

INCORPORATION OF ENERGY PERFORMANCE

DATA IN THE DESIGN PROCESS:

Heating and Cooling Load Estimation and Analysis
in a Computerized Space Allocation Procedure

by

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B.S., Massachusetts Institute of Technology

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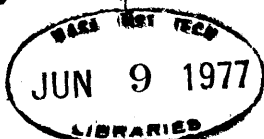
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Submitted to the Department of Architecture
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ABSTRACT

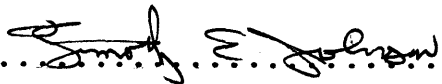
Architectural design is tested primarily by subjective means, but it could benefit from testing against objective measures. Computers have the potential of making such testing possible without gross demands on the architect's time and knowledge.

This thesis develops a method of aiding the designer by providing simple, immediate testing of energy loads while his design is evolving. This is achieved by attaching energy evaluation routines to an existing interactive space allocation computer system.

Because the overriding requirement, speed of calculation for quick feedback, is not fulfilled by existing energy evaluation systems, the programs for this project were necessarily all new developments. This situation allowed the creation of

energy evaluation programs tailored to the special needs of architects.

An energy estimation is used during preliminary design in order to show the architect the effect of design changes on energy performance. The energy analysis, a more precise calculation, performs a similar function for the more detailed stages of design.

Thesis Supervisor:  Timothy Johnson

Title: Reseach Associate and Lecturer in Solar Architecture

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Leo Frawley has been able to provide the valuable perspective of both a mechanical engineer and a computer project leader. He has kept me aware of what goes on in real life.

Dave Bryan took time from his own thesis work to help me run his building through my programs when I was short of time.

The Architecture Machine Group is a unique collection of programmers, machinery, students, architects, and hangers-on. My work would not have been possible without the existence and openness of this group. There is always someone willing to answer questions, start the machine, or

sit down and explain how I have managed, through my ignorance, to destroy some of their work. Those who have helped me are too numerous to mention by name.

My work is only the latest development in the long evolution of a computer system. Masanori Nagashima, Steve Handel, Yona Friedman, Tim, Guy, and many others have contributed to a program which will no doubt outlive us all.

Nicholas Negro Ponte is responsible, one way or another, for everything that comes out of the Architecture Machine, and a fair amount of work in this field at other institutions. This project is no exception.

The National Science Foundation, through a grant (No. 7420974-A02-MCS) for the Architecture-By-Yourself project, has provided the computer time which I used to develop my energy programs.

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Special acknowledgement must go to my wife Patti, and to the rest of my family. When I doubted whether I wished to return to architecture, they knew I should. Twice, after I had been out of school for a time, they convinced me to return. It seems they were right.

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INTRODUCTION

The topic of this thesis is the product of a combination of circumstances. The primary ones are:

- My own background. I have spent four years as an architecture student and three more working as a programmer.

- My interest in energy usage and particularly its relationship to architectural design.

- My perception of the information necessary for an architect to develop an energy-conscious design.

- The existence at M. I. T. of interest and expertise in the ramifications of energy use on design.

- The existence of a sophisticated mini-computer configuration maintained by the Architecture Machine Group.

- The existence of a space-allocation program implemented on the Architecture Machine. The program could benefit from and serve as a vehicle for energy calculation routines.

Given these circumstances, I set out to develop programming which would provide an architect with information regarding energy usage. The information would be used to help the architect make decisions in which energy use is a consideration. This thesis describes that development.

The first section deals with the theoretical basis of the project. The nature of design testing, its deficiencies, and the ways in which energy performance can be tested are discussed. Several ways in which a computer program could provide the architect with energy information, education, and

other advantages are investigated.

The second part concerns itself with various background issues. The energy programs currently available are evaluated in terms of their usefulness to architects. Arguments are presented in favor of the use of interactive systems for this and similar projects, and the implications of that decision are pursued. The space-allocation program development is traced up to the start of this thesis. Hardware requirements and trade-offs are briefly discussed.

Section three outlines the major components of the new energy system development. The system developed provides two levels of detail to the user - a preliminary, large-scale energy estimate, and a more specific, more precise energy analysis. Both are tied into the structure of the space-allocation program. The information display shows the variation in energy use corresponding to changes made in the design. Important energy values are also displayed, and can be changed by the architect during execution.

The fourth part is a detailed description of the analytical techniques used to calculate heating and cooling loads. Hourly computations are made for six days throughout the year, and the results extrapolated to show the yearly loads. The techniques are developed to produce accurate, but quick and not overly cumbersome results.

The final section evaluates the project. A test run is described and evaluated in terms of the mode of operation

and the calculation results. Future development of this project and the potential for new developments are covered briefly.

1. JUSTIFICATION FOR THE THESIS

This section deals with the architectural needs which led to the thesis. It discusses three primary items:

- 1) Testing of architectural design as it exists, and the ways in which that testing could be improved through computer use.
- 2) The problems involved in testing energy performance.
- 3) The type of information needed by the architect, and the time and mode in which it should be presented.

1.1. Testing of Architectural Design

There are many tests which an architect can apply to a design. Most of these tests are highly subjective, dependent on tastes, philosophy, style, and biases of the architect and his client. I have seen only two objective tests applied with any regularity - conformance with the architectural program and the estimated cost of construction. Unspecific architectural programs make the first test insignificant in many cases. Other quantitative tests of design have been avoided because of lack of time and expertise. Perhaps computers have created an environment in which some objective tests can be applied more easily.

Computers can significantly reduce the time required for testing, and they can to some degree codify

expertise if they are used intelligently. Objective testing can be performed in a reasonable time by an architect with limited knowledge of the specific topic under consideration. Moreover, by making the testing quick and relatively simple for the user, he will be able to perform the test more than once, as he makes changes, much as he employs his subjective tests continuously as he modifies his design. Objective and subjective tests can be used together to guide and support the architect in his design decisions.

1.2. Energy Performance

In the past, many buildings have been designed, engineered, and constructed without much thought as to their performance in the use of energy. Over the past several years, many people (including many architects) have become far more aware that energy is important (and expensive). Some architects have also become aware that they can have an effect on energy usage by careful and responsive design. At the same time, better energy performance has gained stature as a valid architectural pursuit.

In this pursuit, the architect is handicapped in many ways. He is often unable or unwilling to collect the necessary data. Energy analysis of a building is an enormously complex problem. It is usually dependent on information in minute detail. The architect normally lacks

the necessary data during the design stage. Even with design complete, he usually has no time or inclination to transcribe the data for a computer. He doesn't want to be distracted from his main purpose of providing a form for the building.

The architect is usually not sufficiently skilled in analysis techniques. Energy analysis can be done in many variations - by exact calculations, empirical formulas, or rough estimates. An architect may know some of the techniques, but he is usually unable to make a complete analysis. He is often unable to evaluate which technique is appropriate to a certain situation. As a result, important items are likely to be omitted, some items are calculated far too roughly, others with needless accuracy.

Perhaps the most important difficulty facing an architect trying to execute and "energy conscious" design is timing. Because of the time, expense, and expertise required to analyse a situation, it is put off until the design is too well established to be modified in response to the information obtained. The architect is forced to fall back on a few general guidelines about massing, orientation, glazing, etc. which may or may not be appropriate to his particular situation. They are also of little help in evaluating a trade-off between architectural and energy considerations.

What this thesis attempts to provide is a means of overcoming these problems. I am using the most universal and, in most cases, the most important component of a building's energy use heating and cooling of the interior. For a variety of situations I provide simple numbers: the amount of energy needed to heat and cool the interior to temperatures in the comfort range. I do not address questions of alternative energy sources, integration of hot water and industrial uses with space heating, or the type of heating system to be used. I merely report the numbers with the implication that those numbers (heating and cooling loads) get better as they get lower. But the numbers are presented in a manner calculated to fulfill the needs of the architect.

1.3. The Architects Need for Energy Information

I will outline here the primary needs of an architect who is interested in producing a design responsive to heating and cooling loads. These are all items which could be made possible for a designer short on time and expertise by appropriate use of a computer system:

- 1) A simple test of the energy performance at a given time.
- 2) Tests to help with preliminary design.
- 3) Tests to aid detail design.
- 4) Education in the effect of design on energy use.

5) Information with which to evaluate or replace engineering data.

The Simple Test

Early in the design, the architect has a need to know a couple of simple numbers stating the loadings for the building. He wants to know if his energy performance is "good enough". If his numbers are to be of any use, then he must have some outside standard by which to judge the results or some specific goal in mind to know when he has produced an acceptable design.

If he is experienced in energy evaluation, then he may be able to look at the size and function of the building and the magnitude of the numbers, and know whether the performance is acceptable. A less experienced architect may be able to compare buildings of similar size and function of which he has knowledge. Alternatively, average or desirable load by area or volume could be used for the uninitiated, although such standards are not readily available. Or the client may have specified limits which must be achieved by a particular building.

The architect is more likely to have monetary limits set on the design - cost per year for heating and air-conditioning. Money is much easier for most people to judge than BTU's. Yet to know whether the cost is acceptable, the energy loads must be provided as a first step.

What this test provides, then, is the key to how "good" or "bad" the design is in terms of energy requirements. What it does not provide is a method to determine the changes necessary to improve the design.

Guidance for Conceptual Design

In the early, conceptual stages of design, many things are decided which have a significant bearing on energy performance. The massing of the structure is outlined - the height of the building, the amount of outside wall and roof area, ground coverage, even overhangs. The orientation of the building is decided on at this stage in the development. Even major decisions on materials and glazing are made early in the design. All of these have a serious impact on energy useage.

Clearly, an architect concerned with energy performance must get some information on that performance during his conceptual design. If it is to help him improve his design, it must be more than the simple test outlined above. If he is considering a change, he must know its effect on the heating and cooling load. If the energy situation improves, his reasons for the change are reinforced. If not, then the other reasons must be re-evaluated against the magnitude of the energy loss. In either case, energy has become a factor to be considered.

What is needed is a test which can be quickly up-

dated to reflect the changes proposed by the designer. Because of the roughness of the design at this point, and the likelihood that many modifications are going to be made later, a good estimation is sufficient. It need not be as detailed as the simple test. By comparing results as they change for different situations, the architect can determine the direction and degree of change in the energy performance due to the design modification. Energy use will become one of the considerations in many of his design decisions.

Guidance for Detail Design and Specification

More specific decision, made at later stages, are also very important to the heating and cooling of a building. The insulating values of walls and glazed areas are obviously going to effect the heat loss and gain. The amount and placement of windows is of major importance. The weight of the structural system and the finish of exterior walls can be of more importance than is usually thought. The heat output of lighting and the usual number of occupants in a space also have their effect.

The results of the testing described in the previous section will not be precise enough at the level of detail design and specification. Increasing the window area of one wall of one room will not make a big difference in the total heating load of the whole building

especially if it is a rough estimate. But the increased area may significantly affect the comfort conditions in the individual room. If that effect could be found, it would help the architect greatly. Specification of many of the items I have mentioned (insulation, glazing, finishes) is based primarily or solely on their effect on energy use.

The needs at this level are different from the earlier, larger scale in two ways. First, the area being evaluated must be reduced to a definable portion of the building more in scale with the changes being made. Second, the detail and accuracy of the calculation should be improved to reflect the smaller fluctuation expected at this stage of the design.

Education of the Architect

Any system of this sort is less than successful if the user does not learn from it. There are two basic ways in which testing of the sort described above can educate the architect.

First, trial and error will eventually result in an improvement of knowledge. If the designer is continually reminded of the effect his actions have on the heating and cooling in his project, he will take note of the most and least effective types of actions. He is provided with a framework within which he can, with time, begin to recognize consistent patterns and

formulate rules of thumb based on his own experience.

If the architect is learning about energy from his associates, courses, or books, use of a system of testing can reinforce his knowledge. Beyond that, it will allow him to apply general energy concepts to the process of design in a real project. It may even lead him to question the more tenuous theses he comes across.

9 Checking or Replacing the Consulting Engineer

The obvious question at this point is, "Since we already have analysed our energy needs, why are we paying an engineer to do the same thing?" There are really two issues here: 1) checking the engineer; and 2) replacing him.

Checking work that the engineer has done saves no money (it is not usually done at all), so that it can only be justified if the cost is minimal. If the testing has been done throughout the preliminary design and in later detail design stages, figures are already available. The designer will have a good idea of what to expect from his engineer. If testing has not been done, and the data has not been entered, it would probably cost too much for simple double-checking of someone else's work, unless there are serious doubts about the engineer's results.

To replace the engineer, the energy calculation must be nearly as accurate as his and cost less. If the testing has already been done, cost is no issue. Whether the accuracy is sufficient for the design of heating and distri-

bution systems depends on the particular method and quality of programming developed, and cannot be answered until test results can be compared with engineer's figures.

Such bonus products should be approached very carefully. There is always the danger that a program molded to suit both architects and engineers will turn out to be suitable for neither. However, if a program developed for one turns out to be appropriate for the other, the potential should be investigated.

2. BACKGROUND

In this section I describe several background items which serve as explanation of why this project has taken the form it has - an interactive energy program added to an existing space-allocation program, implemented on a dedicated mini-computer. There are five main topics:

- 1) The substance and use of existing energy programs.
- 2) The reasons for using an interactive system.
- 3) The effect interaction has on other decisions and on the results produced by interactive programs.
- 4) A brief history of the development of the computer system of which this thesis is the most recent improvement.
- 5) A discussion of hardware alternatives.

2.1. Existing Energy Programs

Energy programs to date have been oriented toward the engineer, rather than the architect. Almost all have been batch jobs, utilizing a given and essentially unchangeable situation. That is precisely what the engineer needs, but such a situation encourages energy analysis at a time when the architect can no longer respond to it.

Existing programs seem to have an obsession with detail. Again, this is more appropriate for engineers than architects, but in some cases, I think the programmer simply gets carried away with his computing power. It is not clear to me that the percentage of shadow coverage varying be-

tween foliage types or the like is worth worrying about at any level. Yet heating and cooling loads are computed to that level of detail.¹ Some programs make exhaustive evaluations of every hour in the year.² By putting such detail into programs, even the computer takes a long time to handle it. As a result, the time and cost of execution make it unlikely that it will run more than once for a project.

With all this detail in the programs, there is necessarily a great volume of data required. For an architect (or even an engineer) to enter this data, even if the input itself is automated, is often prohibitively expensive and time-consuming.³ More to the point, an architect often will not even know what values he will use for much of the data because it is so specific.

It should be clear that energy programs developed for engineers are not appropriate for architects. Some attempts have been made to make programs more helpful to architects. One way has been to shorten the long analysis package to make it more manageable. Unfortunately, the level of detail normally remains, while important considerations are simply eliminated. Thus, a situation can arise where solar influence is calculated using an atmospheric extinction coefficient and several variable coefficients involved in finding the convection losses from a sunlit wall. At the same time, shadows are completely ignored.⁴ The

inconsistency is obvious. The results are questionable, and the problems inherent in the original version still exist, if to a lesser degree.

A second modification to help the architect is to list the areas of greatest load after the analysis is complete so that the architect will know what to change to get the most improvement. Suggestions of design changes might even be made. But still the program is likely to be run only once, when it is out of the hands of the designer, for all the reasons mentioned before.

What is required is a completely new approach to the problem, starting from the premise that the architect should be able to evaluate his design quickly and accurately throughout the design process.

2.2. Importance of an Interactive Environment

There are two important reasons for using an interactive system - the capability of quick reinforcement of design decisions, and the ability to change data during execution.

Reinforcement !

The needs described earlier in the sections on guidance for conceptual design and detail design, and on educating the architect can be provided for in two ways.

One is to have the program evaluate the design and suggest improvements to increase energy efficiency. The arch-

itect could then take this advice, change the design, and reevaluate. This has two problems. The "advisory" portions of this program are a very sophisticated and difficult programming problem, unless a strong bias is assumed (a fiberglass company might offer a program telling you only where to add insulation).⁵ The second problem occurs when overriding factors prevent the recommended changes from being made. Then the architect is stuck. The program is too long and expensive to run many times, checking possible modifications.

The second way to fulfill the architectural needs is by reinforcement. If the architect can get continual updates incorporating his changes, he can try many approaches, consider the ramifications (for architecture and energy), and make his decision. The time required should be short enough that the designer feels justified in trying something without knowing beforehand whether it will work. A batch approach simply takes too long. It would be too frustrating to use the trial and error system proposed. The designer must be able to work in an interactive environment. Reinforcement, both positive and negative, could guide him to the most attractive alternative.

Data Changes

An interactive environment also makes changes or additions to the data somewhat easier. It can be programmed to be responsive to the architect and able to guide him

in his specification. It can also apply that data at the point where it begins to effect the energy analysis, eliminating considerable repetition. The calculation does not have to be started from scratch for every change.

An interactive system allows data entered during execution of one set of routines to be passed to another level of calculation. Any data specified in the preliminary design stage will be automatically included when the calculations are made at the detail level. This capability is a great help when the architect may wish to move back and forth between levels.

2.3. Ramifications of Interaction

Interaction suggests several effects which must be taken into account. The programming, use, and effectiveness differ significantly from other modes of computer operation. Below are some of the ramifications important to this development:

- 1) The time required to perform the calculations and return the results to the user.
- 2) The ability to interrupt execution.
- 3) The ability to vary the amount and values of data during execution.

Elapsed Time

The actual speed of execution is dependent on the machine being used. What is important to the user is the

apparent speed of calculation - the elapsed time between the decision to ask for a measurement and reading the results. If an interactive system is properly constituted the calculation will commence as soon as it is decided on. The results will be shown to the user as soon as the calculation is complete. This type of speed is necessary for the type of iterative, trial and error, reinforcing method envisioned.

Any batch system requires some set-up before execution - identification of data files and display devices for output, insertion of execution instruction, etc. At best, the set-up may be standardized and entered via a terminal. At worst, the user will be dealing with punch cards, listings, and false starts due to minor errors. In any case, the elapsed time is probably too great for the needs of the architect.

In an interactive system, the designer's changes and the energy analysis would take place within the same master program. When the decision is made to evaluate the energy performance of a design, the necessary data is immediately available, the output device has been determined, and a properly tested program should have a minimum of bad executions. Some set-up may still be necessary, but with an interactive system the data input can be simplified. This is especially true of graphic data, where location of a few key points can imply a great deal of data.

Interruptibility

An interactive system implies that the architect is actively involved with the process of modifying the configuration, and calling for heating and cooling loads from time to time. Presuming that the designer wishes continuous updates, it makes sense to relieve him of the responsibility of asking for them by automatically initiating the energy evaluation whenever a change is made.

However, this may prove more of a hindrance than a help. Even if the energy program only takes 10 or 20 seconds, the architect must wait that long before starting another change himself. He would very likely work much faster than that. If he wants to make a whole series of changes, the delay is counter-productive and annoying.

In an interactive system, the programming can be arranged to allow interruption by the user before the normal completion of a task such as energy evaluation. The designer can make a series of changes as quickly as he would like, each time interrupting the energy program before the computation is complete. When he pauses to contemplate his changes, he can let the calculations run their course and give him the new results.

The user is provided energy data automatically without any interference in his primary tasks, and without any additional requirements on him.

Variable Amount of Data

With an interactive environment, a variable quantity of data is available. As the architect adds, modifies, and specifies, the amount of available information increases. With a limited set of data, a quicker, less precise estimate is all that is justified. Once a body of detailed data has been specified, a more precise analysis is possible.

With a batch system, the longer, more accurate program can be run (and usually is) even when the detail available doesn't justify it. Since the time involved is much greater than an interactive system anyway, the difference in execution time is insignificant. In an interactive environment, with the designer waiting there for completion, the luxury of wasted time is not available. A mechanism must be incorporated to allow both a quick estimate and a detailed calculation.

Variable Values of Data

Modifying data values is the area of greatest advantage for interactive systems. First, the actual change is simpler. In a batch system, the value is buried in an input data file. A search must be made, the change inserted, and the program rerun. An interactive system can be tailored in different ways to make changes very easy for the user. The search is handled internally, and the program can continue immediately when the new data is entered.

Secondly, the interactive system can retain information about what data has been changed. In many cases, the changes effect only part of the calculations. By keeping track of the new values, recalculation can be limited to those items affected by the architectural changes. A great deal of needless recomputation of unchanged items can be eliminated.

2.4. History of the Parent System

This section gives a brief overview of the developments of the computer programs leading to the project which is the subject of this thesis. The stages discussed are:

- 1) Early space-allocation optimization programs.
- 2) IMAGE - multiple constraints and user modification.
- 3) U-DESIGN - implementation on a mini-computer.
- 4) MAS - extension to three dimensions.
- 5) addition and performance of an energy package.

IMAGE

Beginning in 1968, several people at MIT set about the development of a space-allocation program which would go beyond the attempts which had been made up to that time.⁶

- Design Criteria

Previous space-allocation programs had been based on specifying weighted affinities for pairs of spaces: e.g.

how close should space A be to space B, and how important is it? So-called optimum solutions were generated from these affinity pairs. This approach to design criteria was considered too restrictive. What was developed instead was a space-allocation system dependent on a considerable range of criteria. With this system, IMAGE, the user could align spaces in any dimension, specify adjacencies, distances, enclosures, allow overlaps or forbid them, and set areas, dimensions, and/or proportions of a space (spaces area all rectangular).

- User Modification

The single "optimal" solution generated by previous programs was also thought to be too restrictive. Many important objective criteria cannot be effectively considered by any such system. Any solution generated by computers might be unacceptable in view of these criteria. In the interactive mode adopted by IMAGE, subjective criteria could be satisfied by allowing the designer to modify positions and shapes of the spaces before or during execution of the automatic space allocation. This has the effect of imposing the architect's personal biases and considerations on the configuration produced. It also provides a means of generating alternative possibilities.

U-DESIGN

In the Spring of 1975, a thesis involved in the up-

grading of IMAGE to make it more responsive to the needs of the designer.⁷

- Interactive Graphics

The interaction in IMAGE involved commands and responses delivered via a typewriter terminal. This requires a command language with its inherent awkwardness and learning period. It tends to inhibit new users and prevent a fluid command and response interaction. Also, the current state of the data being "massaged" by both machine and architect is not easily displayed to the user, especially where the data represents a structure.

U-DESIGN adapted the program to a CRT (TV) terminal for input and output. Besides allowing character output, the terminal can produce graphic displays to give a reasonably comprehensive view of the current geometry. Input can be provided by a light pen applied directly to the screen, as well as from the keyboard. Presented with a list of possible commands and a plan or section of the building, the user can pick a command or manipulate the geometry with ease.

! - Foreground/Background

In the set-up used by IMAGE, the automatic and manual manipulations would essentially take turns. In the real scheme of things, the changes made by the architect should take priority. Instead, the designer is likely to be made to wait while a lengthy optimization procedure is performed

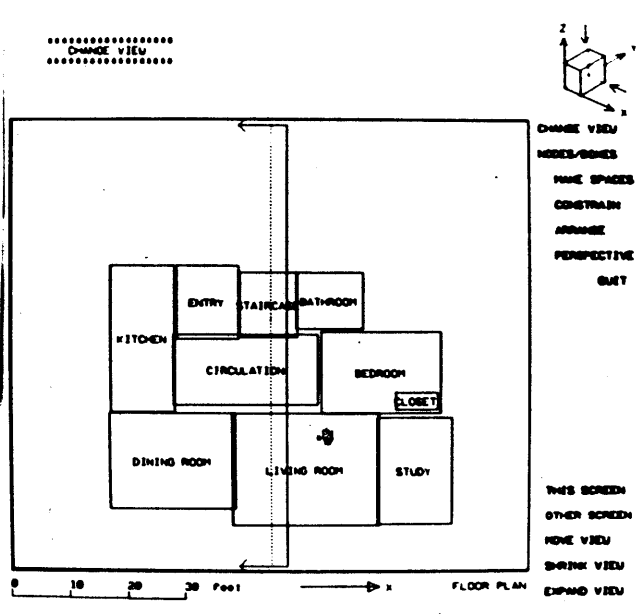
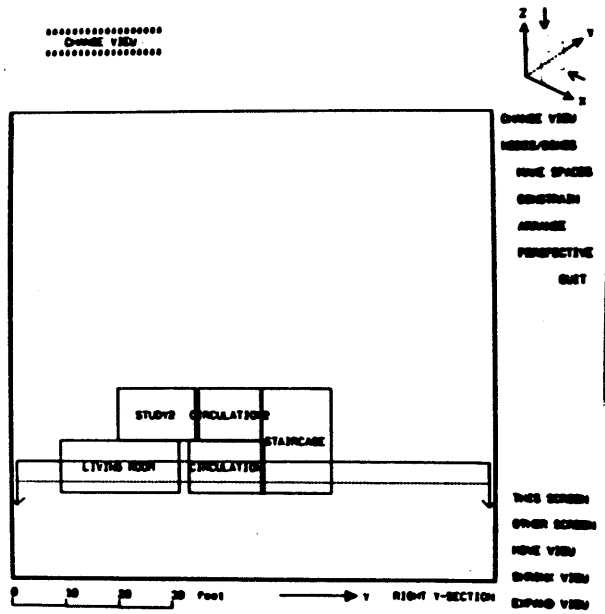
before an important change can be made.

To solve this problem, U-DESIGN implemented a foreground/background method of interaction. In this organization the more important procedure (processing designer changes) was assigned to the foreground. Each time this section is entered, it will run to completion. The less important process (automatically optimizing the configuration) was assigned to the background. When this runs, it is interrupted at frequent intervals to see if the designer has requested a change. If so, the background is abandoned, and the partial results discarded.

The changes made the package responsive to the person using it. He could learn the system quickly, the situation and his options are made clear to him, and he can manipulate the situation easily, quickly, and without unnecessary waiting.

MAS - Three-Dimensionality

IMAGE and U-DESIGN had limited three-dimensional capabilities but no effective way of displaying or manipulating the third dimension had been implemented. MAS is a further development undertaken as a thesis project in the Spring of 1976.⁸ Its primary purpose was to extend the display and change capabilities to three dimensions. This was achieved by adding a second CRT terminal. In this way, two different views can be shown and modified. A perspective capability was added in order to provide a clearer



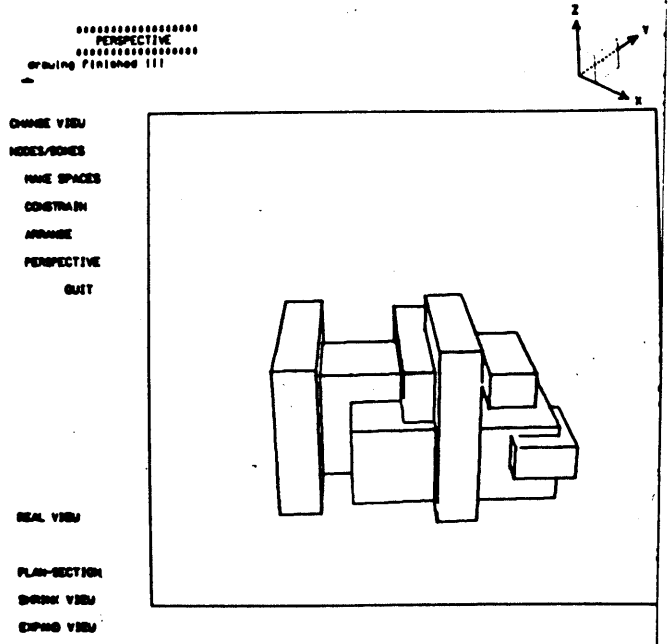
MAS:

The top two illustrations show the two-CRT set-up which allows the 3-dimensional manipulations.

On the right is a floor plan of the first floor.

On the left is a section showing the center of both floors.

To the right is a perspective of another configuration.



visual picture. The designer can now get the whole building into a fully three-dimensional configuration consistent with his requirements. The design is now complete enough to begin to apply effective objective testing.

Energy Addition - Problems

Over the Summer of 1976, an addition was made to MAS. An energy package was adapted to act as a background process. It has serious difficulties, most of which came up in the discussion of existing energy programs. It is far too detailed in some areas, and ignorant of more important ones. The package was received from an outside source, and it was not fully compatible with the data structure in MAS, nor did MAS have all the data necessary. In addition, the results are inconsistent, and it appears likely they are incorrect. Finally, it is not interruptible, so it does not properly perform as a background. The problem is primarily that the energy package was written for one purpose and applied to a different use. That situation always works poorly if it works at all.

The system described would clearly benefit from an addition designed to meet the energy evaluation needs of architects, as described in the first portion of this thesis. The practical purpose of the thesis is to develop a comprehensive energy estimation and analysis integrated with and tailored to the MAS system.

2.5. Hardware Requirements

Dedicated Computer

The environment in which the programs discussed have been developed includes a dedicated computer. When the program is being run, a mini-computer is devoted entirely to executing that one program. This has important ramifications for an architect considering investment in a system of this sort.

A common scenario for a small office beginning to use computers is to start off time-sharing on someone else's computer. This allows them to investigate potentials without a large capital investment. An interactive system can be implemented in such an environment, but it has its drawbacks. Time-sharing calls for each of the programs using the computer to be pulled off and replaced by another at very small intervals of time. This is a very appropriate mode for most interactive systems, which normally require quick response, but not much calculation. To them, the difference between a dedicated machine and a shared machine is the difference between instantaneous response and nearly instantaneous response.

For the system under discussion, however, the computation is considerable. The response time need not be instantaneous, but it should fall within the limits discussed earlier. If the response time is increased by a factor of three or five or more the program still works, but it is

less effective in practice. As the time that the architect must wait for results grows, the likelihood that he will be discouraged from using the capabilities grows accordingly.

If a dedicated machine is more effective, it is also more expensive. It must be purchased and maintained. Such an expense is seldom justifiable for one program. But if other cost-effective packages can be implemented on the computer, the cost can be more easily justified. With architects, these packages have normally been specification writing and editing programs and other administrative functions.⁹

In summary, there are ways of justifying maintenance of a dedicated computer. If that is not possible, a time-sharing system can be used, at some cost in effectiveness.

CRT Terminal

It is also necessary to acquire a CRT terminal in order to use this particular system. Without it, many of the important capabilities are lost. As with the computer itself, justification for this expense requires that it be used for more than the package under discussion.

Whether an office is using its own computer or buying time on someone else's, such a terminal seems worthwhile. The types of programs which would interest an architect include a large percentage of packages using graphic display or utilizing editing capabilities. CRT terminals are ideal for both uses. If an office is serious about its use of

computers, a CRT display is easy enough to justify.

Another point should be mentioned with regard to both mini-computers and terminals. The technology continues to advance, and the cost of machines of similar power and speed is still getting lower.

3. PROGRAMMING PRODUCTION GOALS

In this section I will discuss my plans for extension of the space-allocation system. The development includes four improvements:

- 1) An energy estimation available at the preliminary design stage.
- 2) An energy analysis available at the detail specification stage.
- 3) A more instructive technique for the display of results.
- 4) A more responsive method of data modification.

3.1. Energy Estimation / Preliminary Design

An energy estimate is provided during preliminary design instead of an exact calculation for two reasons: there is not enough time for very exact calculations; and there is not enough data to justify it.

•

Time Limitations

As discussed in section 2.3, the response time must be limited. At this point in the design, the architect is working with the entire building. The energy evaluation necessarily includes the whole configuration. Because of the potential for exhaustive calculation for each space, settling on a rough estimation allows the execution time to be limited in two ways.

First, the most difficult items are not calculated unless they are 1) of primary importance and 2) likely to vary widely with the changes the designer can make at this stage. Thus, the time delay of heat passing through a heavy wall is ignored at this level because it will not have a primary effect in most cases. Likewise, shadow is not considered at this level.

The second method of reducing execution time is to use approximate data values for the whole building, rather than separate values for each room. In this way, the number of operations is reduced by a significant factor.

Available Data

The method of using values for the whole building makes more sense in this case, anyway. During preliminary design the architect simply does not have detailed information on materials and construction, so it is appropriate to use a combination of default and approximated values. Lighting levels, ventilation and infiltration rates are given standard default values, although they can be factored up or down by the designer. Occupation levels are ignored at this stage - the variation can be so wide that a default of zero is as valid as any, and it saves time. The values most important to the energy evaluation can be given more specificity. While they still apply to the whole building rather than individual rooms, they are specified by the type of surface to which they apply. Heat transmission (U-)

values can be set for different types of construction by the designer. The amount of window area is set for walls of different orientations, and thermal capacities can be defined for different internal and external surface types. So the architect can indicate approximate or average values which he intends to specify.

An estimation is the only valid calculation during preliminary design, because the data available is a whole series of estimations itself.

Results - Comparative Data

The results are a rough estimation of the heating and cooling loads. The designer cannot say with confidence that his building will use just that much heating and cooling. The numbers are only an indication. The roughness is consistent, however, from one measurement to another, and that is important. Consistency in the manner of estimation allows use of the results for comparison purposes. If a change is made, the new data is immediately used in a new energy estimation. The designer can then compare the results with the last calculation, or any previous ones. The direction and magnitude of the difference will indicate the effect of the architectural change on energy performance. That is, after all, what the designer needs in conceptual design. He must know whether his change has made energy usage lower, higher, much higher, or much lower in

his design. Or he may want to try several alternatives to find the lowest usage. Comparison of successive estimations fulfills these needs.

Program Configuration

Energy estimation will be established as a background procedure. It will be automatically initiated whenever the architect completes a change in the foreground process. It will be interrupted whenever he begins a change. If the estimation is completed, the results will be displayed and the program will await the next action by the user.

There are two foreground procedures which can be associated with it. The primary foreground will display two views of the building and allow the designer to move spaces in any dimension or change the length of any side of a space. With this foreground, the architect can reorganize his space and improve his massing with energy estimations to help him when appropriate.

The alternative foreground procedure will handle value changes. U-factors, window areas, thermal capacities, lighting levels, and orientation can be changed here. In this foreground, the designer can make major architectural and material decisions which have a significant effect on heating and cooling loads. Because energy performance is often the most important consideration in choosing these values, it is essential that the architect have continual reminder of how different combinations will perform.

3.2. Energy Analysis / Detail Specification

By the term "analysis" I intend to imply only that at this level I have tried to account for every element which may have a non-trivial effect on the heating and cooling loads. It indicates a degree of precision and comprehensiveness. There are two reasons that an analysis is possible at this level: the time limitations are met by reducing the area evaluated, and detailed specification can reasonably be expected to be available at this time.

Scope Limitations

In the estimation, it was necessary to evaluate the whole building because the designer is making changes at that scale. In the analysis, the scope of most of the architect's specifications are at the level of a room. As a result, it is reasonable to limit the computations to the same scope. By performing the analysis one space at a time, the energy information can most effectively be used at the small-scale design.

It is also necessary to limit the scope in order to stay within reasonable time constraints. As in the estimation, the time for a full calculation should be no longer than the occasional extended pause the designer may make to contemplate his design, or to admire it. While this time interval is not exact, suffice it to say that it should be measured in seconds. To evaluate a relatively complex building in its entirety in the detail required at this

stage would very likely take too long. By having the designer work with one room at a time at the detail specification stage, effective interaction is retained. Energy data can be requested for the whole configuration, but there will be a delay while it is computed.

Available Data

Much more data can be made available at this point. This is especially true of the exterior walls. U-values and percentage of windows can be specified for each wall of each room. New modifiable values are available for the walls and roof: absorptancy, thermal capacity, and a thermal delay factor. In addition, some values for the spaces themselves can be entered and utilized - lighting and occupation levels. A few new values applying to the whole configuration are also taken into consideration.

This information is necessary to perform a comprehensive energy analysis, and it is to a large extent dependent on the results of the analysis. Much of it will be specified after the architect has watched the fluctuations of the heating and cooling loads. Because of this interdependence, a default value for each of the variables is inserted as a starting point.

Results - Absolute and Comparative Data

The results should be a reasonably accurate reflection of the heating and cooling needs of the space. Just how

accurate depends on the exact method of calculation, the particular building type and configuration, and the dependability of the data. They can be used as both absolute and comparative data.

Because of the relative precision, the architect should be able to say with some confidence that the results represent a reasonable expectation of what will happen when the building is constructed. Unlike the energy estimation, the numbers produced at this stage would be useful as absolute, not just comparative data. They could be used as the basis for calculation of a yearly cost for heating and air-conditioning. They might also be considered valid evidence that a particular energy goal has been fulfilled by the designer.

On the other hand, the more important use in the design process is still the comparison of a series of results. This comparative concept is identical to that described in the section on energy estimation- The differences are in the scale of the changes being made, the accuracy of the data, and the smaller scale and greater accuracy of the differences between successive results.

Program Configuration

The energy analysis will be established as a background procedure very similar to the set-up used for the energy estimation. Like that procedure, it will be initiated after each change in the foreground, interrupted at the

instigation of the user, and able to display the results immediately upon completion.

The foreground process associated with it will display all the values relevant to the room being evaluated. It will allow the user to specify new values for the variables displayed. It will also allow the user to pick a new room for evaluation. By specifying new U-values, window areas, lighting levels, thermal capacity, and other items relevant to heat gain and loss, the architect is also implying a choice of materials, or family of materials, or a type of structural system.

It is immensely important that energy information be available (from the background) while these choices are being made. Not only do they have a primary impact on energy performance, but in many cases energy is the most important factor in the choice. This type of organization allows the most effective choices to be made.

3.3. Display of Results - Retaining History

Because the use of this package is so dependent on the interplay of the architect's activities and the background heating and cooling calculations, it is important that the results be displayed usefully. The display must fulfill two goals - the ability to compare previous results, and the ability to read them quickly.

Because of the importance to the design process of

comparison of successive results, the display must contain some provision for retaining a history. The important figures are the yearly heating load, the yearly cooling load, and the floor area of the room or building being evaluated. The loadings are expressed in terms of BTU per square foot of floor area. This gives a better idea of the efficiency of the building, and provides a method of comparison between different buildings. A whole series of results, a dozen, are displayed. The designer should be able to see not only the last one or two calculations, but all the way back to the beginning of the manipulations for that building or room. That is important if he wants to keep the whole process in perspective, and avoid basing decisions on the specific problem he may be investigating at the moment. If the limit is reached, the number of results is cut in half by averaging each pair. That way, the entire history could be retained, although it would be "smoothed out" a bit. This list would be in tabular form so that the architect can compare accurately when the difference is small.

Tabular data, however, is hard to take in at a glance, especially if there is a lot of it. To counter this problem, there will be a graphic display in addition to the lists. It should be as simple as possible, just a base line, with a line graph on either side representing the heating and cooling portions of the load. It will reflect the same numbers listed in the tabular data, but the graphic display

can be absorbed almost immediately. Although it is not as accurate as the numbers, the direction and magnitude of the change can be deduced easily, and trends can be discerned.

Both of the sets of results will be displayed on one of the CRT terminals, the other being reserved for a floor plan and other information. The display technique will be employed for both estimation and analysis in identical fashion.

3.4. Value Specification

The program depends on the ability of the architect to be able to change an important value easily and accurately.

Ease of Manipulation

The variables must be changed with enough ease that he can try several values in order to find the most appropriate one. The CRT terminals being used provide two ways to manipulate data - the light pen and the keyboard. Although most people are familiar with keyboard functions, some kind of command vocabulary must be learned before it is used. The light pen, on the other hand, must merely be pointed to the proper place on the screen. With good programming, the use of the pen can be picked up with little or no instruction. The current values of items which might be changed are already displayed on the screen. All the user

has to do is pick the one he wishes to change and point at it.

Range and Accuracy of Specification

There now exists in MAS a method of value changes which uses the light pen exclusively. For each variable a scale is displayed, with a pointer at the current value. With the light pen, the pointer (and the value) can be moved up and down the scale. The method has two problems. The light pen is not the most accurate of instruments, so the architect may have to settle for an approximation of his desired value. Secondly, the scale is limited. If the value he wants is off the scale, he can't get it. And to increase the range would only mean further limiting the accuracy.

By combining the light pen with its most appropriate function (identification of the variable to be changed) and the keyboard with its most appropriate purpose (accurate specification of the new value), a more responsive procedure can be achieved. The user can point to the variable with the light pen, then enter a new, exact value from the keyboard when the program requests it.

Specifiable Data

Below are the values which will be displayed on the CRT and can be changed by the user. (Note that the four wall directions relate to their floor plan orientation on the screen. The four directions are Left, Front, Right, and Back, not North, South, East and West. MAS requires that

all spaces be rectangular and oriented to the same axes. Compass orientation of the whole floor plan can be specified by the user.)

1) Energy estimation

For the whole building

U-values (heat transmission values) - four:

- roof, all exterior walls, overhanging floor areas, all windows.

Percentage of window coverage - four:

- four wall directions (L, F, R, B).

Thermal Capacity (per sqft) - five:

- roof, exterior walls, interior walls, floor/ceiling sandwich, ground slab.

Lighting level (average watts/sqft).

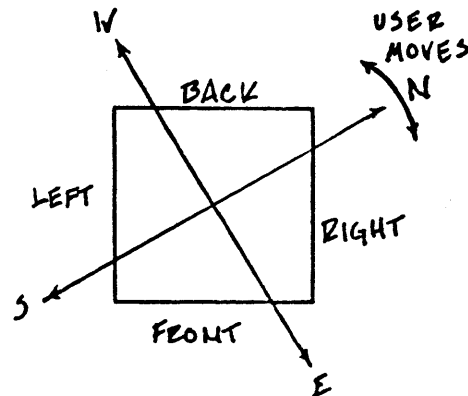
Orientation (direction of North on the plan).

2) Energy Analysis

For each room

U-values - five:

- four wall directions (L, F, R, B), roof.



Orientation

Percentage of window - four:

- the four wall directions (L, F, R, B).

Lighting level - three:

- midnight-8am, 8am-4pm, 4pm-midnight.

Occupation level (number of people) - three:

- same three periods as lighting.

For the whole building

U-values - five:

- windows in four directions (L, F, R, B),
overhanging floor areas.

Thermal capacity - eight:

- four wall directions (L, F, R, B), roof,
interior walls, floor/ceiling sandwich,
ground slab.

Thermal delay factor (hours) - five:

- four wall directions (L, F, R, B), roof.

External solar absorbancy of surface - five:

- four wall directions (L, F, R, B), roof.

Crack ratio (ratio of window perimeter to window area).

Weather stripping (factor indicating tightness).

4. ANALYTICAL DESCRIPTION

This section describes the analytical techniques used in the program - 1) those necessary for the estimation and 2) the more precise analysis techniques. The applicability of these techniques to the problem at hand determine to a large degree the success of the project.

There are several factors to be considered in each formulation. First, the calculation must produce a result which is accurate enough for our purposes. There are obviously differences between the estimation and the analysis in this factor. Second, the calculations must not take so much time that interaction is lost. The manipulations are limited whenever possible. Third, the available room in the machine being used is severely limited for a program of this complexity. As a result, large blocks of reference data are replaced by short calculations when possible.

These three considerations are at odds more often than not. Cutting the execution time, for example, often requires storing more data and/or sacrificing accuracy. Each factor has bounds which cannot be exceeded, so a great deal of give and take is necessary to achieve the proper mix. A fourth factor is reasonably compatible with the space and time limitations - the programming is simplified as much as possible. Unless a complex programming technique produces major positive effects on the other factors it is scrapped in favor of a more straightforward process. This helps both the original programmer, and especially

anyone who picks it up later.

4.1. Estimation Techniques

The important thing to remember in this section is that results must be accurate enough to reasonably show the effect of major design changes. Ten calculation methods are described:

- 1) The geometry of the overlaps and intersections between separate spaces.
- 2) The choice of the number of days and hours to evaluate, what time increments to use.
- 3) The handling of inside vs. outside temperature.
- 4) Air changes due to infiltration and ventilation.
- 5) Heat gain from artificial lighting.
- 6) Thermal conduction through walls, windows, and roof.
- 7) Heat losses through the ground slab and its perimeter.
- 8) Direct solar gain through windows.
- 9) The effect of solar insolation heating the exterior surface of walls.
- 10) The damping effect of thermal capacity on inside temperature fluctuations.

Geometry

The geometry would be simple if it were merely a matter of adding up the surface areas and volumes of the spaces.

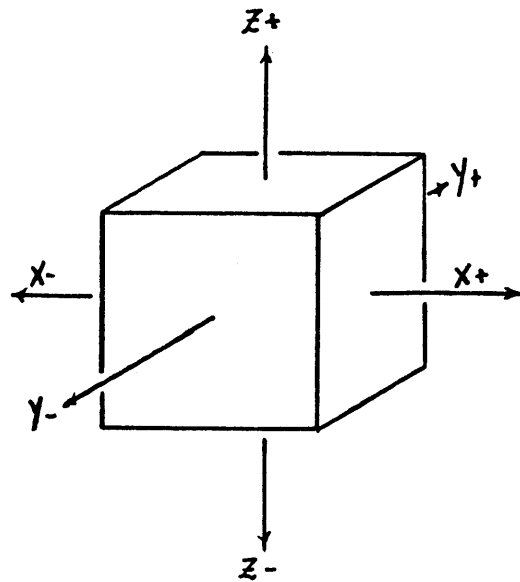
But the spaces abut and intersect, forming a much more complex problem. I should mention that for reasons still unknown to me, the data structure of MAS uses units of $3\frac{1}{3}$ inches. So factors of 3.6 (length), 12.96 (area), and 46.656 (volume) are used in the geometry calculations to convert to feet.

- Surface Areas

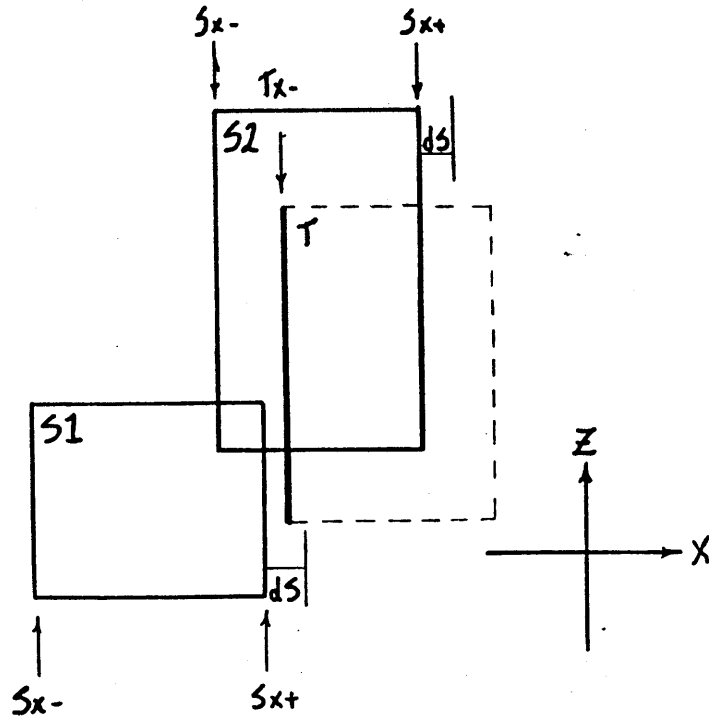
Because the geometry is orthogonal, it allows some shortcuts in the calculations. We are assured that all the surfaces will be normal to the X, Y, and Z directions. The X-, Y-, and Z- surfaces of each space are evaluated. Each surface is checked against each of the other spaces and the overlap recorded. The percentage of each surface of the space remaining exposed to the outside is multiplied by the area of the surface. These three exposed areas are summed as each space is evaluated.

Suppose we are evaluating a surface X- (see illustration on next page) on target space T in relation to space S1 and S2, which may overlap TX-.

There is a potential over-



Surface Directions

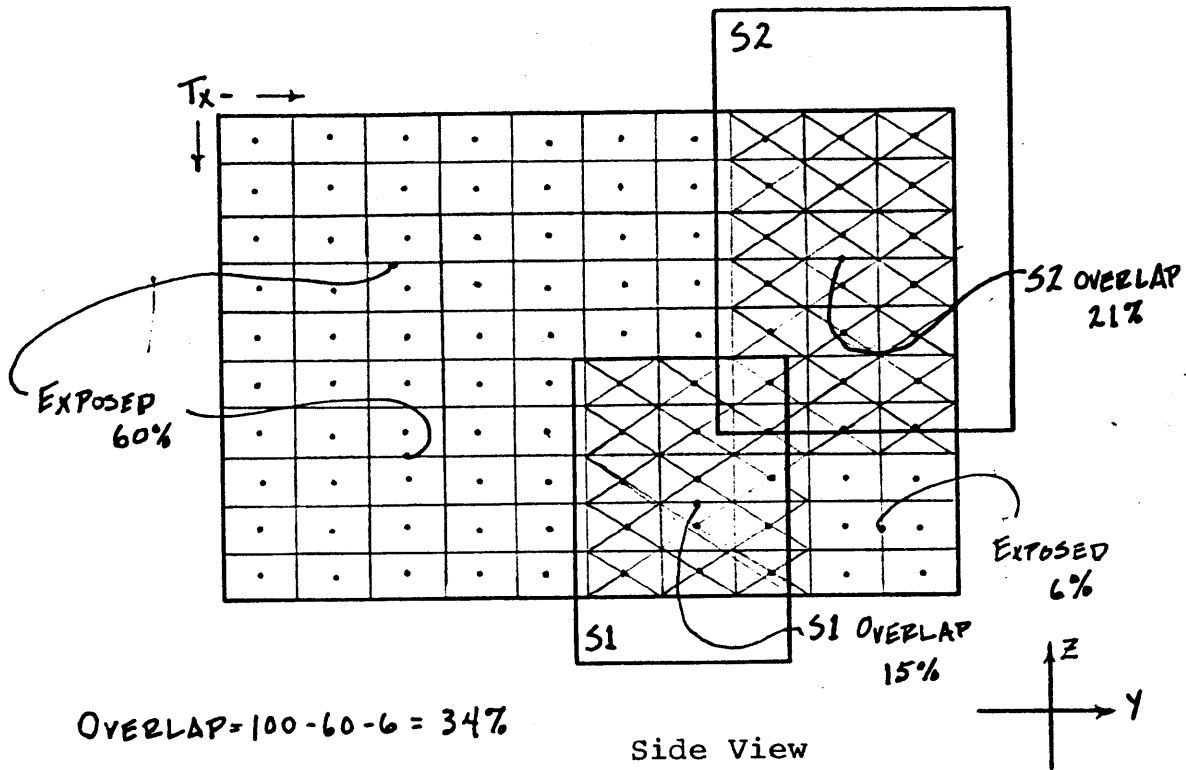


Front View

lap only if the X-coordinate T_{x-} is between S_{x-} and $(S_{x+} + dS)$. dS is an increment meant to cover the inexactness inherent in the CRT graphics. If the two spaces are "very close" it is presumed that the two walls are meant to abut. dS is a small increment set as an allowable inaccuracy. Two spaces with less than dS between them are considered to be adjacent.

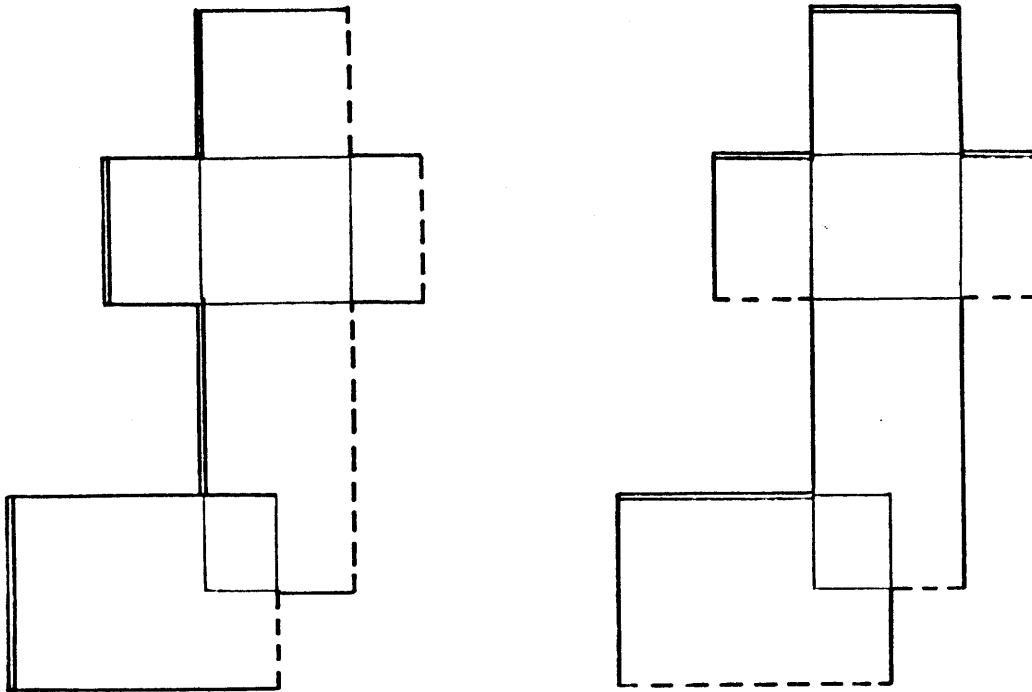
If the range of the coordinates of the two spaces in the other two directions overlap, as the Y and Z coordinates do in this case (see side elevation on next page), then overlap of the target surface is assured.

To determine the amount of overlap on a surface, caused by all the other spaces, the location of the overlap of each space must be known to prevent duplication when the



lapped areas themselves overlap. To accomplish this, the target surface is divided into 100 grids (TX-). If another space is found to overlap the surface (such as S1 or S2) each grid is checked individually for overlap. If the coordinates of the center of a grid are within the ranges of the lapping space, a code is entered for that grid. In this way, if two other spaces overlap the same grid square, it will only be counted once. By counting the number of grids still exposed, the percentage of exposure is found.

By summing the exposed areas as each space is evaluated, the total exposed areas facing in the three negative directions are determined. The exposed areas facing in the opposite directions will be equivalent. This fact can be



Equality of Opposite Surfaces

shown intuitively by noting that the dashed and doubled lines in the drawing above are equivalent in both cases.

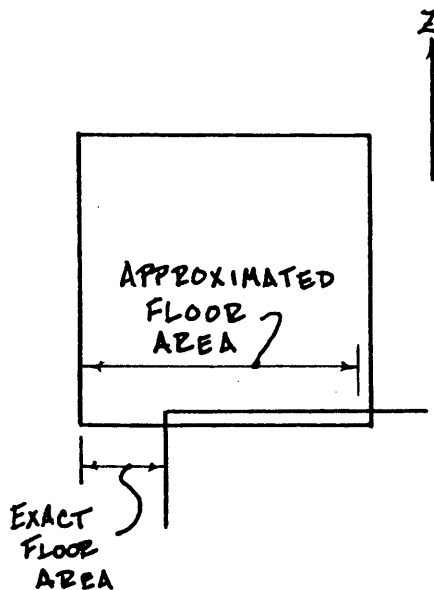
The exposed floor surface (Z-) can be one of two things - a ground slab or an exposed floor (an overhang). As each space is evaluated, the floor area is included in the ground slab figure if it is at or near the ground (the lowest space in the configuration). Otherwise it is added to the overhang figure.

- Volume

As the evaluation of a space is begun, its full volume is calculated. If another space overlaps in all three directions, the three percentages of overlap are multiplied

together and half the resulting percentage subtracted from the room volume. (The other half is accounted for when the target and overlapping spaces are reversed.) This does allow volume that is overlapped more than once to be subtracted more than once, but the effect with volume overlap is relatively minor. And in order to find the second level of intersection, a potentially large storage and comparison procedure would have to be implemented.

Inside floor area is approximated by dividing the volume of a room by its height. This is more realistic than calculating it exactly, because small inaccuracies in the graphics could result in gross errors in the floor area.



Time Increments

Annual energy use is found by summing energy use during representative periods throughout the year.

The question is how many "snapshots" to take of the situation to deduce the likely yearly effect. Full yearly figures are determined rather than worst or average conditions. Only in yearly figures can the building's performance under differ-

ent climate conditions be reflected. Some changes may improve the worst condition, but destroy the performance in March or June.

I decided to look at days representing every other month (Jan., Mar., May, July, Sep., and Nov.). Six provides a full picture of the whole year - the extremes and moderate months in terms of both temperature and solar effect. Twelve would be better, but it would mean twice as much weather data - temperatures, wind, cloud cover, and solar intensity. The solar data is the most important, as it is the largest block of weather data, but each pair of the six months chosen (Jan-Nov, Mar-Sep, and May-July) have identical solar intensities, so that data is halved again.

All 24 hours of the day are evaluated separately. This may seem unnecessary in an estimation, but there are justifications. The solar effect may be important on one wall face for only two or three hours. If only every third or fourth hour were evaluated, an important influence might be missed. The spacing would become important also. If three-hour intervals are chosen, then in March, no significant sun is realized until 9am or after 3pm, whereas the 7-8am and 4-5pm effects are very important to the construction of East and West walls. Finally, if the building must be cooled for half of a longer interval and heated for the other half, the two loads may be unjustifiably cancelled out. It still may seem like far too much extra calculation,

but it is not as much as one might think. Calculations for 24 hours are not 24 times as long as those for one hour. Very few items have to be redone each hour, except those calculations related to the sun (and the sun is only up for 12 hours). The cost of evaluating each hour is not large, considering the benefits.

As each hour is evaluated, the resulting load is added to the total heating or cooling load. If it is a cooling load, much of the cooling may be done without burning any fuel. If the outside air is at a lower temperature than the inside, much of the cooling load can be met simply by blowing in outside air (see Infiltration / Ventilation). As all six days are calculated, they are summed, and the totals multiplied by 61 (365/6) to get the yearly heating and cooling loads.

Temperature Differences

There are three different situations for calculating the temperature difference between inside and outside air. The comfort zone is taken to be 65 - 75 degrees Fahrenheit. If the outside temperature is under 65, then the inside temperature is assumed to be 65. If the outside temperature is over 75, then the inside is assumed to be 75. If the outside is between 65 and 75, the inside temperature will normally be allowed to "drift" toward the outside temperature. The temperature difference is effectively zero, as no energy

need be used to counteract the temperature variation.

Infiltration / Ventilation

One of the major contributors to heating and cooling loads in any building is conditioning air from the outside. Air comes in in two ways: it enters through cracks around windows and doors (infiltration), and it is intentionally drawn in to provide oxygen and remove odors within the building (ventilation). The full amount required for ventilation is seldom all mechanically inlet, because infiltration provides much or all that is needed. Therefore, the two air volumes are calculated separately for each room and the larger one added to the total volume of outside air used in the building.

Infiltration is calculated as a function of the number of exposures of a room, its volume, and the quality of construction. While calculating the geometry, the percentage of each wall exposed to the outside is stored. If more than 10% of the wall is in contact with outside air, it is considered to be an exposure. The volume of outside air infiltrated each hour is found by the formula:

$$\text{Infiltration} = ((\text{exposures} + 1) / 2) * \text{room volume (ft}^3\text{)}.$$

This is based on a rule of thumb that a room with no exposures replaces half its volume of air each hour. Another half-volume is added for each outside exposure.¹⁰

The quality of construction is then included by multiplying by a factor which varies from .6 for tight, weather-stripped construction to 2.0 for poor quality, older construction.

Ventilation is simple. A standard figure is taken ($\frac{1}{4}$ cubic feet per minute) representing the fresh air requirement (per square foot) to dispel odors.¹¹ The standard applies to sedentary occupants of residences or offices. Although this figure might vary considerably for assembly areas, kitchens, machine rooms, and other special areas, such situations are not considered. To do so would require inclusion of tables of ventilation requirements, and specification by the user of special areas, intensity of use, and period of use. For an estimation, this seems far more effort than it's worth. Most importantly, these variations will effect the total figure, but change very little, if at all, with the modifications the designer will make.

The larger volume, infiltration or ventilation, is taken as the total outside air inlet per hour. To get the BTU requirement, the following formula is applied:¹²

$$\text{Energy (BTU/hr)} = \text{outside air (ft}^3\text{/hr)} * .01834 \\ (\text{BTU/deg ft}^3) * dT (\text{deg}).$$

Ventilation must also be considered from another point of view - maximum natural ventilation when it is desirable for cooling. In many cases, overheating occurs inside the

building while the outside temperature is relatively low. Allowing this cool air into the building can reduce the cooling load considerably.

Because of the difference in the inside and outside humidity, outside air must be about 5 degrees cooler before it can help to condition the inside. Even when it is below that temperature, a rule of thumb limits the savings to 75% of the available cooling capacity. This accounts for rainy or excessively humid periods, when outside air is unusable.

Natural ventilation can be estimated from the formula:¹³

Inlet air (ft³/hr) = .15 (effectiveness factor)

* open window area (ft²) * wind velocity (mph)

* 88 ((ft/min) / (miles/hr)) * 60 (min/hr).

The effectiveness factor is based upon on a standard of .60 for a window facing the wind directly (averaged against .00 for the other three sides), or .30 for a window facing diagonally, which would occur on two sides (averaged against .00 for the other two). The open window area is half the total window area of the building. The BTU capacity of this air when raised to the high end of the comfort zone is given by the same equation as used for the other inlet air (Energy = air volume * .01884 * dT). Three-quarters of this potential is applied to the cooling load required. Up to 75% of the load can be eliminated in this manner.

Lights

Lighting levels are presumed to be uniform throughout the building. The user sets the level, varying from a default of 2.0 watts per square foot. The wattage of the lights produces heat directly or light which is transformed into heat as it hits surfaces. Heat is found by the simple conversion:¹⁴

$$\begin{aligned} \text{Energy (BTU/hr)} &= \text{lighting level (watts/ft}^2\text{)} \\ &* 3.4 \text{ (BTU/watts)} * \text{floor area (ft}^2\text{)}. \end{aligned}$$

Conduction

Conduction is usually the largest component of heating and cooling loads. It is also a reasonably straightforward calculation. Basically:¹⁵

$$\begin{aligned} \text{Energy (BTU/hr)} &= \text{U-value (BTU/hr deg Ft}^2\text{)} * \text{area (ft}^2\text{)} \\ &\text{dT (deg)}. \end{aligned}$$

U-values can be changed by the user. There are four values for the estimation - roof, walls, windows, and floors (overhangs).

Overhanging floors are the easiest. The area of overhang is already available. The formula is easily applied. Roofs are almost as simple. By adding the overhang and the ground slab areas together, the roof area is arrived at, and the heat transfer is found.

Walls are more difficult because each wall direction (Left, Front, Right, Back) has a percentage of window

coverage specified by the architect. So the area of the wall must be multiplied by the percentage not covered by the window. Then the formula is applied. For windows, the area of the wall is multiplied by the window coverage and the conduction formula implemented for each of the four sides of the configuration.

Slab Losses

There are two components in the losses at ground level - slab losses and perimeter losses. Both are calculated by empirical formulas. The perimeter formula is:¹⁶

$$\text{Energy (BTU/hr)} = .6 \text{ (BTU/hr deg ft)} * \text{length of perimeter (ft)} * dT \text{ (deg)}.$$

Finding the exact perimeter at ground level would require considerable manipulation, so an approximation is made, utilizing the geometry available. Dividing the total volume by the total wall area gives the relationship between area and perimeter for the whole building. This factor is then applied to the ground area to get the ground perimeter. This will be quite close unless the building configuration changes considerably above ground level.

$$\text{Length of perimeter (ft)} = \frac{\text{slab area (ft}^2\text{)} * \text{wall area (ft}^2\text{)}}{\text{volume (ft}^3\text{)}}.$$

The formula used for slab losses is:

$$\text{Energy (BTU/hr)} = .05 \text{ (BTU/deg hr ft}^2\text{)} * dT \text{ (deg)} \\ * \text{ slab area (ft}^2\text{)}.$$

The temperature difference used, however, is the difference between inside and ambient (ground) temperatures.

Insolation

This source of heat gain is very important, both in its absolute effect and especially in its responses to changes in configuration and values. It also has the greatest potential for overwhelming the computer with calculations and the user with requests for data. I have adopted what I feel to be a reasonably simple procedure with results well within the bounds of accuracy set for the estimation.

- Windows

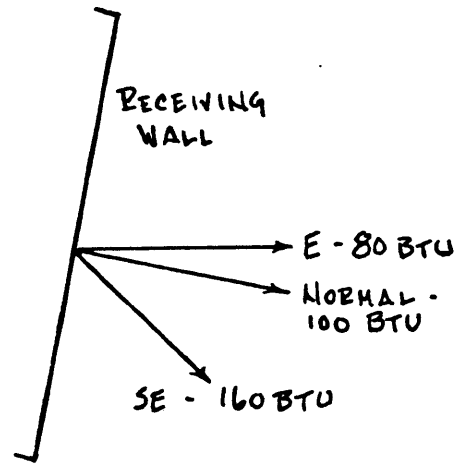
The source of most of the calculations involved in solar insolation is finding the intensity of the insolation striking and passing through windows. The trade-offs here are very important to the success of the whole process. There is potential for a great mass of table data or very involved and time-consuming calculations. I opted for a minimum of calculation and tried to limit the tables of data as much as possible.

I was able to find a table which accounted for almost all the variables involved.¹⁸ The sun angle is used in setting up the table to account for atmospheric extinction,

reduction from the normal intensity by the COSINE law, and reflection off the glass as the angle gets sharper. The direct and diffuse components of the solar insolation are combined in the table to give a total insolation. Standard window frame construction is assumed to find the percentage of glazing in the window. Latitude is accounted for when the weather data for the particular site (including the tables for intensity) are formed, long before the actual design process is begun. What results is a table of the amount of sunlight which actually reaches the building's interior through a square foot of glass at various dates and hours. This table covers each daylight hour of the six days chosen for evaluation. Intensities are provided for each of the eight major compass points and a horizontal surface for each of these hours. These tables can be cut in half twice, because they are symmetric about the soltices (March 21=September 21, November 20=January 21, etc.), and they are symmetric about noon (what happens on a southeast wall at 8 a.m. also happens on a southwest wall at 4 p.m.). With this simple, manageable table, extensive hourly calculations are avoided.

To find the solar gain through windows on a specific wall, the direction of the normal to the wall must be determined. This is done by comparing the direction on the CRT (left, right, front, back) with the orientation chosen by the designer on the same screen. The wall direction will fall between two of the eight compass

directions. The two intensities for that hour and day are simply interpolated to find the estimated intensity on the wall. For instance, if the wall orientation were three times closer to East than to Southeast, 75% of the East intensity and 25% of the Southeast intensity would be added to get the intensity on the wall. That figure represents the BTUs entering the building through one square foot of glass on that wall in that hour on a clear day. To find the area of glass, it is only necessary to multiply the area of the wall by the percentage of window, as was done in the conduction calculation. Clouds, however, must also be considered, as they can cut solar gains by a considerable fraction. Fortunately, a fairly simple empirical formula is available to convert the cloudiness of a climate into its effect on solar gain:¹⁹



Interpolation of
Solar Intensity

$$\text{Real solar gain (BTU/ft}^2\text{)} = (.30 + (.65 * \% \text{ potential sunshine})) * \text{potential solar gain}$$

The real solar gains can be as little as 30% of the potential (that much sunlight gets through, even if it is always cloudy).

In summary, for windows:

$$\text{Energy (BTU/hr)} = \text{solar intensity (BTU/hr ft}^2\text{)} * \text{wall area (ft}^2\text{)} * \% \text{ window} * (.30 + (.65 * \% \text{ clear sky})).$$

- Walls

The intensity absorbed by the wall surfaces can be determined using the amount passing through the windows. A factor relating the transparency of standard glazing and the absorptivity of common building materials is applied. However, only a small part of the heat absorbed by the exterior surfaces reaches the interior. It is reduced by two factors: the amount of heat amount of heat available is reduced by convection and radiation losses to the outside, and the U-value limits the amount of heat transmitted through the wall.

Convection and radiation losses are primarily a function of the wind speed. The following formula has been derived from more complex calculations of sol-air temperature:²⁰

$$\text{Available heat (BTU/hr)} = \text{absorbed heat (BTU/hr)} \\ / \text{SQRT}(2 * \text{wind speed (mph)}).$$

For a wind speed of 12 mph, the heat gain would be reduced by a factor of five.

After multiplying by the U-value, the heat gain may be $\frac{1}{25}$ th of the gain through an equivalent area of glass. The question may well be asked, why I bother with such a minor component. There are two answers. First, it can be important where there are large wall surfaces and minimal win-

dows, especially with large roof areas, which often get the most intense sun. Second, the equation is actually quite short, and need only be done once for each wall. This is because the complex portions of the calculation have already been done for the window gains.

Internal Thermal Capacity

During the course of a day, the situation may well occur where heating is required at night, and cooling during the day. This changeover does not take place instantaneously. The air conditioning does not turn on as soon as the heating shuts off. There is a range of temperature in which most human beings are comfortable (I have set it at ten degrees, from 65 to 75 degrees). While the heating is on, the temperature inside is kept at 65 degrees. The air-conditioning will not turn on until the temperature of the interior, walls and floors included, has risen ten degrees.

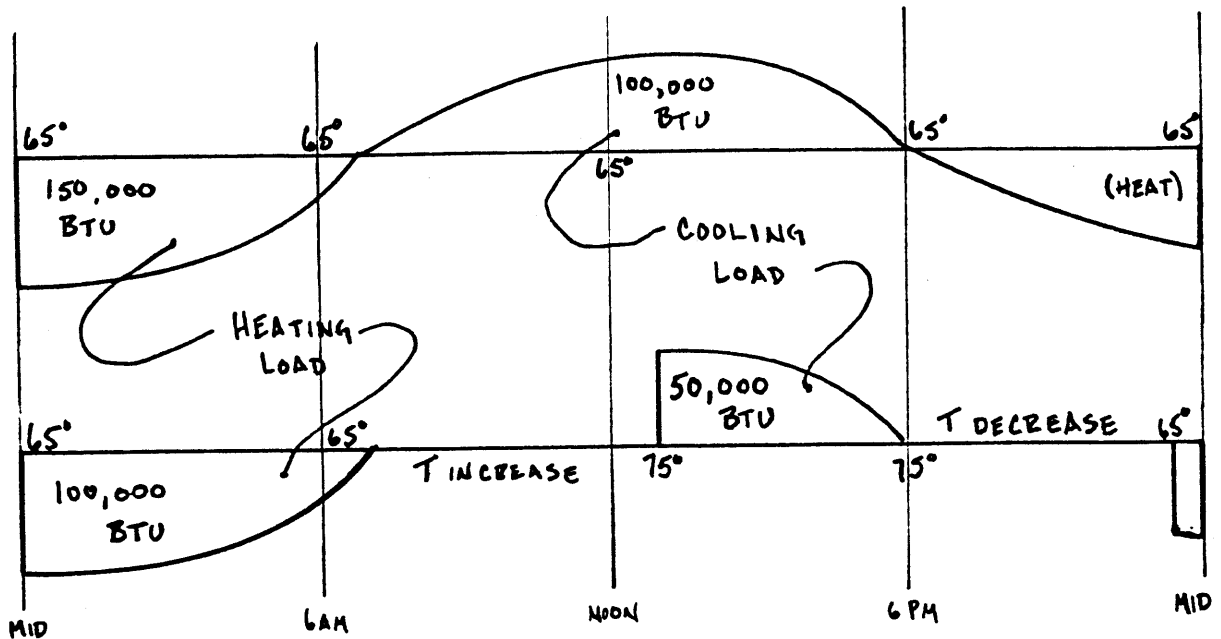
The thermal capacity of the various parts of the building can be entered by the user. There are values for exterior walls, interior walls, roof construction, interior floors, and the ground slab. Thermal capacity is the BTU's stored in a square foot of surface while the material rises one degree in temperature. The user can calculate the thermal capacity of a surface material by the formula:

$$\text{Capacity (BTU/ft}^2\text{)} = \text{specific heat (BTU/ft}^3\text{)}$$

* thickness (ft).

Only half the capacity of exterior surfaces can be used. They are affected just as much by the outside temperatures as by the inside, so the change in inside temperature is effectively using only half the full thermal capacity. The total thermal capacity of the building is half the capacities of the roof, exterior walls, and ground slab, and all of the interior floors and walls. Multiply this by the ten degree comfort range, and you have the potential BTUs absorbed or released by the structure while the temperature moves from one end of the comfort zone to the other.

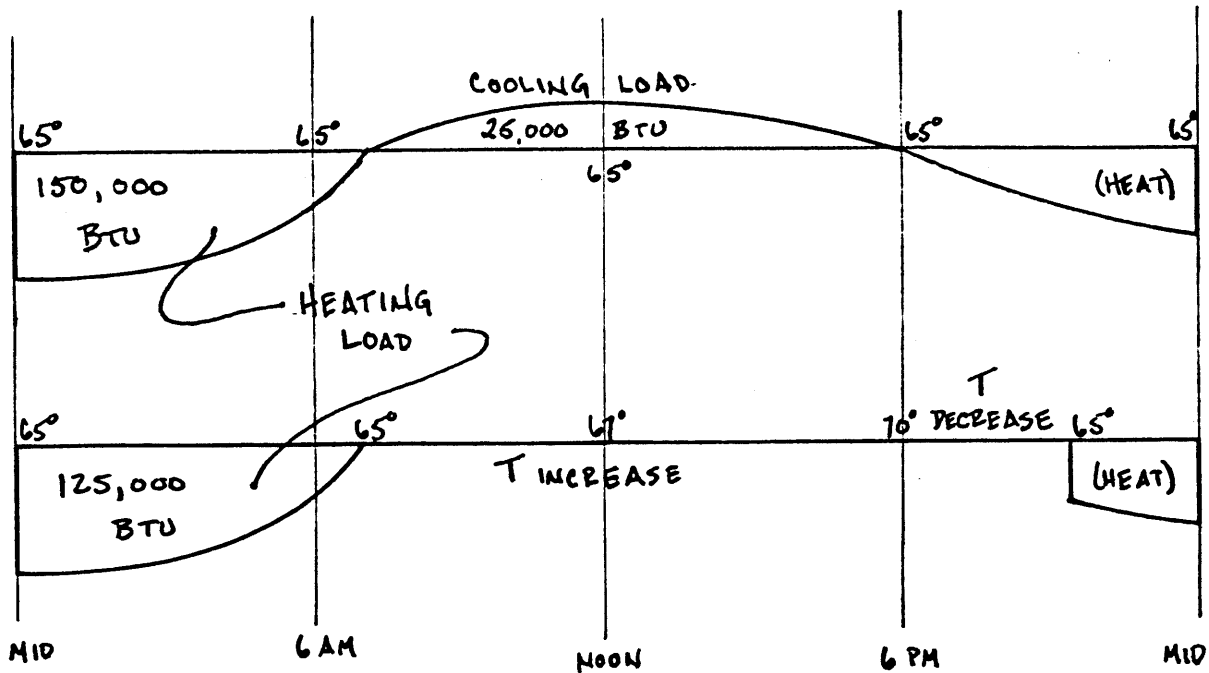
Cancellation to Limits of Capacity



The loads for a particular day may look like this. The total cooling load may be 100,000 BTUs, the heating load 150,000 BTUs. Suppose the thermal capacity of the

building were 50,000 BTUs. Then for the first half of the cooling load, the temperature would be allowed to rise and no cooling would be done. Likewise, when heating is required, the temperature is allowed to drop from 75 back to 65 before the heater is turned on again. 50,000 BTUs are saved going each way. If one of the loads is less than the capacity, say a cooling load of 25,000 BTUs, then the temp-

Cancellation to Limits of Smaller Load



erature would only climb to 70, and only half the capacity would be available during the heating period because only half the temperature drop is available - from 70 to 65. If there is no heating load or no cooling load, the inside temperature is kept at the extreme of the comfort zone, and no cancellation of loads is possible.

In my calculations, I find the total heating and cooling loads for a day, ignoring the thermal capacity. Then I find the lowest of the three quantities - heating load, cooling load, and thermal capacity. This figure can be subtracted from both loads to account for the portion of the loads covered by inside temperature fluctuations.

4.2. Analysis Techniques

Some of the procedures used in this section are similar to, or extensions of the estimation techniques. The difference is that the analysis must include effects which were too minor to consider during the estimation. Twelve calculation methods are described:

- 1) The geometry of each space, with relation to the rest of the spaces.
- 2) The choice of time increments.
- 3) The computation of inside temperatures.
- 4) Air intake from infiltration and ventilation.
- 5) Heat gain from artificial lighting.
- 6) Heat gain from people occupying the space.
- 7) Thermal conduction through walls, windows, and roof.
- 8) Heat losses through the ground slab and its perimeter.
- 9) The amount of shadow occurring on a given wall at a given hour.
- 10) Direct solar gain through windows.
- 11) The effect of solar insolation heating the exterior

surface of walls, including the effect of time lag.

12) The effect of thermal capacity on temperature fluctuations.

Geometry

Two geometric items must be computed for the analysis: exposed surface areas, and surface grid matrices. Volumes are not used in any analysis computations.

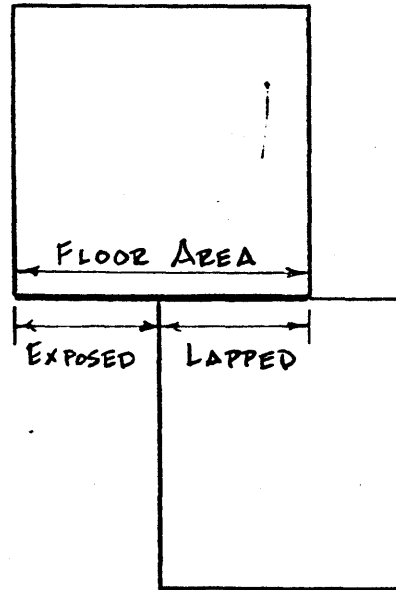
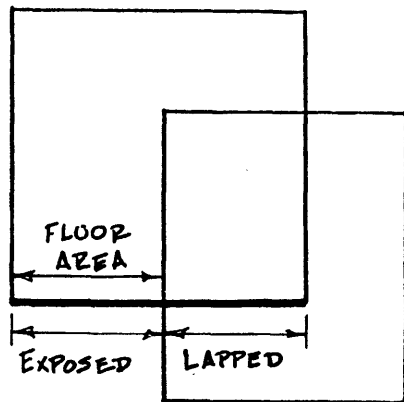
- Surface Areas

Surface areas exposed to the outside are calculated in the same way as they were in the estimation. However, the data is stored for each room, rather than for the whole configuration. In this way, whenever any value referring to a surface of a specific room is changed, that change can be pro-rated to the entire building, according to the percentage of the total surface represented by the room to which the change applies. This pro-rated value can be sent back to the estimation routines to reflect the changes made in the analysis section.

Although exposed areas of opposite sides are equivalent when the building as a whole is considered, they are often different for individual spaces. As a result, the exposed areas are computed for each of the six surfaces of a space. If the space is on the ground, the area in contact with the ground is saved as well.

The floor area is calculated more precisely than in.

the estimation. It is done by a small modification of the exposed, /overlapped area technique. When a secondary space abuts (rather than overlaps) the lower surface, it does not reduce the inside floor area, even though it cuts down the outside exposed



area. As the exposed area is calculated, the floor area is computed as well.

All of the surface areas, the floor area, and the ground contact area are computed for each room when the analysis routines are first called. The foreground for the analysis does not allow modification of the geometry, so the calculations need not be repeated until the entire module containing the analysis is exited and reentered.

- Grid Matrices

However, when the analysis is being performed on a particular space, the location of the exposed area on each surface is necessary. Because shadowing is considered, the potential area of sunlight must be known. Therefore, the six 10x10 grids used to compute the exposed areas are passed on to the routines which calculate the sun and shadow effects.

Each time a new space is chosen for analysis, the grids for that room are reproduced.

Time Increments

The estimation deals with "average" days in each month. But variation from day to day can sometimes result in different loads from the average. This is particularly true of months which have both heating and cooling periods during the day. Solar heating varies greatly between clear and cloudy days. On a clear day it may cause overheating which would not occur on a cloudy day. To account for this potential variation, I evaluate two days in each of the six months - one cloudy and one clear. The average clearness is used to determine the percent of sunshine on the two days. If it averages 60% clear, the clear day will be 100% clear, the cloudy day 20% clear. As much of the clearness as possible is allocated to the clear day. The rest of the climatic data is left the same. While individual days do tend to be cloudy or clear, it is difficult to know what the

associated variation in temperature or wind would be. In all, 12 days are evaluated, but for half of them, only new solar intensities must be calculated. The rest of the data remains the same as the other day in that month.

Temperature Differences

The internal temperature of the room is recalculated each hour (see Thermal Capacity for the method). The temperature difference is found by subtracting the inside temperature from the outside.

Infiltration / Ventilation

Both of these items are computed more precisely, because more information is available and more precision is necessary for such an important component. As in the estimation, the infiltration and ventilation are computed separately, and the higher figure each hour taken as the volume of outside air to be conditioned. Each hour the energy use is found by the same formula used in the estimation.

- Infiltration

I have used a simplification of the crack length method. First, the length of crack around windows must be found. Window areas are computed for each wall. Two window areas are determined - the largest area on a single wall, and half the total for the room. The larger of these is the one

used in the computations. A "crack ratio" can be entered by the designer, which is a factor relating the window area to the window perimeter. In this way, the length of opening which will be letting air in can be found.

Once the length is found, the volume of air inlet can be found by an empirical formula related to wind speed:²¹

$$\begin{aligned} \text{Volume (ft}^3\text{/hr)} &= (\text{crack ratio (ft/ft}^2\text{)} * \text{window area (ft}^2\text{)} \\ &* (\text{wind speed (mph)} * 3 + (\text{wind speed (mph)}/5 - 1)^2) \\ &* \text{quality of construction.} \end{aligned}$$

The quality of construction factor is similar to that in the estimation. It varies from .6 for weather-stripped windows to 2.0 for poor construction.

- Ventilation

The architect may specify the number of people in the room at three different periods of the day. Ventilation requirements for each of the periods are based on the occupancy. There are two reasons for changing inside for outside air - to provide oxygen and to disseminate odors, primarily caused by the occupants. Odor dissemination is normally the larger of the two. For sedentary people (the usual state) about ten cubic feet of outside air per minute (600 per hour) are required to eliminate odors. The volume of air required for ventilation is:²³

$$\text{Volume (ft}^3\text{)} = \text{occupation (people)} * 600 \text{ (ft}^3\text{/hr person).}$$

Lights

Heat gain from lights is calculated from the same equation used in the estimation. In the analysis, however, the lighting levels for three periods of the day can be explicitly defined by the architect.

People

The number of people in the room at a given hour, specified by the architect, add to the heat in the room. Again, I have assumed sedentary people, for whom the heat exuded is about 400 BTU/hr apiece. So the simple formula is:²⁴

$$\text{Energy (BTU/hr)} = \text{occupancy (people)} * 400 \text{ (BTU/hr person)}.$$

Conduction

The conduction is figured in the same manner as in the estimation. The only difference is the greater variation and precision allowed the user in his choice of U-values and window areas.

Slab Losses

The slab losses are calculated in essentially the same way as in the estimation. The exposed perimeter is calculated by dividing the exposed wall area by the height of the space under consideration.

Shadow Areas

Shadow identification is easily the most time-consuming calculation involved in the analysis. They must be redone every daylight hour of every day, and every room casts a shadow which may effect the surface being evaluated. Still, I think they have been simplified to a manageable size in this program. I have done this by eliminating unnecessary calculations at every step along the way.

Each hour the solar altitude and azimuth must be determined. The altitude is found by the formula:²⁵

$$\begin{aligned} \text{SIN}(\text{altitude}) &= \text{COS}(\text{latitude}) * \text{COS}(.2618*H) * \\ &\text{COS}(\text{declination}) + \text{SIN}(\text{latitude}) * \text{SIN}(\text{declination}). \end{aligned}$$

where the latitude is passed in with the weather data and converted to radians, H is the number of hours from noon, and the declination is a constant, a function of the date. The azimuth is computed from:²⁵

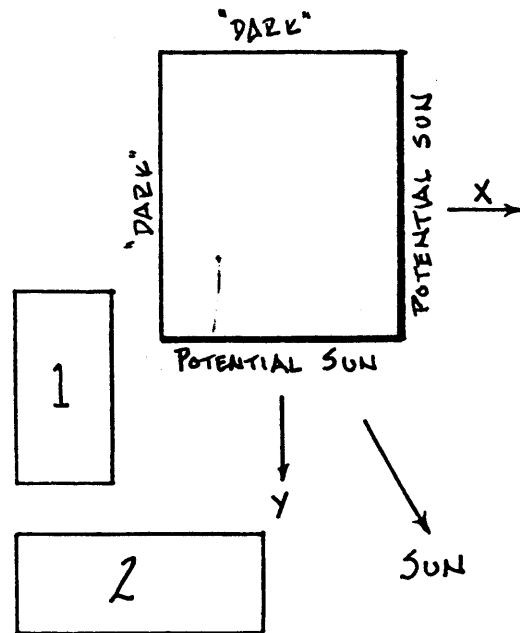
$$\begin{aligned} \text{SIN}(\text{azimuth}) &= \text{COS}(\text{declination}) * \text{SIN}(.2618*H) \\ &/ \text{COS}(\text{altitude}). \end{aligned}$$

The azimuth is rotated to reflect its position relative to the Y-axis of the configuration as displayed. In this way the sun angle is identified in terms of the coordinate system of the design.

Given this azimuth, the two walls which will receive sunlight (along with the roof) are identified. For example, if the azimuth is in the fourth quadrant, the front and

right walls of the configuration will get sun and be candidates for shadowing.

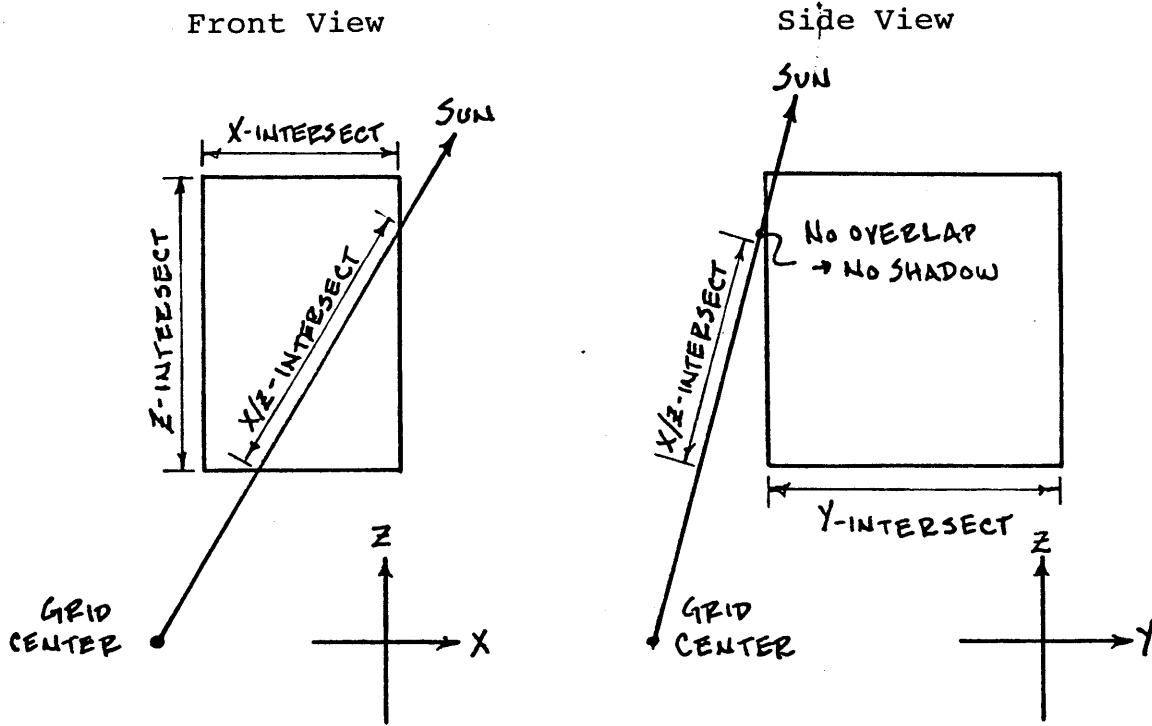
Each of the other spaces is then checked. If the other space is entirely on the "dark" side of the target room in any dimension (space 1 in the X-direction), it is eliminated as a potential shadowing form. In the example, a space to the left, rear, or below the target room would be eliminated. Then each of the target surfaces is evaluated. If the second space is on the dark side of that surface, it is eliminated from consideration of that surface (space 2 when evaluating the X surface).



The next step is to evaluate each grid on the surface which has not previously been found to be overlapped or shadowed. To find whether the second space casts a shadow on the grid, the coordinates of the center of that grid are calculated. I will describe graphically the manipulations I make to determine whether a shadow is cast on that spot by the rectangular box representing the shadowing space.

A line is drawn from the center of the grid toward the

sun. If the line intersects the box, the grid is in shadow. The intersection of the line with the Z-dimension of the space is computed, then the intersection of the resulting segment and the X-dimension of the room is found. Finally,



the intersection of that segment and the Y-dimension is determined. This final segment is the intersection of the line to the sun and the shadow-casting space. If such a segment remains, the grid is in shadow. If, at any step along the way, no intersection was found, then the grid can still "see" the sun.

When all the other spaces have been checked for all the grids on the surface, the number of grids still in sunlight is divided by the number exposed to the outside

(sunlit plus shades). That number is the percentage of exposed wall in sunlight.

Insolation - Windows

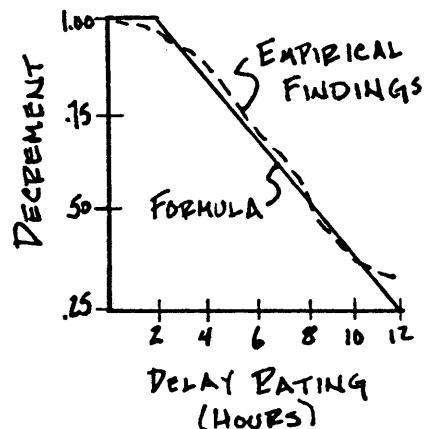
The solar insolation of the room through windows is calculated much the same as in the estimation. The amount of window area can be specified for the individual room to give the designer more control.

Shadow is taken into consideration by modification of the factor controlling cloudiness (a surface in shadow is equated to the same surface on a cloudy day):

$$\text{Clearness factor} = .30 + (.65 * \% \text{ clear} * \% \text{ in sunlight}).$$

Insolation - Walls - Heat Lag

For heavy construction, the heat entering a room through the walls is delayed, sometimes several hours. This delay has the effect of depreciating the value of the heat delivered to the interior. Experience has shown this depreciation related to the number of hours of delay by the following relationship:²⁶



$$\text{Depreciation factor} = 1 - (\text{delay (hrs)} - 2) * .075.$$

(Delays of two hours or less are insignificant.)

The amount of insolation reaching the surface is found by the same formulas used for windows, multiplying that by the modification factor converting it to wall absorption. This is converted into a sol-air temperature for the wall by the formula used in the estimation:

$$\begin{aligned} \text{Sol-air temperature increase (deg)} &= \text{insolation (BTU/ft}^2 \text{ hr)} \\ &* \text{ absorbancy / SQRT}(2 * \text{ wind speed (mph)}). \end{aligned}$$

The effect of the sun on outside walls is found by a formula which approximates the variation of heat load caused by the delay:²⁷

$$\begin{aligned} \text{Energy (BTU/hr)} &= \text{area (ft}^2) * \text{U-value (BTU/hr ft}^2 \text{ deg)} \\ &* ((\text{average sol-air T (deg)} - \text{outside T (deg)}) \\ &+ (\text{current sol-air T (deg)} - \text{average sol-air T(deg)}) \\ &* \text{depreciation factor}). \end{aligned}$$

The average sol-air temperature for this equation is found by using the sol-air equation above, inserting the average insolation over 24 hours.

Internal Thermal Capacity

Thermal capacity is used to determine the internal temperature. The capacity of the room is found by the same methods used in the estimation, except that all capacities

are halved because all surfaces are shared with another inside or outside space.

The starting temperature for the day (1am) is found by taking the monthly average and adding 5 degrees (inside temperature will maintain itself somewhat higher than the outside ambient). If it is within the comfort zone, that is the starting temperature. If not, the nearest extreme (65 or 75) is taken as the starting temperature.

If the room temperature is more than 65 during an hour when heating is required, then the potential thermal capacity at that time is:

$$\text{Potential capacity (BTU)} = (\text{room } T \text{ (deg)} - 65 \text{ (deg)}) \\ * \text{ capacity (BTU/deg)}.$$

If the energy required is greater than the potential capacity, the room temperature is reset to 65 degrees and the energy requirement is reduced by the potential capacity. If the energy needed is less than the potential capacity, the energy requirement is eliminated and the temperature change is found by inverting the previous equation:

$$dT \text{ (deg)} = \text{energy (BTU)} / \text{capacity (BTU/deg)}.$$

Similar manipulation are performed when the temperature is less than 75 and cooling is required.

5. EVALUATION

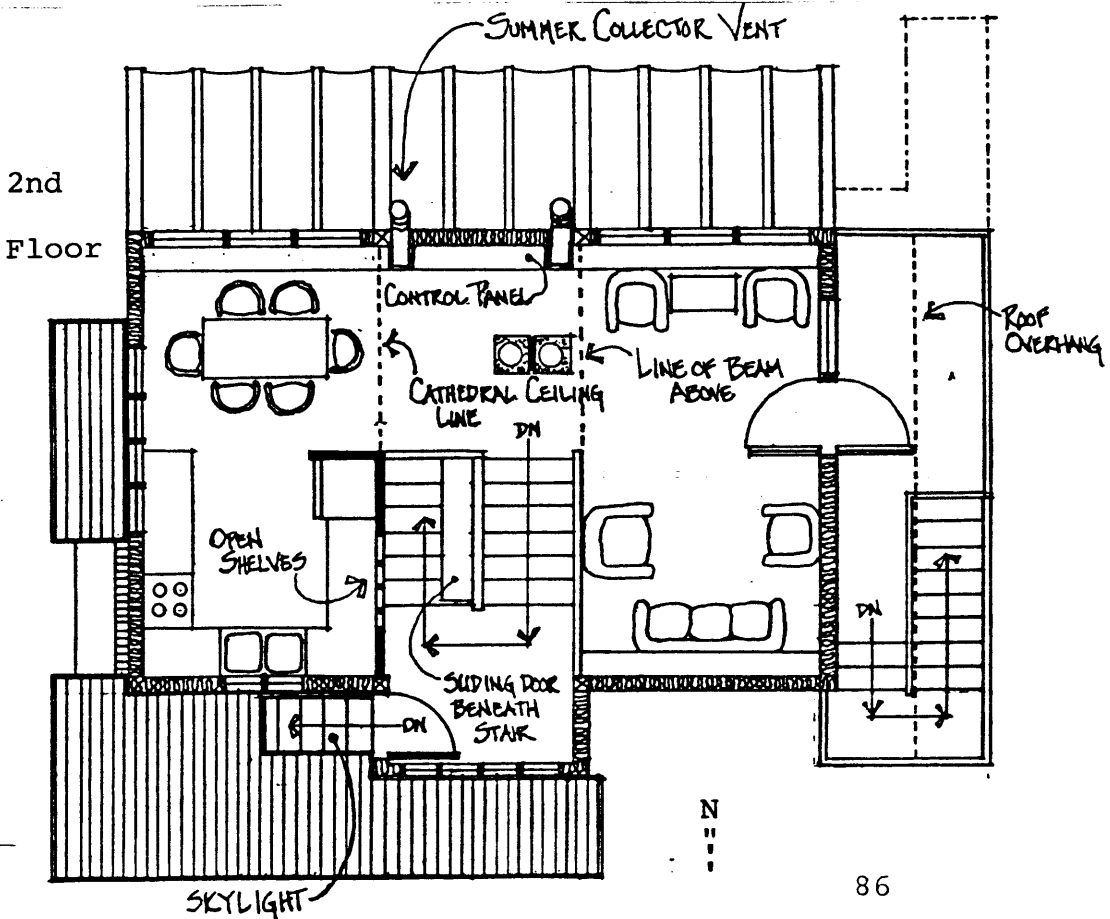
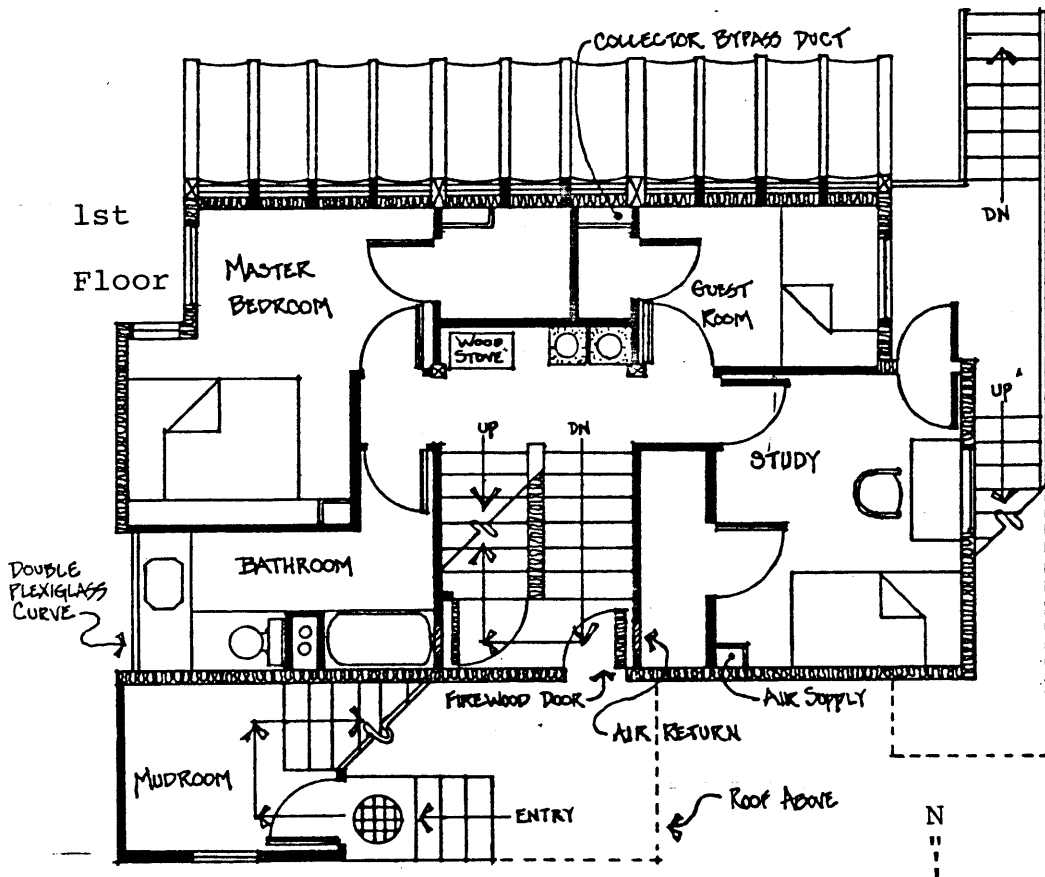
This section investigates the capabilities of the programs as they exist at the end of this semester. Three sections are included:

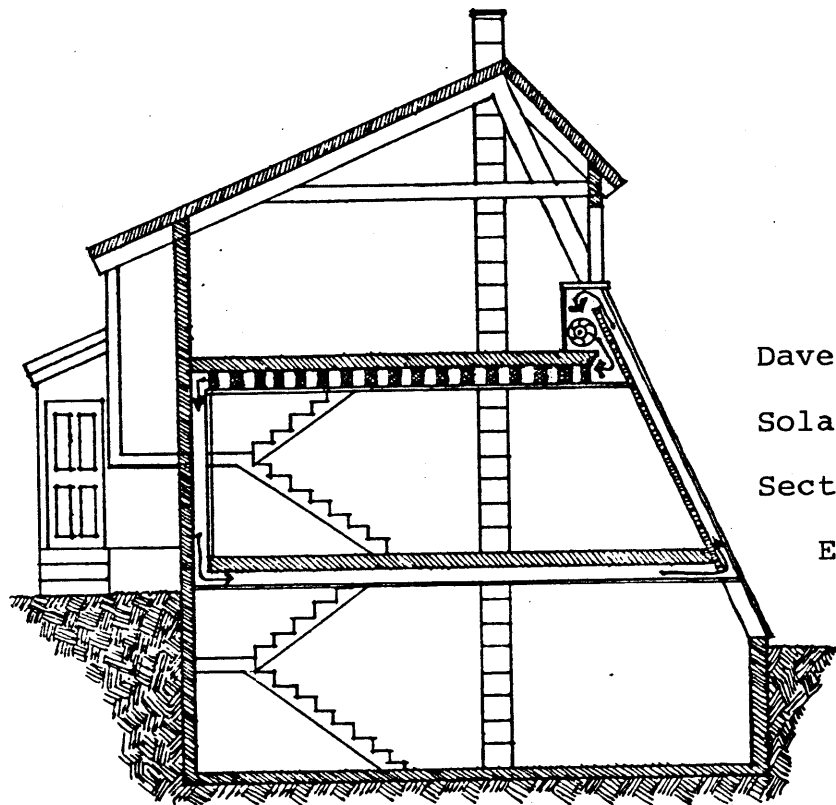
- 1) A trial run, using an existing building as the model, and its builder as the operator of the program.
- 2) A detail breakdown of the energy load of a test problem into the many components computed by the estimation program.
- 3) A discussion of possible future improvements to the space-allocation/energy estimation system, and guidelines for new developments.

5.1. Trial Run

As part of his own thesis, Dave Bryan has been working with a solar house which he built, and has been monitoring.²⁸ He agreed to run the energy estimation using his building, shown in the drawings on the following pages. His wish was to discover the effect of various modifications to his house. He had made decisions on the basis of both energy and architectural considerations, and was eager to know what the ramifications of those decisions are.

I hoped to learn several things. First, I wanted to find out how difficult it would be to enter the data and geometry of the building into the program. As can be seen from the section of the building, it is not easily adapted to the rec-





Dave Bryan's
Solar House.
Section facing
East.

tangular format required by the space-allocation portion of the program. Second, I wished to observe how easily the method of manipulation could be picked up by someone totally unfamiliar with the program or, in fact, interactive graphics in general. Third, the test would show whether the types of modifications a designer might wish to check could actually be modelled on this system. Finally, I wanted to see whether the energy information produced after a design change accurately reflected the change, and whether they provided usable data.

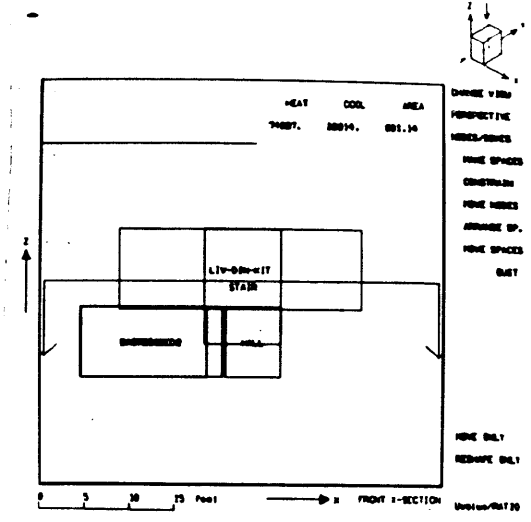
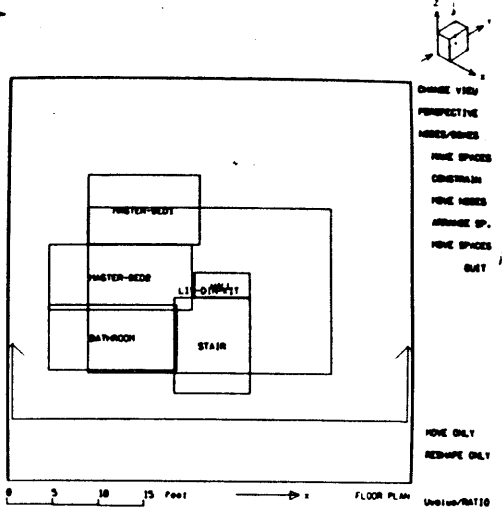
Input Preparation

Before approaching the machine at all, we sat down for about half an hour to model the real building in the restricted terms of the program.

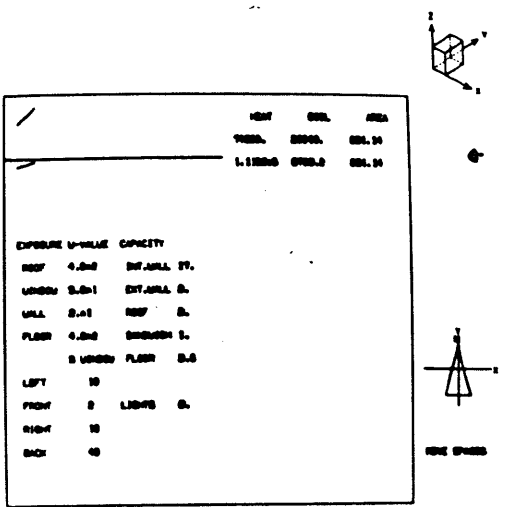
The peaked roof could not be entered as such, but Dave had already calculated an effective U-value for the roof, as if it were a flat ceiling. So we simply assumed the roof to be flat, with the modified U-value. The basement, being underground, also presented a problem, but it is an unheated space. As such, the effective heat transmission into the basement is quite similar to that of a slab on grade. The losses should be slightly reduced, but the effect on the overall building would be negligible. We decided to ignore the basement and treat the ground condition as a slab.

The geometry, in plan, is basically rectangular, with a staircase connecting the two floors. However, the vertical wall facing South is actually sloped and contains a large solar collector. The shape was approximated roughly by simply stepping back the second floor. We treated the collector itself as a windowless wall, as it is heavily insulated from the building. The solar collection system is actually a heating system, and not directly involved in the passive heating and cooling effects which create the loads we wanted to measure.

Finally, there is no provision in the program for special internal thermal capacity, in this case a heavy chimney. So



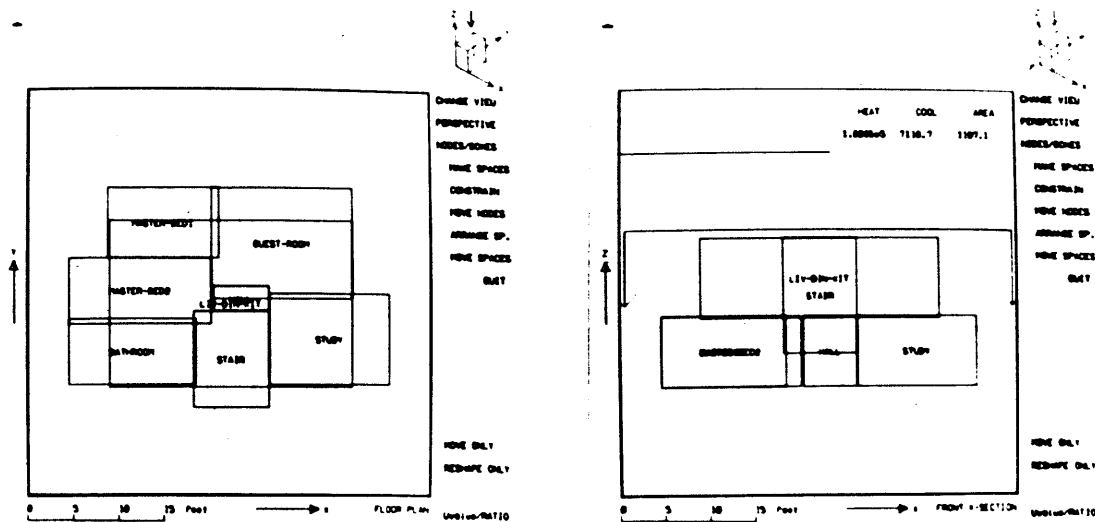
These views show the data for the trial run partially entered. Two rooms must be added, and some of the values in the lower drawing are still incorrect. One screen will always show the floor plan. The other will display heating and cooling loads. The second screen will also show either a section or a list of values. Both the geometry and values are changeable.



we found the total capacity of the masonry and increased the value used for the floor to account for it. The effect should be identical.

Data Entry


The data values for U-values, light levels, orientation, etc. were easily entered in a few minutes. The geometry, however, took perhaps an hour. This was rather disappointing, but understandable. Most of the delay resulted directly from the difficulty in using the light pen as a precision instrument. With many spaces close together, it is hard to manipulate the geometry without occasionally moving the wrong wall and destroying the dimensions of another space so care-



Completed Geometry

fully constructed earlier. Whether the answer is more hardware or a different manipulation technique is difficult for me to know, and probably beyond the scope of this project. We did eventually set up the configuration in the way we wanted. The entry of the specifiable data for this building nicely illustrates the historical aspect of the information display.

Specification of Model



	HEAT	COOL.	AREA
1.000000	7190.7	1397.1	
04977.	0277.1	1397.1	
04977.	0277.1	1397.1	
02040.	17880.	1397.1	
02040.	14970.	1397.1	
40209.	13047.	1397.1	

EXPOSURE	U-VALUE	CAPACITY
ROOF	4.0-0	INT.WALL 2.0
WINDOW	5.0-1	EXT.WALL 2.
WALL	5.0-0	ROOF 2.
FLOOR	4.0-0	SHROUD 1.
	3 WINDOW	FLOOR 2.0
LEFT	10	
FRONT	0	1.0-0 1.00
RIGHT	10	
BACK	10	

The defaults are replaced, one by one, with the values which apply to Dave's house. As each replacement is made, a new set of loadings are listed and graphed. The first change made is to correct the orientation, which was 180 degrees off originally. The first segment of the graph shows a significant drop in the heating load, along with a much smaller rise in the cooling load. This is to be expected when more of the windows are facing the sun, and solar gains increase. The second change greatly reduced the thermal capacity of the inside walls. The lack of any change indicates that the relatively low capacity is sufficient for this site and configuration. The third segment on the graph again shows reduced heating load while in-

creasing the cooling by a smaller amount. This is a reasonable result of specifying a higher lighting level. Less heat must be generated in winter and more must be dispelled in July. When the window area on the South wall was reduced from the default value to the relatively low value of the actual building, the heat load went up because of less solar gain. For the same reason the cooling load was reduced. The fifth and final segment on the graph shows the heating load dropping again while the cooling is essentially unaffected. This resulted when the U-value for walls was cut down from the default.

Investigating Alternatives

At this point, Dave had a reasonable facsimile of his building entered. He could begin to model alternative situations to discover their potential effects.

His first two attempts dealt with different kinds of window treatments. The first was the addition of movable thermal shutters on the windows. Figuring in the length of time they would be open,

			HEAT	COOL.	AREA
			9580.	12047.	1197.1
			26289.	14881.	1197.1
			28485.	12888.	1197.1
			9580.	12047.	1197.1
			9580.	12047.	1197.1
EXPOSURE	U-VALUE	CAPACITY	9580.	12047.	1197.1
ROOF	4.0-2	INT. WALL 2.2	9580.	12047.	1197.1
WINDOW	5.0-1	EXT. WALL 2.	48918.	12888.	1197.1
WALL	5.0-2	ROOF 2.	9580.	12047.	1197.1
FLOOR	4.0-2	SHADOW 1.	48918.	12888.	1197.1
	5 WINDOW	FLOOR 1.	48918.	12888.	1197.1
LEFT	10		9580.	12047.	1197.1
FRONT	2	LIGHTS 1.25			
RIGHT	10				
BACK	10				



THREE SPACES

he had already determined an average U-value of .15, instead of .58 for his unshuttered glazing. When this was inserted, the heat load dropped by 20%. A second type of movable shading used a value of .30 and saved about 15%. These figures indicated that window modification should certainly be pursued as a potential addition. The changes are shown by the dip in the first part of the graph.

The next modification added to, then reduced the internal thermal capacity. Only a minor effect was shown. This was something of a surprise. It should have shown a larger difference. Perhaps the season when heating and cooling are most balanced, and thermal capacity is most effective, fell between the days evaluated by the program. Or perhaps the effect really is quite small.

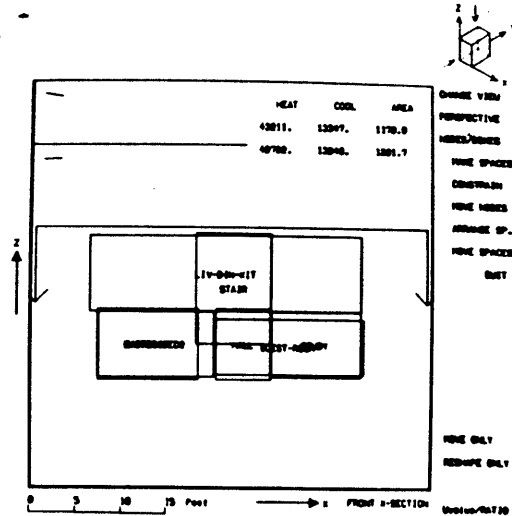
We decided to play a little bit with the orientation. We thought that the optimal orientation would be very close to due South, but perhaps slightly East or West. But no matter how much or how little he varied the orientation, he could not find a better orientation than due South. That may change in other circumstances, but a South orientation is best for this building.

Finally, Dave wanted to check the energy cost of the projections, which were added to provide views and visual interest - for architectural reasons. By molding the building into one large rectangle, shown on the next page, he was able to reduce loads by 10%, slightly higher than he expected, but not high enough to convert him into a

builder of unadorned rectangles.

Modified Geometry

The only situation the program was unable to model was a change in snow cover. This greatly increases the amount of ground reflection. In some climates it is a very important component in solar gains. This was an oversight on my part, and such a factor should be included as an improvement in the future.



Mode of Operation

The manipulation of the situation seemed quite fluid. I was pleased to see that my assumption of quick understanding of an interactive graphic system was justified. Dave ran the system from the beginning, with only an occasional instruction from me. Only once or twice did I actually have to demonstrate a particularly difficult maneuver. By the end of an hour, Dave had mastered the operation of the program. He was able to work rapidly and to good effect, which helped to maintain his enthusiasm, and encouraged him to try more modifications.

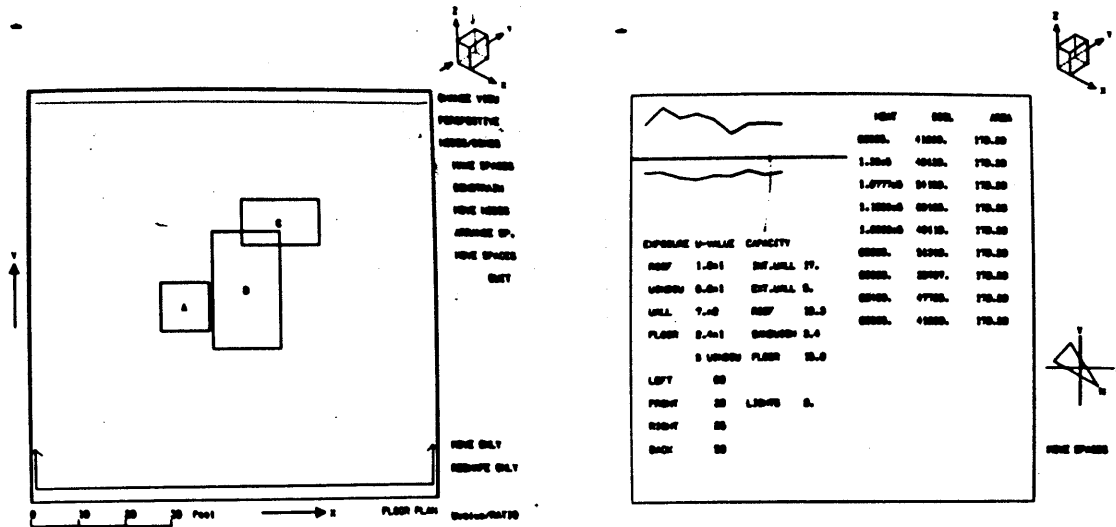
Making changes was somewhat difficult in the first foreground, where he tried to modify the geometry. It was just

not precise enough to make the types of changes he wanted. This is the same problem encountered trying to establish the geometry in the first place. Changes of the energy variables in the second foreground was handled smoothly. He was able to enter new values quickly and easily.

The time lapse during the background calculations was easily within an acceptable range. With the eight rooms in the example, the geometry took only seven seconds to complete, the heating and cooling loads only three. Thus, when the geometry is modified, ten seconds elapse, and a new set of results is displayed. When one of the variables is changed, new results appear in three seconds. It appears that the geometry calculation time varies linearly with the number of rooms, so it should always be within usable limits.

5.2. Sample Energy Load Components

This section shows a breakdown of the components of the energy estimation loads for a simple one-storey test problem. I changed the geometry, the orientation, and the other variables until I had the configuration I wanted. The evaluation showed a net cooling load on a May day of only 9214 BTUs, and no heating load at all. But a great deal of computation went into both those numbers. I had the program list the intermediate results for that particular day. They are tabulated here, along with the variable values and



Load Component Test Problem

air temperatures. I have listed below several items of particular interest.

Even though spaces A and B do not touch, the program recognizes that those surfaces are not intended to be outside walls. The area of the exposed left surface of B is therefore 150 square feet instead of the full 250.

Two-thirds of the conduction losses are through windows. Another fifth are through the roof. Only 10% are through the wall construction.

Solar gains are virtually all through the windows, except for the roof. The contribution of the roof, however, is a significant 15%, at least for this admittedly "roof-heavy" design. (A relatively high U-value contributes to

the importance of the roof in both solar and conduction components.)

Note the variation in the solar gains as the sun rises in the left-front, moves to the left side, then to the back, at sets at the right-back. The roof gains, of course, are symmetrical around noon, as only the height, not the direction of the sun is relevant.

Although very large net gains are made during all the sunlight hours, the temperature never rises above 63. So most of the cooling load can be handled by natural ventilation.

More than 60,000 BTUs of both heating and cooling loads are calculated. These figures have not accounted for the action of the internal capacity, which is greater than either of these. Therefore, the smaller of the two, the heating load, can be used to offset an equivalent cooling load, resulting in the net loads of 0 and 9214 BTUs.

The next three pages list the various calculations and components which went into that final result.

5.3. Future Directions

There are several points I would like to make about the future of this particular system and similar ones. I think this type of development should be pursued, and I have some ideas on the direction such development should take.

Detailed Breakdown

Variables:

U-values: Roof = .18, Walls = .07, Windows = .66.

Window Areas as a percentage of Surface in each direction:

Left = 60%, Back = 50%, Right = 25%, Front = 30%.

Capacities: Defaults (masonry construction);

Lighting Level: 2 watts/ft².

Orientation: the Left Surface faces slightly East of South-East.

Geometry:	A	B	C	Total		
X-Dimension	FT	10.6	15.0	17.2		
Y-Dimension		10.6	25.6	10.0		
Z-Dimension (height)		10.0	10.0	10.0		
Left Wall Area	FT ²	105.6	153.3	70.0	328.9	= Right
Front Wall Area		105.6	150.0	86.1	341.7	= Back
Floor Area		111.4	382.6	170.3	664.3	= Roof
Air Change/hour	FT ³	2785.	9566.	4257.	16608.	

Conduction, components:

Walls = 10.4%, Windows = 68.0%, Roof = 21.6%.

Solar Gains, components: % thru Windows % from Opaque areas

Left Surface	99.5	0.5
Back Surface	99.2	0.8
Right Surface	97.5	2.5
Front Surface	98.1	1.9
Roof	0.	100.0
Approx. totals for whole building	85.0	15.0

Hourly calculations using this data are on the next 2 pages.

Time T AM	Cond- uction	Out- side Air	Lights	Slab	Peri- meter	- - - - Left	- - - - Back	Solar Gains Walls	- - - - Right	- - - - Front	- - - - Roof	Total before Vent.	Total
1	53	-6432	-3755	4518	-451	-936							-7056
2	53	-6432	-3755	4518	-451	-936							-7056
3	52	-6968	-4067	4518	-451	-1014							-7982
4	52	-6968	-4067	4518	-451	-1014							-7982
5	53	-6432	-3755	4518	-451	-936							-7056
6	54	-5895	-3442	4518	-451	-858	7187	584	335	7617	542	10136	2534
7	55	-5360	-3129	4518	-451	-780	12587	1166	580	8970	1582	19683	4921
8	57	-4288	-2503	4518	-451	-624	15680	1399	685	7362	2688	24466	6116
9	58	-3752	-2190	4518	-451	-546	16551	1516	742	4601	3642	24631	6158
10	60	-2680	-1564	4518	-451	-390	15028	1633	799	1884	4335	23112	5778
11	61	-2144	-1251	4518	-451	-312	11577	1965	799	1091	4791	20581	5145
12	62	-1608	-939	4518	-451	-234	6505	5293	799	991	4942	19816	4954
	PM												
1	63	-1072	-626	4518	-451	-156	2633	9895	800	990	4791	21321	5330
2	63	-1072	-626	4518	-451	-156	2124	13310	1288	991	4335	24260	6065
3	62	-1608	-939	4518	-451	-234	1859	15015	3347	920	3642	26068	6517
4	62	-1608	-939	4518	-451	-234	1626	14463	5516	849	2688	26428	6607

- continued -

Time PM	T	Conduction	Outside Air	Lights	Slab	Perimeter	- Left	- Back	- Right	Solar Gains Walls	- Front	- Roof	Total before Vent.	Total
5	61	-2144	-1251	4518	-451	-312	1344	11790	6821	708	1582	22604	5651	
6	60	-2680	-1564	4518	-451	-390	671	6897	5873	304	542	13769	3442	
7	59	-3216	-1877	4518	-451	-468							-1494	
8	58	-3752	-2190	4518	-451	-546							-2422	
9	57	-4288	-2503	4518	-451	-624							-3348	
10	56	-4823	-2816	4518	-451	-702							-4275	
11	55	-5360	-3129	4518	-451	-780							-5202	
12	54	-5895	-3442	4518	-451	-858							-6129	
Totals		-96477	-56320	108432	-10824	-14039	95372	66239	28384	37328	40102	Heat Cool	-60005 69220	

000

Capacity of building = 161,990.

Lowest of Heating, Cooling, and Capacity is Heating = 60005

...60005 can be subtracted from both Heating and Cooling Loads.

Final Heating Load = 60005 - 60005 = 0 BTUs.

Final Cooling Load = 69220 - 60005 = 9214 BTUs.

Continuation of the Current System

There are ways in which the system described in this thesis could be improved or expanded. I will note a few that have come to my attention.

- Possible Local Inaccuracies

There are several items which come to mind as sources of inaccuracy in both the estimation and the analysis. Most of them contribute to inaccuracy primarily because information is lacking which would make closer estimation possible. On some of these, I made the decision to forego possible improvement in results in order to preserve simplicity and to keep from overwhelming the user with demands for information. Others were postponed in order to assure proper treatment of more important items.

One of conscious simplifications is the comfort zone. I have assumed 65 and 75 degrees as set limits. Obviously, this is oversimplified. For different times and climates, these limits may be different, either higher or lower. In addition, different spaces may have different comfort requirements. Circulation spaces, unoccupied areas, and special-purpose rooms may have widely divergent comfort zone requirements.

Another item is special heat sources. The most obvious is kitchen appliances, both commercial and residential. Other kinds of machinery contribute heat, often significant amounts.

In general, I have made scant provision for special situ-

ations such as these. To allow for them would very quickly reach a point of diminishing returns, as the time required to specify the special case would be excessive. Nevertheless, a reasonable criticism of the project could be made based on the presumption that many buildings require "special case" treatment. I would answer by noting that most of these special situations, whether they be heat sources, heat sinks, or special climate control specifications, are localized within the building, and have specific heating, cooling, or ventilating systems of their own. The results produced by this program are still valid, particularly in the comparative sense.

Climate descriptions could be much more specific in two ways. First, I am no more specific than monthly averages, but each day in January is not like every other one. Unfortunately, the heat load for 30 days with varied combinations of weather events is not the same as for 30 days with average values. I have tried to overcome a major part of this problem by evaluating days with extreme values of cloud cover in the energy analysis. The saving grace is that weather is always inexact and undependable. It can easily be argued that defining weather conditions too finely is of very limited practical value. The natural variations in weather and site are likely to be far greater than the inaccuracies caused by using monthly climatic approximations.

Micro-climate is the second item missing from my weather description. Local variations in wind, temperature, or

available sunlight can have important effects. However, climatic data is simply unavailable for local conditions. Most will conform roughly to the regional data that is available. Estimating the actual conditions on an unusual site, and designing to take advantage of these extraordinary local conditions is the realm of an architect skilled in that specific topic.

- Space

There are a few other items which could be improved upon if more space were available. The limitations of the machine have been reached in regard to the current set-up. Little more can be added without splitting up the overlays and thereby destroying the fluid interaction. However, the system could just as well be implemented on a larger computer, and no doubt it will in time. When that happens, the following improvements could be made.

Wind direction could be accounted for. This would provide more precise values for crack infiltration and potential natural ventilation.

Humidity and its relation to the entropy of inlet air could be used to better calculate the amount of energy needed to heat or cool it to comfort levels.

Slab areas and perimeter lengths could be calculated more exactly. The type of foundation and/or basement construction could be specified in order to get a more accurate determination of the heat losses involved.

Less stringent space requirements could also improve the system in more general ways. There is a primary trade-off between speed and space requirements - if an item has been stored, it need not be recalculated. With more space available, a more efficient and quicker program could be installed.

- Extensions

The system could be extended in two ways. It could be given more depth in the energy evaluation. Or more tests could be added to give information on other aspects of the design. Both of these require the development and/or storage of more information. Therefore, extensions beyond the current capabilities would probably require implementation on a larger machine as discussed above.

With more space, however, more detailed information could be shown to the user. The yearly loads could be broken down to the individual day or hour. This might be especially helpful to designers who have some knowledge of the subject, and could gain insights by looking at the profile of a time period. The information could be further separated to indicate the sources of heating and cooling loads. If the designer has an accurate picture of the relative importance of various components, he can determine which improvements have the greatest potential for reducing his loads. The architect might also find it advantageous to specify simple ground and roof conditions. The current assumption of slab below and flat roof above could be im-

proved upon.

With more space, new overlays could be added to test other considerations. A natural lighting test could help with the location of windows. Efficiency of simple construction methods might be tested to evaluate the shapes and sizes of spaces. More sophisticated tests could involve mechanical system alignment, cost estimations, or circulation analysis.

New Programs

Each of the last few items mentioned as extensions to the current system could easily be the base of an entire new project. I would like to suggest a few general guidelines for new development in this area.

Whatever success has been achieved in this project is due to the role which the computer plays in the design process. The program is not the designer, nor is it a partner in design. Architects don't often appreciate other people telling them how to design, much less a computer. A program which pushes its solutions on its user will not be used very long. The program should be more like an aide to the designer, whispering relevant information over his shoulder. The designer can pay close attention to the whispers, listen with one ear, or ignore them altogether. Although he depends on this source of information to produce the best results, the architect is in control.

To operate in this way, the program must first of all be responsive. It must provide information responsive to the needs of the architect. If results are not applicable to the designer's work, they are of little use. It must also be able to respond quickly and predictably to commands and requests. If answers are too hard to come by, no more questions will be asked.

The program should be as objective as is reasonable. The programmer may have strong feelings about how design should be done, or how much emphasis certain considerations should have. But these should not be incorporated in a computer program aiding design. Even if his biases are well supported or even superior to those of the designer using his programs, they will tend to alienate a designer who doesn't share those views. Too often biases shown by computer programs are pointed to as evidence of a program's uselessness.

Computer systems should encourage the architect to learn while using them. This can be done by allowing the designer to make the important decisions. The program takes the subordinate role of providing information and making minor decisions, almost in the form of suggestions. Given information and suggestions, the architect must make the decisions, and evaluate the resulting information given him by the computer. As this procedure is reiterated, expertise will increase, and the designer should find that he is able

to generate the best solution more quickly. He should have learned the approaches most likely to improve his design.

If these guides are followed when planning programs to aid design, I believe the maximum benefit will be obtained.

FOOTNOTES

- 1) Kusuda, Tamami, et al, "NBSLD, the Computer Program for Heating and Cooling Loads in Buildings", Washington: National Bureau of Standards, H.U.D., 1976.

This is a good example of infinite detail and input requirements.

- 2) The energy simulation program ESP-I, to be released by A.P.E.C. (Automated Procedures for Engineering Consultants, Inc.) evaluates all 8760 hours of the year. So does a N.A.S.A. program - NECAP.
- 3) Thirteen types of input sheets and preliminary hand calculations are necessary to run one program which only handles gains and losses through glazing, and this program uses gross approximations of climatic data.
- 4) The original energy package which is replaced by this thesis work was set up in this way.
- 5) ---, "Economic Glass Cost Analysis for Glass Used to Glaze Exterior Building Walls", Toledo: Libbey-Owens-Ford Co., 1975.

This is used "for showing architects and building owners the benefits of high-performance glass" by calculating heat transfer.

- 6) Weinzapfel, Guy, "The IMAGE System: Computer Assistance for Architectural Programming, Design, and Evaluation",

Cambridge, Mass.: Department of Architecture, M. I. T., 1975.

Johnson, Timothy, Guy Weinzapfel, John Perkins, Doris Ju, Tova Solo, David Morris, "IMAGE: An Interactive, Graphics-Based Computer System for Multi-Constrained Spatial Synthesis", Cambridge, Mass: Department of Architecture, M. I. T., 1970.

- 7) Handel, Steven, "A Computer-Aided Participatory Design System", Cambridge, Mass.: Department of Architecture, M. I. T., 1975.
- 8) Nagashima, Masanori, "Development of a Computer System for 3-Dimensional Space-Allocation in the Early Stages of Architectural Design", Cambridge, Mass.: Department of Architecture, M. I. T., 1976.
- 9) Decision Graphics of Boston was able to market a space-allocation program along with a hardware package including a mini-computer and several peripherals, by combining it with administrative programs, notably specification editing.
- 10) ---, "A.S.H.R.A.E. Handbook of Fundamentals", Menasha, Wis.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1972; pg 332.
- 11) McGuinness, William, and Benjamin Stein, "Mechanical and Electrical Equipment for Buildings", New York: John Wiley & Sons, Inc., (Fifth Edition), 1975; pg 208.
- 12) A.S.H.R.A.E., 1967, pg 393.
- 13) A.S.H.R.A.E., 1967, pg 415.

- 14) A.S.H.R.A.E., 1972; pg 566.
- 15) A.S.H.R.A.E., 1972; pg 379.
- 16) A.S.H.R.A.E., 1972; pg 378.
- 17) A.S.H.R.A.E., 1972; pg 378.
- 18) Carrier Air-Conditioning Co., "Handbook of Air-Conditioning System Design", New York: McGraw-Hill, 1965.
- 19) Anderson, Bruce, "The Solar Home Book", Harrisville, N. H.: Cheshire Books, 1976; pg 61.

There is a good discussion of the relationships between the percent of potential sunshine, diffuse and direct radiation, and reflection.

- 20) A.S.H.R.A.E., 1972; pg 410.

The term " $\text{SQRT}(2 * \text{wind speed (mph)})$ " is my own approximation of the empirically derived term h_o .

- 21) A.S.H.R.A.E., 1972; pg 337.

The formula is one which I derived, which makes a close fit to the table on this page. Average window fit is presumed.

- 22) This number is also taken from the table in the previous note.

- 23) McGuinness & Stein; pg 208.

10 cfm ($600 \text{ ft}^3/\text{hr}$) is taken as a "normal" figure for quiet adults.

- 24) A.S.H.R.A.E., 1967; pg 497.

The 400 BTU is for people engaged in light work.

- 25) ---, "Energy Primer", Menlo Park, Cal.: Portola Institute, 1974; pg 18.

The whole section on sun angle and insolation is well explained.

- 26) Wellesley-Miller, Sean, "Uses of Energy in Buildings", (M.I.T. course 4.45). The original source of this material is unknown to me.
- 27) A.S.H.R.A.E., 1967; pg 495.

Some typical decrement factors are given on page 491.

- 28) Dave Bryan's thesis involves an evaluation of the design and control of his solar house. His solar system transfers heat by air flow through the collector. It is held in a water storage area in the sandwich between the two main floors. The evaluation should be completed sometime this summer.