A Visualization Model for Computerized Energy Evaluation During the Conceptual Design Stage (ENERGRAPH)

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Research background and objectives

Energy performance is a crucial step toward responsible design (Schmitt, 1988). Currently there are many tools that can be applied to reach this goal with reasonable accuracy. Often times, however, major flaws are not discovered until the final stage of design when it is too late to change (Shaviv 1990, Brown 1990). Not only are existing simulation models complicated to apply at the conceptual design stage, but energy principles and their applications are also abstract and hard to visualize. Because of the lack of suitable tools to visualize energy analysis output, energy conservation concepts fail to be integrated into the building design. For these reasons, designers tend not to apply energy conservation concepts at the early design stage. However, since computer graphics is a new phase of visual communication in design process, the above problems might be solved properly through a computerized graphical interface in the conceptual design stage.

The research described in this paper is the result of exploring the concept of using computer graphics to support energy efficient building designs. It focuses on the visualization of building energy through a highly interactive graphical interface in the early design stage. The major research objectives are:

1) to facilitate the description of a building's geometry through an integrated graphic input model,
2) to apply computer graphics feedback of building energy design within the design loop, and
3) to permit designers to visualize and understand energy conservation concepts.

This project (ENERGRAPH) involves the conceptualization and development of a computer program which might help designers in the following aspects:

1) to create building layouts by using automated spatial synthesis algorithm or by manual design,
2) to analyze, interpret, and present weather information for a given location,
3) to simulate the relationships of sun path, building envelope, orientation, shadows and thermal load in dynamic animation according to a given date within the year,
4) to provide suitable building energy design parameters as default values to designers according to the selected building type,
5) to analyze building energy performance dynamically through the simplified energy analysis algorithm,
6) to detect the adequacy of energy design parameters automatically and provide possible solutions for designers to create energy-efficient building designs,
7) to present energy analysis feedback in various graphical formats, such as 2D and 3D images and animation, and
8) to provide on-line help information for designers to control the system.

Through the visualization of energy impacts, designers may more effectively reach the goal of energy conservation in buildings. To achieve the highest possible graphic resolution and dynamic real-time animation, this program has

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been developed on the Silicon Graphic workstation (Personal IRIS, 4D50 and Powerseries-VGX) under the UNIX environment.

The energy analysis algorithm which utilized in ENERGRAPH is degree-hour methodology and deals with the whole building plan as a single zone. Also, some other algorithms have been developed to create ENERGRAPH with an open-framed structure which enable the program to be updated easily with new or modified algorithms. Examples of such algorithms are building geometric description, graphic modeling, sun motion calculation and building database, artificial intelligent, etc. In this paper, we do not describe in detail how to develop the algorithms or create ENERGRAPH, instead, we introduce the concepts and the features of ENERGRAPH which is a starting point for further research.

Efficient design tools

Any building design tool that is intended to promote energy-efficient design practices must stress techniques for displaying energy efficiency concepts. It must clearly present the information which is necessary to adequately describe the relationship of building design and energy performance and also deal with the structure under which this information is organized for decision making. It is necessary to define what kind of information designers expect from an integrated design tool. Some of the major criteria for such a system are as follows:

1) The structure of the system should be flexible and easy to be modified or further developed. For example, ENERGRAPH could be further developed as an expert system by providing a well defined artificial intelligence system, or the energy simulation could be replaced by new building description and energy analysis algorithms.

2) The systematic control should be very flexible. The designers should be able to create or revise input and receive feedback in various ways. For example, designers could generate building layouts either through the auto design mode with manual modification or totally through the manual design mode.

3) The input of describing the building layout and energy design performance should be minimum and the description should easily be modified.

4) The numerical information, such as building geometric data and energy performance data should be translated into the proper graphical format and be easily understood.

5) The building energy performance should be presented both in numerical and graphical format.

6) All changes in building parameters should be analyzed interactively and dynamically.

7) All the design input (including geometric and energy design) should be incorporated into the energy analysis report.

Using the above objectives, ENERGRAPH has been divided into seven parts. These are: 1) building geometric information, 2) building location and local climate information, 3) sun path and thermal load, 4) energy design parameters, 5) design advise 6) graphical energy performance feedback, and 7) on-line help screens.

System flexibility

An architectural project presents a unique challenge. Buildings have to be designed for specific clients in order to satisfy some predetermined objectives. The current system responds to this by using the concept of Object-Oriented Design and a Knowledge Database System to enable designers to create or modify many different floor plans easily and efficiently. Once the designers finish creating the building layout, all the related energy information will be loaded from a database into the system automatically. Designers can either modify the building layout or use the default energy design parameters and get the updated feedback instantly. The database contains 13 building types, all of which contain unique default values; e.g., indoor temperature setting, HVAC system type, occupancy and lighting density, and fuel type, etc.
Those building types are

1) Office
2) Educational
3) Hospital
4) Clinic
5) Assembly/Theater
6) Assembly/Arena
7) Restaurant
8) Mercantile
9) Warehouse
10) Hotel
11) Nursing home
12) Residential
13) Others

Computer-aided space planning

Currently there are many commercial CAD programs that can plot 2D or 3D drawings. In a conventional sense, this interpretation of CAD is “Computer-Aided Drafting”. Although this application can save a significant amount of time and effort, it falls short of demonstrating the true advantage of using CAD where “design” is actually at issue. In this project, a automated space planning algorithm is applied in the early design stage to help the designer define building layouts. This is done interactively by using the designers’ space relationship criteria and some predefined geometric knowledge. With this tool, designers can easily create and modify building layouts and apply the results to test the energy performance during the early design process.

Computer-aided floor plan algorithms are not new. The earliest development of such algorithms can be traced back to the 1960’s. Many algorithms were developed to reach this goal in the last two decades (Eastman 1973, Mitchell 1978, Flemming 1986). Each algorithm has its own advantage and disadvantage. Until right now, there is still a large debate among those algorithms. This is due to the fact that there is no single algorithm that can create the floor plan which matches all the design constraints in every case. The better way to deal with computer-aided floor plan design is to provide suitable algorithms according to the designer’s specific requirements. However, this intelligent approach is not within the research scope of ENERGRAPH.

ENERGRAPH uses a common method of defining a space relationship matrix that weights the affinity between the various space functions. The main purpose of this has always been to provide a quick starting point for the design process that follows. There can, however, be problems, two of which would be:

1) When the system has ill-defined design criteria, there are numerous solutions that can meet the requirements. In this case, the designer may get an unwieldy number of space layouts and is left with no method for choosing the true optimum.

2) If the design criteria are over-specific, then there is no solution that can meet the designers’ requirements. In other words, the procedure fails to generate even a single space layout.

To avoid either of these problems, ENERGRAPH provides effortless access to databases and programmed rules that generate tentative building geometric layouts. The initial definition of the space relationship matrix is done interactively and intuitively. However, it is expected that the quality of the generated layout solution will still be challenged by the designer, since it is based largely on predefined design criteria. So, the system is devised to permit easy manipulation of the generated plan layout. For example, within one design alternative, setting different space relationships will let the system create different building layouts. The space number and space dimensions are the same.

The system is also sensitive to what kind of information that it requires of the designer. In order to minimize subjectivity, only five values are used to define the affinities over the range of closely related, more or less related, not related.

In other words, this relationship between elements can be estimated by any design criteria (cost, circulation frequency, etc.) that the designer wishes to use. Moreover, the designer can define more specific criteria in order to have more detailed and satisfactory building plan.

To initiate the space layout process, the program requires only six pieces of information: 1) building type, 2) space number, 3) space name, 4) minimum and maximum space dimensions, 5) space relationship values, and 6) building’s number of stories (see Figure 1).
All the required input information is controlled by picking preferred items or using sliders to change their values. The program provides 13 common building types with default space names, number and dimensions for the designer’s selection — such as hotel, clinic, educational, etc. All the building geometric information is shown in the message window in the bottom of the screen. Such as space name and its dimensions and area, total exterior wall areas in the north, east, south, west directions and total floor area, etc. If, after the building plan is generated, the designer does not wish to accept it, he/she may modify it by selecting a building exterior wall and relocating it to a new location (see Figure 2). The designer can also generate a building layout totally by manual methods by sketching into a blank matrix on the screen (see Figure 3). Also, all the geometric information will be updated interactively while the changing of input and reflected back to the designers in the message window.

The features described above permit the designer to describe building geometry visually, rapidly, and with a high degree of flexibility. Thus, the designer does not have to spend large amounts of time in this step and can concentrate on the energy analysis or other further design issues.

Currently, ENERGRAPH can handle a maximum of 36 different exterior walls with their own orientations in either auto or manual design mode. However, because of the limited research period,
environment which most nearly approaches human comfort conditions with minimal investment in utility bills. In architectural terms, this means that the building design should utilize natural climatic features to improve conditions with minimal use of mechanical apparatus. But how much benefit can be gained from the natural environment of the given location? What is the strongest climatic feature of given location? To find the answers, designers need to scrutinize the local climatic conditions. Most designers do not involve themselves in this sort of in-depth study, because a comprehensive sets of local climatic data often contains thousands of numbers that are hard to understand (and certainly hard to visualize). Thus, an efficient graphical presentation plays an important role in helping designers understand the local climate.

The bioclimatic chart (Figure 4) describes the measures necessary for human comfort in varying climatic conditions. To evaluate the climatic situation of a given location, a detailed analysis covering the complete yearly cycle is necessary. Local weather data supplied by meteorological stations may give the architect information that will enable designers to conduct their own evaluation.

The bioclimatic chart was built up with dry-bulb temperature on the ordinate and relative humidity on the abscissa. This chart shows the comfort zone in the center. The climatic elements around it are shown by means of curves which indicate the nature of corrective measures necessary to restore the feeling of comfort at any point outside the comfort zone. If the point is higher than the upper perimeter of the comfort zone, winds are needed. How wind effect can restore the feeling of comfort and offset high temperatures is charted with the nearly parallel lines following the upper limit of the comfort zone. The numbers indicate the needed wind velocities in feet per minute. If the temperature is high and the relative humidity is low, we feel too dry and hot, and winds are of little help here" (Olgay 1963). Because this clearly plots the relationship of dry-bulb temperature and relative humidity of given site with a simple graph, designers can get an overall picture of local climate information very easily and rapidly.

No corrective measures are necessary for any point of known dry-bulb temperature and relative humidity which falls within the boundary of the comfort zone. For any point falling outside this zone, corrective measures needed to restore the feeling of comfort can be taken directly from the chart.

Weather summary chart

This chart provides the information that can be quickly understood by designers. It contains four major components that impact energy consumption in a monthly breakdown: 1) heating
degree hours plotted in red in the upper part of the chart, 2) cooling degree hours plotted in blue at the bottom of the chart, 3) average monthly maximum and minimum temperature, and 4) the human comfort zone (from 68 to 80 degrees F). With this chart, designers can easily understand the overall temperature situation of the given location and know how many months the building needs cooling or heating and the magnitude of requirement. Also, with this chart, designers know the monthly range of maximum and minimum dry-bulb temperature and can get ideas for selecting building materials.

**Psychrometric chart**

The psychrometric chart (also in Figure 4) is much more detailed and powerful than the previous two displays. However, it needs more knowledge to understand and use it. The psychrometric chart contains 5 basic pieces of information on local climate: dry-bulb temperature, wet-bulb temperature, dewpoint temperature, relative humidity and moisture content. The psychrometric chart allows the description of a "zone" of air conditions in which man may comfortably exist.

**Sun path and thermal load**

Any building design should be in harmony or have a complementary relationships with its natural surroundings. It is the designer's role to determine the physical limits of this specification by constructing an envelope that can obtain the suitable amount of impact from the environment. The amount of this benefit is directly derived from the size and shape and orientation of the building. This means that the envelope also must properly respond to the annual rhythm of the sun. ENERGRAPH can simulate the seasonal thermal impact and can help the designer to replace, limit or reduce the need for mechanical cooling/heating.

**Building shadow**

This system contains four different viewports (3D view, plan view, south view and east view) that can help designers to visualize and understand the relationship of sun movement, building location, shape and orientation. The building geometric data can be derived either from automated space allocation algorithm or manual design by designers. The building location is selected from the weather database which contains 194 cities of climatic information in the United States. This database contains the information of solar, wind, peak temperature, average temperature, degree days, etc. which covers a wide range of local climatic information of each city. Designers can choose any month and any date within a year, then the program will automatically animate the sun motion according to the given parameters (see Figure 5). Also, the program will create animation of the building shadows which properly depict the relationship between the building shape, orientation and current sun position with 24 hours period. If the designer changes building orientation or the time period of the sun movement, the system will update the animation with proper building shadows dynamically. Within these animation, the sun position is updated each hour automatically and the building orientation is toward the north by default. Designers could easily change building's orientation, viewport and the time step of sun motion (the system offers 15-, 30- and 60-minute step) through the input device.

![Dynamic sun motion and shadow simulation](image)

**Building thermal load**

Besides drawing the building shadow, ENERGRAPH also can depict the solar gain on a given building by using the animation technique. When the designer selects the preferred
location and date, the program will automatically
calculate the hourly solar gain of each exterior
wall and display the solar gain with prescribed
colors. According to the color theory (Thorell
1989), each color has three basic components —
R,G,B (red, green and blue). Each component can
also be divided into 256 different levels. By
combining those different levels of each
component, we can have millions of different
colors. By using spectrum theory (Thorell 1989),
different colors have different thermal units.
Conversely, different thermal values can be
translated back to different colors. Thus, the
hourly solar gain of each wall can be viewed
within the animation by displaying different
colors according to its thermal value (see Figure
6). ENERGRAPH thus presents an hourly
qualitative solar impact on building shadows and
openings. This feature is very useful in helping
designers to understand the relationship of sun
movement, building shape effects, and orientation,
and might result in an improved thermal design
for the building.

![Figure 6: Simulation of thermal response to solar heating](image)

**Energy design parameters**

Currently, there are many energy software
packages which can help designers to check their
energy performance accurately. However, most
software programs have three inhibiting features
which prevent designers from successfully
integrating building, design and energy analysis.
Those features are the following:

1) Most energy design parameters are input
manually and are difficult to modify.

2) The analysis loop cannot execute
interactively and dynamically during
design changes. Designers usually have
to go through the whole run procedure
and wait for output before the next change
is attempted.

3) Many energy performance programs have
separate steps for inputting data and
performing the energy calculations. This
does not allow the designer to experiment
with quick changes while the program
is executing.

To avoid these problems, we apply three methods
to help designers in working with energy design
parameters easily and efficiently. These methods
are:

1) **Use of default energy design parameters
   for specific building types**

Some energy design parameters are highly
dependent on the building type. Some
of these parameters are: winter and
summer indoor design temperatures,
building occupancy hours, hot water
usage, cooling system type, heating fuel
type, occupancy density, etc. In
ENERGRAPH, these parameters are
provided by the system as default values
according to the selected building type.
If designers do not prefer the default
value, they can ask for help to print
out detailed information and then change
the value by using the pointing device.

2) **Use of a GUI (Graphical User Interface)
   to edit building materials**

Describing building materials is one of
the most tedious jobs during the energy
design stage. Different walls and windows
might have different design parameters.
This adds to the complexity of work at
the input stage. In this system, we use a
GUI to help designers in describing these
parameters. When designers decide to edit
building materials, ENERGRAPH will
show the building layout and various
building materials in the icon format.
Typical of these building materials are: 4-inch block, 8-inch insulation, single glass, double glass, etc. Within this system, designers can describe wall, glass, roof materials and glass area either by selecting a single wall or multiple walls at one time. In this stage, designers can freely assemble the selected material icons in any order and thus form the desired wall sections (see Figure 7). Once the designer selects the building material icons, the program will print out the default R-values of the layers and the total U-value of entire assembly. All the editing control is by using the mouse to select desired walls, material icons, or change R-values through the scrollbars. All the user input data are stored in the database. Designers can update it easily and freely. Through this GUI system, designers can integrate the building layout and describe their energy design parameters in less time and do it more accurately.

3) Use of interactive energy analysis and user input loop

After designers finish inputting the design, they may change any parameter. The system will interactively refresh the feedback display screens for instant review and pondering. Also, the system displays the design parameters and its calculation results in separate windows simultaneously and thus provides an integrated visualization to the designers. This endless interactive loop and integrated visualization of input and results can help designers to have a constant idea of current energy efficiency.

Intelligent advice

Architectural design is a creative procedure and very often designers are art-oriented rather than technology-oriented people. Furthermore, most current energy analysis software is developed for use by building energy experts and not by building designers. This is because most energy software requires the technical knowledge which building designers do not have. As a result, designers may find it hard to detect the problems with their design. ENERGRAPH provides simplified intelligent capabilities which can automatically check the adequacy of most design parameters according to the building type, layout, orientation and location. If the input parameters are not within the reasonable range (the range data is stored in database), ENERGRAPH will automatically give warning message to designers. At the same time, ENERGRAPH also provides the possible solutions to designers to improve the energy design according to the given input (see Figure 8).

Figure 7: Envelope material specification through icon selection; upper part is the designer’s input window, lower right is building plan and lower left is building material editing window.

Figure 8: The intelligent feature of ENERGRAPH which can detect the adequacy of user’s input and provide design suggestions according to the given design conditions.
For example, if the design condition is as follows: building type is a clinic; building location is College Station, Texas; most exterior walls' U-values are 0.2 and 80 percent of south facing walls is window. Such design will cause high solar gain through south facing glass and other high U-value walls. In this case, designers will receive the messages from ENERGRAPH in the message window which is as follows:

**DESIGN WARNINGS**

1. You have some walls with U-values that exceed 0.2.
2. The glass/wall ratio in the south facing walls is too high for this climate.

**DESIGN ADVICE**

**REDUCE THERMAL HEAT GAIN**

1. Reduce U-value of most exterior walls to a reasonable range (0.12 – 0.07).
2. Reduce solar gain from south facing wall:
   a. Reduce glass area in the south facing.
   b. Provide shading devices in the south facing wall.
   c. Reduce U-value of south openings.
   d. Use double-glazed heat absorbing glass in the south facing windows.
   e. Increase natural ventilation.
   f. Use fluorescent lights in place of incandescent.
3. Change building orientation.

ENERGRAPH will print out most of the possible solutions for designers to improve their energy design. Designers can either apply single or multiple suggestions in their design. This advice is dynamic according to the latest given design situations and will update the model dynamically whenever the change is made. Different design situations will receive different design advice. For example, if designers already use double-glazed windows in the south facing wall, ENERGRAPH will not print out item d. With this feature, designers could detect the possible design problems and get the possible solutions easily. Designers also could be educated about their energy consumption concepts through the on-line advise.

**Graphical feedback**

Because of the complexity of a typical energy analysis, the energy performance data might sometimes get lost when it is presented in numerical format. Designers lose the opportunity to have energy-efficient design. Thus, a graphical feedback model is the one tool that might help designers to understand energy performance and thus improve energy efficient building design. In choosing what types of graphics images to present, several questions had to be addressed beforehand. These were as follows (Robertson 1988 p. 10):

1) What will designers do with this picture?
2) What do designers know about the presentation subject?
3) What do they expect of data?
4) Can designers get the information elsewhere?
5) Will designers just want to have a quick impression of the data? Or will designers use it as source to apply real design decision making?

Before the graphical presentations were programmed into the system, we did a simple survey of fifteen building designers who have some experience of energy-efficient building design. During the survey, we used many 2D and 3D pictures to find out what kind of graphical presentation would provide the information that would help in understanding the energy problem and building design. The results indicated: 1) there is no single picture which can present all the information of energy performance evaluation, 2) the preferred pictures are as simple as possible, and 3) the pictures which contain energy analysis data should refer to the building geometric information and building occupied period. In other words, designers should get the information from the pictures concerning when and which parts of the building cause high energy consumption. Accordingly, this resulted in the use of five different graphics displays to aid in the decision making process. Some graphics are
presented in annual terms, some are monthly, and some are hourly. Each graphic output has its own usage in presenting energy data.

The graphic forms chosen are:

1) **Bar chart**: helps designers to understand the percentage of different components of annual heating, cooling, and cost

2) **3D surface plot**: helps designers to understand the overall monthly/hourly energy consumption of annual thermal performance data

3) **Group divided bar chart**: helps designers to compare energy use among design alternatives

4) **Animation**: helps designers to understand the relationship of building energy intensity with building shape, location, orientation, materials and date of the year through the hourly dynamic animation

5) **Peak load chart**: helps designers to understand the time and the values of components of annual peak energy performance

Items 1, 2, and 4 from the above list are operational in the current system. Items 3 and 5 are currently being developed and will be available after this paper is published.

**Bar chart**

The bar chart might be the most valuable in comparing different components. In this case, the output compares cooling load components (walls & roof, windows, solar, ventilation, lighting and occupants), annual energy (space cooling, space heating, hot water use, lighting and fans/motors), and total annual cost (hot water, lighting, heating, cooling and fans/motors).

**3D surface plot**

This form of graph is a surface mesh similar to that in the SOLAR-5 program (Milne and Labib 1990). The surface plot, however, adds the feature of plotting in different scaled colors to make it more easily understood (see Figure 9). Using this sort of graphics, the annual thermal performance data is a three-dimensional picture showing hourly values of energy for the average day of each month in a graduated color scale. Designers will be adept at understanding these colored 3-D plots and extracting some very subtle distinctions in energy performance that otherwise may go undetected.

**Animation**

Unlike some previous simulations of the shades and shadows, the major concept of this animation is to show the overall energy performance of the building's shell on any given day of the year. Animation include both shadowing and thermal insulation intensity distributions. Both animations are created by applying the spectrum theory and the concept of Finite Element Analysis (FEA) to convert building energy to specific colors and then plot both in the 3D view and plan view. Within this animation, the building plan is divided into many cells of the same size (5-foot square cell). The program will calculate the final energy performance of each cell according to the surroundings and plot it dynamically (each hour) in different colors according to its energy intensity (see Figure 10).
Within this system, red, green and blue color means heat gain, balance and heat loss respectively. With different intensity of red, green and blue, the system can use millions of colors to represent the energy performance. The more intense the color, the higher value of its representation. At the same time the animation of sun motion is displayed by the hour, the system updates the annual energy performance as well — thus, reflecting the altered inputs dynamically. Moreover, if the designer changes building orientation through the pointing device, the system will update the energy intensity of each cell simultaneously. By using this animation, designers can easily understand when and which part of the building is responsible for high energy consumption. Moreover, designers can easily visualize how the overall energy performance changes according to the building shape, envelope materials, orientation, location, date of the year and other design parameters.

Conclusions

As a tool for the energy-efficient building design, ENERGRAPH can be used both in the early and late design stages. At the early design stage, designers can easily get the general information of project’s geometric layout and energy design criteria, or can rapidly get the design feedback from changing design parameters, such as different building materials or different building orientations. At the late design stage, ENERGRAPH can be used in comparing different design alternatives or different performances of many components in various ways. The final objective is to produce a thermally comfortable environment with the aid of less mechanical conditioning. Although the current version of ENERGRAPH still needs to be enhanced to be applied in practice or education, we provide an example of integrating building design and energy analysis utilized computer graphic technology which might enhance designers’ understanding of energy-efficient building design.

Acknowledgments

Silicon Graphics workstations utilized for this project were made available by the Visualization Laboratory, School of Architecture, Texas A&M University.

Parts of the data utilized in the software default database were derived from the course handouts from the National Energy Courses that the American Institute of Architects (AIA) developed and sponsored during the period from 1981 through 1985.

The energy analysis algorithm utilized in ENERGRAPH was taken from a previously developed “degree-hour” methodology in EnerCAD, a PC-oriented software package developed at the Department of Architecture, Texas A&M University (Degelman 1992).

References


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