used in an iterative fashion. The architect may evaluate a design solution and generate a new design solution based on that evaluation. Finally, it is evolutionary. The base of design information about a given project becomes more and more complete as the design progresses. There is clearly a close fit between the features included in the ENERGY design environment and those needed by architectural designers who are concerned with energy issues.

Interactive computer graphic energy programs would benefit the architectural profession in a number of ways. They would extend the capability of the architect by enabling parametric studies of thermal performance. relating numeric output to graphic representation of data, and allowing ease of data input for energy analysis. Designs would be evaluated on a rational basis, thereby allowing the architect to become more accountable for design decisions. Time for data input would be reduced and interpretation of analyses would be enhanced, thus making energy analysis more cost effective. Finally, it would force the improvement of energy analysis routines due to the availability of precise geometric input data.

In a more general sense, the ENERGY design environment is a prototype for the use of computer graphics in the architectural design process. It is focused on energy analysis but addresses concepts and issues that are relevant to all architectural problems. It attempts to provide a partnership between architect and computer which will extend the architect's capability to deal effectively with increasingly complex problems.

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