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KNOWLEDGE-BASED SYSTEM ARCHITECTURAL DESIGN GUIDE TOOLS

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By

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ABSTRACT

KNOWLEDGE-BASED SYSTEM ARCHITECTURAL DESIGN GUIDE TOOLS

by Robert J. Hitchcock

Architectural design is a multiple-goal, knowledge-based, problem-solving process. The task of representing and manipulating human knowledge on a computer, in a manner which approximates this type of process, has long been studied. One product of this study which is currently available for microcomputers is called knowledge-based system software.

This thesis develops a model of the architectural design process from literature on research into this subject. The technology of knowledge-based systems is explained. The potential for using this technology in the development of architectural design tools is explored through the creation and illustration of two prototype systems. The integration of design tools similar to these prototypes into the design process is discussed. Particular attention is given to tools which help to optimize energy efficiency in the final building design.

ACKNOWLEDGEMENTS

This thesis is a culminating product of the very long process of transformation from ski-bum to working stiff. Numerous people have contributed to this process. Thank you to Leslie for introducing me to computers and the research environment, and for constantly encouraging me to undertake new endeavors. Thank you to Ren for instilling in me the habit of exploring new software. Thank you to the Building Systems Analysis Group for providing an environment in which enjoyable skills can be applied to meaningful tasks. Thank you to my thesis committee members for waiting for years and then sprinting to the finish. Thank you to Don for being an invaluable mentor and good friend. Thank you to Marie for helping me to develop the motivation to finally complete this degree program.

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CHAPTER I

INTRODUCTION

STATEMENT OF THE PROBLEM

Architectural design is a creative, non-linear, iterative, and evolutionary process. The presence of multiple goals, some conflicting, some compromising, precludes the use of an algorithmic problem-solving approach to this process. Designers must rely on their access to experience, expertise, and intuition. This type of goal-directed, knowledge-based problem-solving is one at which humans excel and present day computers falter.

Many computerized tools are currently available to aid in the evaluation of architectural designs. These tools are regularly applied to a variety of tasks ranging from structural stress analysis to the simulation of the energy consumption of a proposed building. The input required for these tools generally includes numerical or geometrical descriptions of the building design. For this reason, the full usefulness of these tools is realized only after a building concept has reached the stage where it can be represented in the requisite detail.

The issue of energy efficiency in buildings is presently an esoteric concern. A relatively small group of researchers study this field. A smaller group of architectural practitioners apply the knowledge generated by these researchers. One barrier to the application of this new knowledge is the lack of means of technology transfer. The knowledge generated tends either to be too specialized and detailed or to come in the form of generalized rules-of-thumb which defy codification and obscure the underlying logic. Either extreme prevents the busy architectural professional from assimilating and applying this ever changing state-of-the-art knowledge.

The problem of optimizing energy efficiency in a building design receives less consideration than it might for a second reason. The goals of energy efficiency often conflict with what is currently perceived as traditional architectural form and function. Energy efficiency is seen as an additional problem to be overcome. Simple solutions to this problem are often either expensive or perceived as inhibiting creative freedom. In many cases this is true because the solution is sought and applied *after* the overall building design has been conceived.

STATEMENT OF THE PURPOSE

The purpose of this thesis will be to explore the potential for using knowledge-based system technology in the development of architectural design tools. Knowledge-based system technology (frequently called expert system technology) is seen by many to be the first commercially viable application of so-called computerized artificial intelligence (AI). It is an attempt to codify the human knowledge (expertise) of a specific domain in a manner in which it can be implemented on a computer. The exploration of the application of this technology to design tool development will focus on tools which can promote energy efficiency in the operation of the resulting building. Of primary consideration will be tools developed to aid in the generative phase of architectural design, as opposed to the evaluative and/or corrective phases.

A goal of this thesis will be to illustrate and evaluate the integration of knowledge-based design tools into the architectural design process. To be both useful and used, a tool must fulfill a need in an easily applied fashion. Evaluation of these tools requires an understanding of the architectural design process and the prescribed inclusion of the tool within this process.

The nascent technology of human knowledge representation and manipulation on desktop computers may hold promise for the development of new, more effective, design tools. This thesis will be an initial attempt to explore this potential.

SCOPE OF THE THESIS

To accomplish the objectives of this thesis, three key topic areas need to be addressed. These topic areas are: the architectural design process, knowledge-based system technology, and design tools. Treatment of these topic areas will be restricted in several ways.

Architectural design is an ill-defined process. A review of research into models of this process will be discussed to build a basis for discussion. These models will focus on those elements which are seen as being critical to the issue of design tool integration.

Knowledge-based system technology is a substantial field of study within the larger field known as artificial intelligence. Although steadily increasing, the computing power of microcomputers severely limits the application of this technology. A software package called EXSYS is one microcomputer implementation of knowledge-based systems. Explanation of computerized knowledge representation and manipulation will be restricted to the methods used by EXSYS.

Two example knowledge-based system design tools will be designed, implemented, and evaluated. The example tools developed will be functionally limited prototypes. One purpose of this development is to provide working samples of this relatively new and uncommon type of computerized tool. A second purpose is to familiarize the author with this tool's development process. Neither of these purposes require a fully functional, commercially viable software package.

CHAPTER II

THE ARCHITECTURAL DESIGN PROCESS

Most people spend the majority of their time in a largely manufactured and built environment. The objects, or artifacts, within this environment are widely critiqued by all inhabitants. The motives and solutions of the designers of these artifacts are viewed with a mixture of admiration, curiosity, and scorn. Yet, the process of design is largely unknown and taken for granted by non-designers. This process is performed by professionals in offices which are well out of reach of not only the end users, but also the makers and builders of the artifacts.

Design has not always taken place so far removed from the making and use of the artifact being designed. Vernacular design took place as a process applied by makers or builders as the artifact was constructed. Design happened as a process of trial and error which produced solutions to problems which remained largely stable over time.

Many of the characteristics of vernacular design have changed in the modern world. These changes are largely a result of three factors: the establishment of a design profession, a shortening of the design time frame, and an increase in the complexity of the artifacts to be designed. This is particularly true for architectural design. The design process now takes place almost exclusively in the architect's office. Few people design even their own homes, let alone their workplace or any other commercial building. The pressures of profits and construction project deadlines require that design be completed in a timely fashion. The increase in the complexity of buildings brings with it an increase in the complexity of design decisions.

Architectural design has become highly complex. This is partly due to the complexity of the building structure: its size, choice of materials, levels of detail, interaction between building elements, cost, and construction techniques. This is also partly due to the variety of the building's use: its function, aesthetics, occupant comfort, and multisensory impact. Design problems tend to have a variety of goals and constraints which are highly interrelated. Making a design decision which increases the size of a window may provide more interior illumination, but it also may potentially produce unwanted internal heat (or the reverse, increase heat loss), cause glare, and reduce desired privacy. It is this interconnectedness of factors which is the essence of design problems (Lawson 1980, p.45).

The fact that architectural design must now cope with increased complexity, in less time, legitimizes the need for a skilled design professional. This situation also argues for tools which aid the design professional in dealing with complexity in an efficient and effective manner. A potential platform for implementation and use of such tools is the modern day computer. The computer is seen by many to be a highly effective productivity tool. Yet, unless used properly, the computer can in fact be useless, or worse, a copious waste of time, money, and effort.

As powerful as computers have become, with ever increasing operational speed and memory capabilities, they are still machines which require well defined tasks and well defined approaches to accomplishing these tasks. Therefore, the implementation of computerized design tools requires a clear understanding of the design process. However, despite the professionalization of design which has roughly a 200 year history (Lawson 1980), the design process still defies the definition of one clear, systematic procedure.

An increase in effort has taken place within the last thirty years to study the field of design methodology. This effort has studied the principles, practices, and procedures of design. It is concerned with how designers work and think, how the design process might be appropriately structured, and how new design methods, techniques, procedures, and tools might be developed. The following sections will review this research in an attempt to build a better understanding of the design process and how computerized tools might be integrated into this process.

EARLY MODELS OF THE DESIGN PROCESS

Design is a creative process which utilizes intuitive and non-linear aspects of thought, guided by the unique experience and knowledge to which the designer has access. This is not to say that design is devoid of rational, logical thought. However, any approach to defining a systematic procedure for design must recognize the ill-structured nature of many of the problems encountered during the design process.

Since mid-century our environment has been going through accelerating technological, economic, and social change. These changes have brought an increase in complexity to the tasks of design in general and specifically to architectural design. The activities of operations research during and following World War II hold promise for coping with increased complexity. These activities concerned systematic methods of planning large operations involving arrays of materials, resources, time schedules, and conflicting criteria for evaluating success. The theories and methods of operations research therefore seemed prime candidates for development of a systematic approach to complex design. Architectural design and its practitioners have, however, required some deviation from the established operations research premises.

Several design methodology researchers have drawn on this field of study in an attempt to apply a systems approach to design of all kinds, including architectural design. The aims of this attempt were to increase the efficiency and the reliability of the design process. Early research into this area centered on a systematic process which, in general, included the sequential phases of analysis, synthesis, and evaluation. There were variations and expansions of this sequence, but the core of each procedure remained these three phases. A more in depth look at one expanded procedure will serve to illustrate this suggested approach.

J. Christopher Jones delineated the three phases of analysis, synthesis, and evaluation in the following way (Jones 1962, p.11).

1. Analysis

    1.1 Generate a random list of factors

    1.2 Classify factors

    1.3 Consult various sources of information

        1.3.1 Literature

        1.3.2 Libraries and Information Services

        1.3.3 Experienced Persons

        1.3.4 Observation

        1.3.5 Experiment

    1.4 Identify interactions between factors

        1.4.1 Charts

        1.4.2 Diagrams

        1.4.3 Interaction Matrices

        1.4.4 Interaction Nets

    1.5 Develop performance specifications (P-Specs)

        1.5.1 Restate design criteria in terms of performance only

        1.5.2 Define a sub-problem based on each P-Spec

    1.6 Obtain agreement from all participants

2. Synthesis

    2.1 Perform creative thinking

        2.1.1 Brainstorm

        2.2.2 Use intuition

    2.2 Develop partial solution for each P-Spec

    2.3 Constrain the partial solutions within their limits

2.4 Select likely sets of partial solutions by trial and error and intuition

2.5 Combine selected partial solutions by permutation to give alternate whole solutions

3. Evaluation

3.1 Apply experience and judgement to evaluate alternate whole solutions

3.2 Simulate selected whole solutions

Jones and fellow researchers made some attempt to stress the fact that this sequence of steps was not strictly linear. In practice, they indicated that these steps might often be done in tandem, their distinctions blurred, with frequent reiterations required. Several diagrammatic models of this process emphasized the aspect of feedback loops within the suggested procedure. One example is that of L. Bruce Archer shown in figure 1.

Archer's (1963, p.64) model groups programming, data collection, and analysis into an analytical phase of design. Methods applied to performing this phase include observation and measurement. Synthesis and development are categorized within a creative phase. Evaluation is a part of this phase. This phase involves the application of professional judgement, decision-making, and deductive reasoning. Communication is termed an executive phase which primarily involves description.

The approach suggested by these models was meant to systematize the overall design process. It was hoped that this systematization would free the designer's imagination to pursue ideas, solutions, and hunches without confusing the process. The method provided a structure within which the designer must still make some "creative leaps" to produce the final design. Particularly, when faced with incomplete information, the designer must rely on previous experience and knowledge to formulate a reasonable course of action (Cross 1984, p.4). This is the "creative leap" activity of synthesis. It should be noted that the analytical phase of the process tends to have more

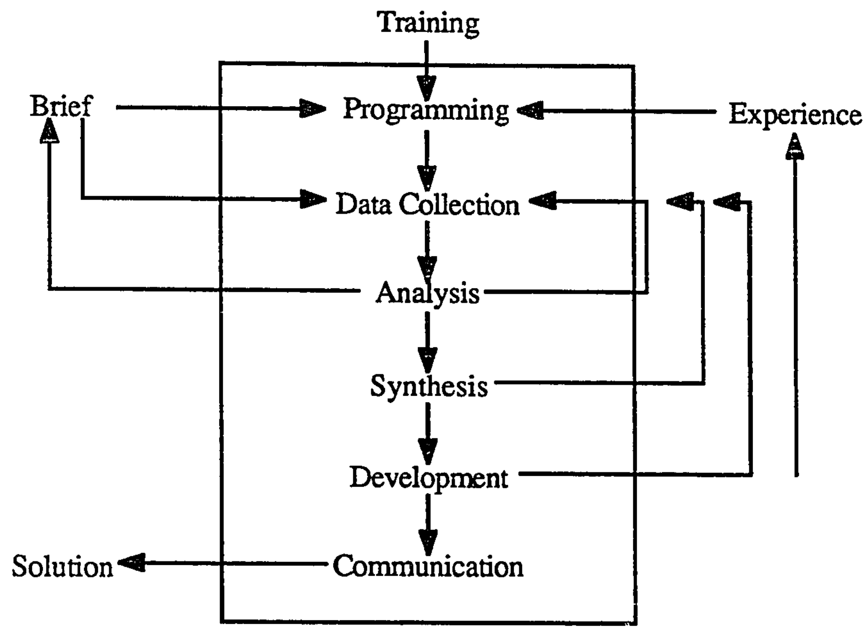

Fig. 1: Flow Diagram of a Systematic Method for Designers

(From *Developments in Design Methodology* ed. Cross)

concrete methods associated with it. Researchers suggest less concrete methods during the synthesis phase. The words intuition, experience, knowledge, judgement, and deductive reasoning appear instead.

The analysis-synthesis-evaluation model of design was held in favor by methodology researchers throughout the early 1960s. It suggested a comprehensive procedure within which several operations research methods could be applied to design. These methods, however, were of primary use during the analysis phase of design. The procedure provided a framework within which synthesis could take place. But, few methods were identified which might enhance the creative processes at play during this more intuitive phase of design. Practicing architects tended to resist this overall systematization of the design process. Their principle source of hesitation was the difficulty of performing comprehensive analysis of a design situation preceding the synthesis phase. Eventually, researchers also began to realize that design problems may not be amenable to complete analysis.

Attention turned away from systematization and generalization of the entire design process toward an attempt to define and structure the thought processes involved in dealing with design problems. This shift in focus resulted in modifications to the analysis-synthesis-evaluation model of design.

MORE RECENT MODELS OF THE DESIGN PROCESS

The analysis-synthesis-evaluation model of systematic design had its conceptual roots in a systems approach to operations research. The overall procedure of this model was based on the assumption that the design problem could be adequately formulated by an exhaustive collection and analysis of information regarding the goals and constraints of the desired design. The assumption that a sufficiently complete analysis of the design problem could be accomplished was now called into question. Methodologists turned their attention to the definition of the nature of design problems. Under this attention, a new model of the design process emerged.

Rittel and Webber refer to design or planning problems as "wicked" problems. One of the characteristics of such problems identified by these researchers is that they have no definitive formulation. "The information needed to *understand* the problem depends upon one's idea for *solving* it." (Rittel and Webber 1973, p.136) They feel that problem understanding and problem resolution are inextricably combined and therefore that the problem cannot be defined until a solution has been found. The process of formulating the problem and of conceiving a solution are identical to them.

Herbert A. Simon refers to design problems as ill-structured problems (1973, p.151). An ill-structured problem is a problem which lacks definition in some respect. Simon looks at architectural design as a situation in which initially the sole problem is designing a building. Although the client may have given the designer some constraints, the design goals will nonetheless remain incompletely specified.

These and other researchers believe that the process of design remains ill-defined primarily because the problems which this process attempts to solve are themselves ill-defined. For this reason, their research began to focus on the activities which practicing designers apply in their attempts to develop solutions for this type of problem. This research utilized interviews with designers, observation of controlled design experiments, and protocol analysis. Protocol analysis is a study of the transcript of a subject's verbal report of what he or she is thinking and doing while working on a given design problem.

A consensus emerged from these various studies to the effect that designers, and in particular architectural designers, approach problem-solving in a manner different from problem-solvers such as engineers or scientists. Instead of the "problem-focused" strategy common to scientists, architects tend to take a "solution-focused" approach (Cross 1984, p.170). That is, architects tend to first generate a potential solution from incomplete information about the problem. The potential solution is then evaluated for its relative satisfaction of known goals and constraints. This process of generation relies heavily on the designer's knowledge and experience as well as a developed skill of conjecture.

The findings of this research resulted in a revised model of the design process. This revised model is not especially different from earlier models. The major modification is a combination of the analysis-synthesis phases into a single phase. The complete analysis of a design problem was accepted as being either impractical or impossible given the nature of incomplete information.

The two separate phases of analysis and synthesis collapse into a phase generally termed conjecture or generation. Within this phase, activities conceptually related to synthesis are given initial attention in the problem solving sequence. Activities related to analysis are given a supporting role. This emphasis on generation of problem solutions seems more accurately to represent the designer's solution driven approach observed by researchers.

Jane Darke (1979, p.180) modified the model of architectural design to one of generator-conjecture-analysis. This model resulted from numerous interviews with practicing architects. These interviews indicated a common approach taken by architects when faced with incomplete knowledge regarding an ill-defined design problem. The architect identifies a critical aspect of the design problem and uses this aspect as a generator of a potential solution to the overall problem. Darke calls this critical aspect a primary generator. Examples of primary generators are: a desirable view from the building site, a physical handicap of the building occupant, or a key goal of the building owner such as energy efficiency. The purpose of a primary generator is to reduce the variety of possible solutions down to a cognitively manageable set. This attempt at solution set reduction occurs very early in the design process. With a concrete solution in mind, the architect then proceeds to iteratively analyze (or evaluate) this proposed solution and generate new solutions. Darke sees this primary generator as a concept which allows the architect to make the creative leap across the "rationality gap" between partially analyzed problem specifications and a proposed design solution.

Darke points out that a difference between practicing architects and architectural students is their accumulation of experience and knowledge which is used to produce a conjecture from a primary generator. Likewise, the differences between conjectures produced by two practicing architects might be said to be the experience and knowledge which each applies to the generation process.

Simon (1973, p.154) describes one way of organizing the architectural design process as a system of productions. The elements of the design problem which are clearly stated or have been evoked from memory, and the aspects of a design solution which have already been proposed, combine to serve as stimuli for producing the next proposed design solution. Those elements either stated or evoked from memory correspond to Darke's generators. Simon includes the equivalent of Darke's phases of conjecture and analysis in the production of the next proposed design solution.

The production model described by Simon is shown diagrammatically in figure 2. The diagram shows the interaction between a problem-solver's long-term memory, the external environment, and the design problem at hand (the immediate problem space). Part of the process is a noticing mechanism which picks up cues from the external environment. An example of this might be the designer strolling through an existing building and noticing an architectural solution to a problem similar to the one at hand. Another part of the process is an evoking mechanism which retrieves relevant information from the designer's long-term memory. These two parts of the process Simon calls a recognition system which the problem-solver is continually employing in an attempt to better structure the problem space and to generate solutions. This is analogous to the experience and knowledge which architects employ during the conjecture phase of design identified by Darke.

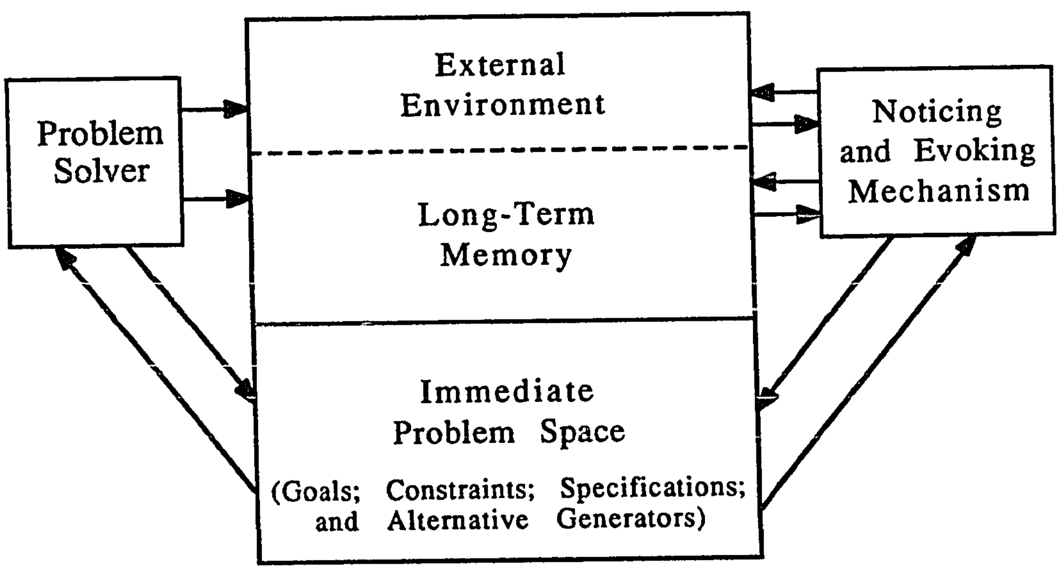

Fig. 2: Schematic Diagram of a System for Ill-Structured Problems

(From *Developments in Design Methodology* ed. Cross)

An important characteristic of Simon's production model of architectural design is the decomposition of the overall design goal into sub-goals. Taking into account the inability of a designer to bring all relevant information to bear on the design problem at once, sub-goals must be identified. A number of iterations through Simon's production process can then generate a partial solution for each sub-goal.

Simon points out some difficulties which can develop from this approach to problem-solving. Interrelations among sub-problems may be neglected. Some appropriate design criteria may not be included in the process. These omissions may have significant impact on the final design solution since early decisions may establish global parameters which impose constraints on later design decisions.

Yehuda E. Kalay (1985) defines design as a special case of general problem-solving processes comprised of two major components: design states and the generator/test cycle which facilitates transitions between them. Kalay sees design as a process of searching through alternative solutions to discover those which satisfy the goals and constraints for a particular design problem. He identifies two characteristics of this process which distinguish it from other types of problem-solving. One characteristic is that an alternative solution must be generated before it can be evaluated. The other characteristic is that the search for alternatives is a heuristic one which is guided by both internal and external information. Internal information consists of those constraints and goals identified for a particular design such as required floor space or various required building functions. External information consists of guidelines resulting from such sources as social, cultural, economic, and psychological norms. Whether internal or external, Kalay stresses that design information is always incomplete.

Kalay thus sees design as an iterative, trial and error process of generating new alternative solutions and evaluating these solutions to produce a new state of design. He states that the most difficult task within this process is the generation of new design alternatives.

DESIGN PROCESS MODEL SUMMARY

The preceding sections have attempted to develop an understanding of the process through which architects work while performing design. Early attempts to systematize this process were based on an analysis-synthesis-evaluation procedure taken from operations research. Later research revised this model into a conjecture-evaluation procedure. This later model stressed the importance of the "creative leap" (or generation of alternative design solutions) activity which differentiates architectural design from many other forms of problem-solving effort.

Although researchers differ regarding the details of the generation phase of design, there are several characteristics of this phase which have been commonly identified. These characteristics bear repeating. Conjectures must be made which generate design solutions before these solutions can be evaluated. These conjectures must be made using incomplete information without the benefit of complete problem analysis. Designers supplement this incomplete information with their own unique experience and the knowledge to which they have access, as well as personal biases and tastes. The phase of conjecture occurs very early in the design process. Early decisions impact later decisions by setting global parameters of the final design solution. Humans are limited in their ability to bring numerous criteria to bear on a problem at one time.

DESIGN PROJECT STAGES

The design process discussed in the preceding sections is a problem-solving procedure utilized within the larger context of an architectural design project. This larger context consists of several stages which must happen sequentially to move from an initial design proposal to a constructed building. Figure 3 shows these sequential stages of an architectural design project (Robbins 1986, p.14).

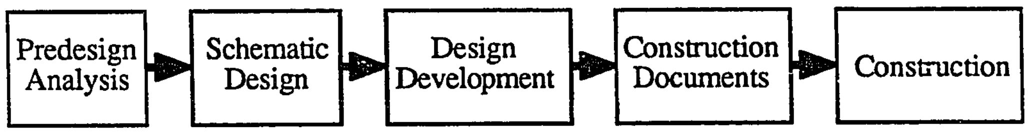

Fig. 3: Sequential Stages of an Architectural Design Project
(From *Daylighting: Design and Analysis* by C. Robbins)

The stage of predesign analysis involves development of the building brief, site analysis, and architectural programming. The schematic design stage may also be referred to as the conceptual design stage. This is the principal stage in which the process models discussed above are employed. The design development stage involves refinement of the design and materials specifications. The construction documents stage generally includes further design refinement and specifications as well as the drafting of detailed design drawings. The construction stage should also include supervision to insure design compliance.

Due to the sequential nature of this overall procedure, major decisions made early in the schematic design stage are difficult to change at later stages. For small office buildings these decisions include parameters such as: number of stories; proportion of glass area to wall area; and heating, ventilating, and air conditioning system (HVAC) type. These decisions can have a significant impact on the energy efficiency of the final building design. It has been stated that design decisions which can result in half or more of the potential energy savings from a constructed building will have been made by the end of the schematic design stage (Burt/Hill/Kosar/Rittelmann 1985, p.286). The stage of design development is too late to change the parameters set by earlier decisions.

It has also been stated that "few architects, engineers, or lighting designers have a sufficiently strong intuitive understanding of daylighting and of commercial building energy performance" to make this type of early decision with confidence (Robbins 1986, p.14).

DESIGN TOOL INTEGRATION

Early design decisions which are based on incomplete information and insufficient intuitive understanding of their impact on the final design makes a strong argument for the integration of design tools beginning during predesign analysis. This integration should continue throughout the schematic design stage. The nature of the conjecture phase which is at work during these stages of design argues for a tool which specifically aids the designer in the generation of appropriate design solutions.

The majority of computerized tools currently available to the architectural designer are of an evaluative nature. An information booklet entitled *Design Tool Selection and Use* (Anderson, Blum, and Holtz 1988, p.7), published in December of 1988 states that "design tools do not make decisions or even suggest design modifications; they simply provide information that will help the designer make those decisions or indicate the impact of a decision or design modification." This publication further states that "design tools are not a substitute for knowledge, but a means of quantifying, refining, and calculating the impact of the design decisions." Unfortunately, practicing architects cannot possibly assimilate all of the latest knowledge related to "good" building design. In particular, given the low priority of energy efficiency in building design, few architects ever develop a working knowledge of this aspect of design.

This section of the thesis has attempted to model the architectural design process in a manner which exposes a need for a new type of design tool. If much of what an architect does is generate building solutions based on experience and knowledge, and if few architects have ready access to the latest experience and knowledge regarding energy efficient design, and if the promotion of energy efficient design is a desired action, then a design tool which might aid the designer in leaping this knowledge gap is something to be pursued.

CHAPTER III

KNOWLEDGE-BASED SYSTEM TECHNOLOGY

TRADITIONAL DATA PROCESSING VS. KNOWLEDGE PROCESSING

The data processing prowess of computers has been increasing at an incredible rate over the last fifteen years. One measure of the numerical processing speeds of today's computers is the number of floating-point operations which they can perform in one second (flops). The lowliest of microcomputers so ubiquitous on desktops today (e.g. the IBM PC with an 8086 processor and an 8087 math coprocessor) are capable of 100,000 flops. This speed is dwarfed by a Cray-1 supercomputer which is 1000 times faster.

Given this rate of numerical data processing, it is no surprise that number crunching predominates as the basis of today's software applications. The dominant programming languages in use today reflect this data processing paradigm in the manner in which they offer control over the hardware platform. The current "tradition" in hardware and software development is based on this strength in computer technology.

It has become a trivial matter, therefore, to ask a computer under traditional programming control to combine two known quantities, using an arithmetic operation, to produce a third, previously unknown, quantity. However, the conceptually similar process of combining two known facts, using a logical operation, to produce a previously unknown fact, can easily daunt the traditional programmer.

The term logical operation does have meaning in the traditional programming lexicon. Traditional languages contain relational operators which represent quantitative relationships such as *less than* or *not equal to.* These operators allow the computer to determine the truth or falsity of statements such as *A is less than B.* The logical operators *and* and *or* allow compound logical expressions such as *A is less than B and B is* *less than C* to be evaluated for truth by the computer. Finally, a so-called decision structure affords the traditional programmer a form of logical reasoning exemplified by a programming statement such as *If A is less than B and B is less than C then TAKE ACTION.* There are two critical limitations to statements like this. Relational operators can be used only for comparison of numeric or alphabetic values. For example, the computer can determine that 10.0 is less than 20.0 or that SMITH is less than SMYTHE. It cannot, however, compare concepts like "sprinkle" and "downpour" unless these concepts are expressed quantitatively. In addition, *TAKE ACTION* is limited to those actions which the computer is capable of performing. Allowable actions are, in general, restricted to the fundamentals of: fetching quantitative values from somewhere (INPUT), manipulating these values numerically or alphabetically (PROCESSING), and displaying fetched and/or manipulated values somewhere (OUTPUT). A precluded action is that of drawing a conclusion or formulating a new relationship. A statement such as *If A is less than B and B is less than C then A is less than C* is meaningless (as well as syntactically incorrect) in a traditional programming language.

The form of deductive reasoning implied by the previous statement cannot be accomplished even within the favored arena of numerical analysis. Imagine then, the futility of asking the traditionally controlled computer to draw a conclusion or make a recommendation based on the known facts *it is raining* and *I am outdoors.* Remember that this is an oft quoted test of elementary human intelligence.

The capability to perform this type of deductive reasoning requires four capacities not offered by traditional programming control. First, the computer must be given the capacity to represent qualitative, as well as quantitative, facts. Second, the capacity to represent logical relationships between these facts, which surpass simple comparative tests, is required. Third, the capacity to dynamically store known facts for a given situation is requisite. That is, during interaction between the computer and the computer user, facts elicited from the user concerning the particular problem at hand, must be temporarily stored for use in the current deductive reasoning session. Finally, the capacity to sift through the relationships between known facts in a manner in which new facts can be deduced, is needed. The first two capacities can be termed knowledge representation; the second two, knowledge manipulation.

These capabilities are proffered by the computer technology known as knowledge-based systems (frequently referred to as expert systems). This technology is seen by many to be the first commercially viable application of research into artificial intelligence (AI). Knowledge-based systems are an attempt to codify the human knowledge (expertise) within a specific domain in a manner in which it, and the manipulation of it, can be implemented on a computer.

In the past few years, software packages known generically as expert system shells have become available for microcomputers. These software packages are designed to ease the representation and subsequent manipulation of human knowledge. One such expert system shell is called EXSYS. The manner in which EXSYS provides the capabilities identified above, is described below. This is the software package used to implement the example design guide tool prototypes discussed in the following section.

It is important to distinguish between the environment which EXSYS provides for developing knowledge-based systems and the specific knowledge-based systems which are developed within this environment. A knowledge-based system developer uses the EXSYS tools which enable knowledge representation. A knowledge-based system user takes advantage of the EXSYS tools which manipulate a system of represented knowledge. The developer must either be an expert or have access to expertise within a particular domain. Once the knowledge has been implemented on the computer, the knowledge-based system can mimic the interaction with the human expert. Ideally, a user can then consult the computer in a manner similar to that in which he or she would consult the human expert.

KNOWLEDGE REPRESENTATION IN EXSYS

Representing Facts

Facts may be represented in EXSYS by assigning values to three different types of factual entities. These three types are: variables, qualifiers, and choices.

The use of variables in EXSYS corresponds to the traditional programming use of this term. Variables may be assigned numeric quantities and used in arithmetic expressions to calculate other quantities. Variables may also be assigned character string values and be used in comparisons with other string values. Factual entities of this type may be used to perform intermediate calculations and to display known quantities to the user of a knowledge-based system.

An example of the use of numeric variables can be taken from a knowledge-based system developed to advise a home-owner wishing to add a greenhouse (sunspace) to a home. The recommended amount of glass (glazing) built into a sunspace is dependent on three numeric quantities: the latitude of the building site, the average outdoor winter temperature, and the floor area which the owner intends to heat with the sunspace. The knowledge-based system can be designed to prompt the home-owner to enter values for the variables LATITUDE, WINTER TEMPERATURE, and FLOOR AREA for his or her home. Given these values, the knowledge-based system can calculate the recommended GLAZING AREA using arithmetic functions. An additional, non-traditional use of variables by EXSYS will be illustrated later.

While variables allow EXSYS to represent quantitative values, qualifiers provide the very important capacity to represent qualitative values. Qualifiers are factual entities such as *weather* or *construction materials* which may take on a variety of qualitative values. For example, the weather may be: clear, partly cloudy, overcast, raining, snowing, etc. A house may be constructed of: concrete, brick, adobe, stone, or wood. In EXSYS, the developer defines a qualifier by first entering the qualifier text and then entering a list of potential values which the qualifier may be assigned. The text and each of the potential values should be worded so that when a particular value is assigned to the qualifier, the combination reads as a grammatically correct sentence. For the above construction materials example, the qualifier text might be *The type of building construction material is.* The potential values may then be one or more words which complete the sentence and describe a specific material type. When a developed knowledge-based system is used, qualifiers will be assigned values by the deductive reasoning techniques provided by EXSYS, if possible. If a value cannot be deduced for a needed qualifier, EXSYS will prompt the user to enter the correct value(s) given a list of possible selections. Each qualifier may have up to 30 possible values. More than one of these values may be assigned to a qualifier during each use of the knowledge-based system.

The third type of factual entity used by EXSYS is called a choice. Choices represent the sought for goals of a knowledge-based system. Since knowledge-based systems are generally developed to be problem solving tools, choices represent possible solutions to the problem under consideration. In the case where a knowledge-based system is developed to be a design guide tool, choices may be used to represent design recommendations. The goal of EXSYS is to select the most likely choice based on the known facts regarding a particular situation. If more than one choice is possible, EXSYS will list all possible choices arranged in order of likelihood. The manner in which EXSYS determines this order of likelihood is discussed in the knowledge manipulation section below.

All possible choices for a particular knowledge-based system must be identified by the developer at the outset of the development process. Choices are defined by entering text which articulates a specific problem solution, aspect of a solution, or recommendation. *Electricity is a recommended heating fuel* is an example of a choice taken from a knowledge-based system developed to give predesign recommendations regarding commercial building heating, ventilating, and air conditioning (HVAC) systems. Other examples of choices for this knowledge-based system might include: *Oil is a* *recommended heating fuel, Packaged Terminal Air Conditioner HVAC System is recommended*, and *A glazing area of 25% is recommended.* The system developer may define as many choices as are needed to represent all possible problem solutions or situation recommendations.

Representing Relationships Between Facts

The representation of human knowledge cannot end with a simple listing of all quantitative and qualitative facts, problem solutions, and situation recommendations related to a particular domain. Expertise also consists of rules which define relationships between facts. The generic form of a knowledge-based system rule is *IF a set of conditions is true THEN these conclusions can be drawn.* Rules of this type can be used to conclude previously unestablished facts given incomplete evidence regarding a situation under review. Rules can also be used to make recommendations or reach problem solutions based on the known facts regarding a specific case within the knowledge domain. This representation of relationships between facts, using rules, is so fundamental to knowledge-based systems developed using a software package such as EXSYS, that they are often referred to as rule-based systems.

Rules are structured in EXSYS as shown in figure 4. Conditions within the IF block of a rule may make use of any of the three types of factual entities. Numeric variables may be compared to other numeric values. String variables may be compared to other string values. Qualifiers may be tested to see if a particular value has been assigned to them. Choices may be tested to see if they have a certain level of likelihood. Conditions within the THEN and ELSE blocks of a rule are used to assign values to variables and/or qualifiers. Choices within the THEN and ELSE blocks of a rule are used to assign levels of likelihood to a choice. The NOTE portion of a rule can be used by the knowledge-based system developer to attach explanatory text to a given rule. The REFERENCE portion of a rule can be used to attach a reference to the source of the knowledge contained in the rule.

IF

conditions

THEN

conditions

choices

ELSE

conditions

choices

NOTE:__________

REFERENCE:_____

Fig. 4: Structure of rules used in EXSYS.

An example rule taken from a knowledge-based system designed to advise a homeowner wishing to add a sunspace to a home is shown in figure 5. This rule uses two qualifiers in the IF block. The *heat transfer method* qualifier is tested to see if the value *passive convective* has been assigned to it. The *common wall material* qualifier is tested to see if the value *concrete* has been assigned to it. If both of these conditions are true, then: the choice *Concrete wall with vents* will be given a likelihood of 9/10, a value will be calculated and assigned to the numeric variable *GLAZING AREA* based on the formula shown, and the variable *CONCRETE THICKNESS* will be marked for display. This utilization of the variable *CONCRETE THICKNESS* illustrates the non-traditional use of variables mentioned earlier. In EXSYS, a variable may be defined which will never be assigned either a numeric or a string value. Instead, this special type of variable will only have explanatory text associated with it. When this type of variable appears as part of the THEN block of a rule where all IF conditions are true, the explanatory text will be displayed at the end of a system run. In this example

IF

The heat transfer method is passive convective

and The common wall material is concrete

THEN

Concrete wall with vents - Probability=9/10

and [GLAZING AREA] is given the value

INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)

and The recommended thickness of the concrete wall is 12 inches.

Fig. 5: Example rule from sunspace knowledge-based system.

knowledge-based system, the variable *CONCRETE THICKNESS* has the associated explanatory text *The recommended thickness of the concrete wall is 12 inches.*

KNOWLEDGE MANIPULATION IN EXSYS

Dynamic Storage of Known Facts

Knowledge-based systems are most usefully developed as problem-solving or situation management/consultant tools. A system is fully developed when all pertinent knowledge related to a domain has been represented using the above concepts. This means developing a sufficiently complete set of rules known as a rule-base. Although individual rules may contain very specific knowledge, the complete set of rules must contain generalized knowledge. A generalized knowledge rule-base represents the expertise necessary to deal with all specific problems/situations which arise within the domain of the system. This rule-base is static knowledge in that, unless the system developer modifies it, this knowledge remains the same for each system consultation session.

For any given situation, there will be a unique set of known facts. The first requirement for manipulation of the knowledge related to a particular situation is therefore the ability to dynamically store this set of facts. Referring back to the *construction materials* qualifier mentioned above, in general a house may be constructed of: concrete, brick, adobe, stone, or wood. A specific house, however, will likely only be constructed of one or two of these materials, one of which will be the primary material. EXSYS must be capable of "remembering" the material of which the house currently under study is constructed.

At the outset of a knowledge-based system consultation session, no facts are known about the specific situation at hand. As facts become known, they must be dynamically stored for subsequent use by EXSYS until the session is terminated. This task is accomplished by storing currently assigned values for all factual entities in the computer's RAM. EXSYS is also capable of permanently storing the facts related to a specific situation to the computer's disk memory for retrieval and use in a later session.

Deducing New Facts

As might be anticipated, knowledge manipulation is not entirely distinct from knowledge representation. The rule displayed in figure 5 illustrates the structure of knowledge representation in EXSYS. All expert knowledge related to a particular domain must be represented, in EXSYS, in the form of rules. A list of all of the rules in an EXSYS knowledge-based system will display all of the static knowledge incorporated into that system. However, part of the capability referred to as knowledge manipulation will also be displayed by this listing. Each rule contains a discrete portion of the reasoning which a human expert might apply when attempting to reach a decision regarding a specific situation within the system domain.

The final, and most powerful, capability offered by EXSYS is that of sifting through all of the rules in a knowledge-base in a manner in which new known facts may be deduced. The deduction technique employed by EXSYS for this purpose is known as backward chaining. The end goal of a knowledge-based system consultation session is to determine which of the available choices apply to the situation under study. This goal is accomplished by first searching the set of rules for one which includes a possible choice as its conclusion. Backward chaining then evaluates the premises of the located rule to determine if they are true. If the premises cannot be evaluated due to incomplete knowledge, EXSYS searches the rule-base for other rules which might conclude the required knowledge. If the required knowledge cannot be deduced by a complete search of the rules, then the user will be prompted to enter facts. In this fashion, the set of rules is searched until the choice is either proved or disproved. EXSYS repeats this exercise of searching for rules which conclude choices and then working backwards through relevant rules in an attempt to prove or disprove the choice, until all possible choices have been evaluated.

In most knowledge domains, choices will not be either absolutely true or absolutely false. That is, since choices represent alternative solutions to a problem, or recommendations for action, there is often more than one "correct" choice. Furthermore, it may be desirable to make alternative recommendations with relative levels of confidence. A rule-base of even limited complexity is likely to contain more than one rule which concludes a particular choice. The premises of one rule may strongly suggest that a choice is true while another rule may only weakly suggest its truth. Other rules may suggest various degrees of this choice's falsity. This poses the necessity of combining the various conclusions of rules to determine the final likelihood of each possible choice.

EXSYS offers several optional methods of combining likelihoods. A so-called 0 to 1 system can be employed for knowledge domains in which choices are always either absolutely false (0) or absolutely true (1). Any rule which concludes the truth of a choice sets the likelihood of this choice at a value of 1. Any rule which concludes the falsity of a choice sets the likelihood of this choice at a value of 0. A 0 to 10 system allows degrees of certainty in the likelihood of a choice to be represented on a scale of 0 to 10. When a developer includes a choice in the THEN or ELSE block of a rule under this system, a level of likelihood for this choice from 0 to 10 is assigned. A value of 0 corresponds to absolutely false and sets this level of likelihood for a choice. A value of 10 corresponds to absolutely true and sets this level of likelihood for a choice. Once a level of likelihood has been set to either of these extreme values, subsequent deductive reasoning will not alter the value. Values of 1 to 9 correspond to subjective degrees of certainty. If multiple rules assign multiple levels of likelihood to a choice, then the final likelihood will be the average of all assigned values. A system of -100 to +100 allows the most complex methods of assigning levels of likelihood to choices. The system developer may assign a degree of certainty from -100 to +100 to any choice in the THEN or ELSE portion of a rule. The developer must also select one of three methods of combining multiple degrees of certainty for a choice. One method is the simple average of all assigned values. A second method combines the values as though they were dependent probabilities. That is, the values are multiplied as percentages. A third method combines the values as independent probabilities. That is, each value is represented as a percentage and subtracted from 1.0, the resulting values are then multiplied, and the result of the multiplication is subtracted from 1.0. It should be noted that since these last two methods treat the assigned degrees of certainty as probabilities, some strange final values result when negative degrees of certainty are combined. For these methods, assigned values should be considered subjective probabilities and restricted to the range of 0 to 100 so that their fractional representations will properly range from 0 to 1.

CONSULTATION CAPABILITIES OF EXSYS

As previously mentioned, it is important to distinguish between the development and the use of a knowledge-based system. The above discussions focus on system development in EXSYS. An understanding of these concepts is helpful to the person who will use a developed system as a surrogate human expert. A complete understanding of system development is not, however required for effective use of a system. EXSYS includes capabilities which are meant to mimic aspects of a consultation session with a human expert. These capabilities allow the system user to interact with the computer.

A consultation session begins with the computer displaying the subject of the knowledge-base and its developer. Next, a brief explanation of the knowledge-base, written by the developer, is displayed. Following these displays, EXSYS begins the task of determining which of the possible choices included in the knowledge-base apply to the problem/situation of concern to the user.

Since no facts are initially known about the current situation, the computer prompts the user to answer one or more preliminary questions. These questions may ask for the correct values for either qualifiers or numeric variables. The computer will continue asking questions (and, in the background, backward chaining through the rule-base) until sufficient information is known to evaluate the likelihood of all possible choices.

The user may ask the computer why it is asking for specific information. Instead of answering a question, the user may respond by typing the word WHY. This response will cause the computer to display the rule which it is currently attempting to evaluate. The user may then review the line of reasoning (i.e. backward chaining) which has caused the computer to ask for the information required to evaluate this rule.

Following evaluation of all possible choices, EXSYS will display the results of this consultation session. The displayed results include all choices which have achieved a level of likelihood greater than a threshold level selected by the system developer. These choices will be arranged in descending order of their likelihood. The results will also include the value or explanatory text of any variable which the system developer chooses to have displayed.

The user is given an opportunity at this point to ask the computer how it reached the conclusions which are displayed. In a fashion similar to that followed after responding with WHY to a system question, the user may explore the line of reasoning which leads to each conclusion.

EXSYS provides a method of performing sensitivity analysis regarding a particular consultation session. The user may change one or more responses to the questions posed by the computer while maintaining all other responses. EXSYS will then redo its evaluation of the rule-base and display the new results for comparison with the original.

SUMMARY OF KNOWLEDGE-BASED SYSTEM TECHNOLOGY

This section has described the methods by which the expert system shell EXSYS implements knowledge-based system technology. It may be useful at this point to generalize this description and to emphasize that EXSYS fits this generalization while incorporating only one approach to this technology. The basic structure of an expert system is shown in figure 6 (Feigenbaum and McCorduck 1983).

The *Expert* or a *Knowledge Engineer* makes use of the *Knowledge Acquisition Facility (tools)* to develop a representation of the domain knowledge. In EXSYS this means mentally devising the rule-base following the EXSYS rule structure and using the software editor to store it in the computer. This rule-base is the *Knowledge-base.* Other expert system development shells may provide different structures and tools for developing their knowledge-base. The *Inference system* used to manipulate the knowledge-base is dependent on the structure of knowledge. Most existing expert systems use some form of backward chaining to process knowledge structured in the form of a rule. More sophisticated shells employ additional forms of knowledge representation and manipulation. The *Input/output system* combines the basic I/O system of the computer on which the knowledge-based system is running and a variety of consultation capabilities similar to those described above for EXSYS. It is this input/output

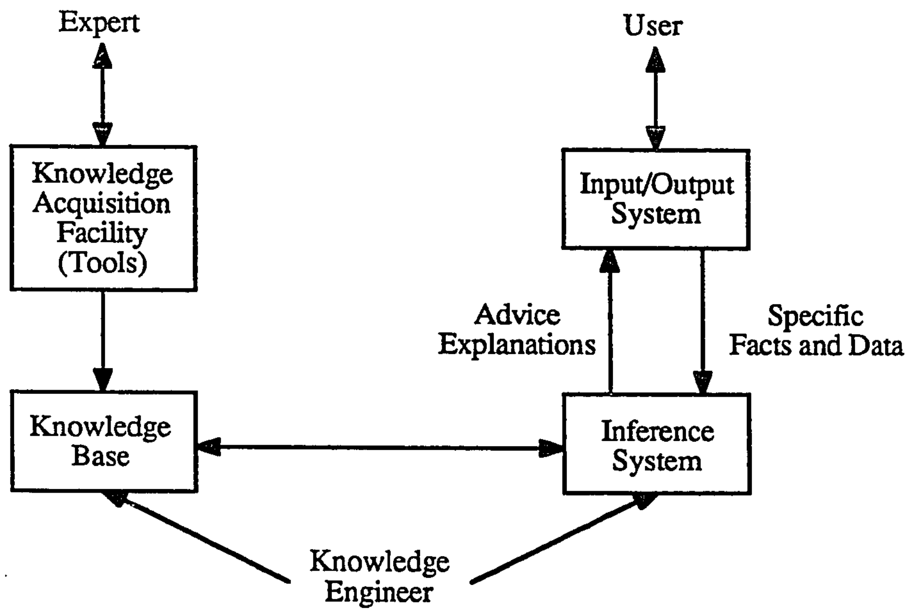

Fig. 6: Basic Structure of an Expert System

(From *The Fifth Generation* by Feigenbaum/McCorduck)

system which allows the interaction of the *User* and the developed knowledge-based system.

CHAPTER IV

KNOWLEDGE-BASED DESIGN GUIDE TOOL PROTOTYPES

Two examples of manual design guide tools have been explored for their possibility of being implemented on a computer. The first tool is documented in *The Passive Solar Energy Book* by Edward Mazria (1979). The second tool is documented in the *Small Office Building Handbook* compiled by Burt Hill Kosar Rittelmann Associates (1985). These tools appear to be candidates for implementation using knowledge-based system technology. Edward Mazria's rules of thumb (or patterns, as he calls them) represent the type of knowledge amenable to knowledge-based system processing. These patterns constitute a domain of expertise which cannot easily be codified using traditional computer programming methods. The Burt Hill Kosar Rittelmann Associates' tool is something of a hybrid. While making use of general rules of thumb, this tool also employs some calculation intensive decision-making. At first glance, it is not clear that knowledge-based system technology can encode this body of knowledge more effectively than traditional methods. For this reason, it may be deemed a testing ground for evaluating knowledge-based system implementation tools.

A modular subset of each of these manual tools has been implemented into a working prototype on an IBM-PC microcomputer using EXSYS. These prototypes are documented below. Complete listings of these prototype knowledge-based systems are contained in appendices A and B.

SELECTING AND SIZING GREENHOUSE SYSTEMS

The Knowledge Domain

The Passive Solar Energy Book by Edward Mazria is subtitled "A complete guide to passive solar home, greenhouse and building design." The book begins with material on the fundamental concepts of solar energy, heat theory, and thermal comfort. The text then describes a variety of types of passive solar systems which are capable of using the solar energy resource to heat and cool residential buildings. Following these system descriptions, Mazria begins a listing and detailed description of something which he calls *design patterns.* These patterns are the rules of thumb which Mazria has accumulated from experiences in designing and building passive solar homes. As a whole, these patterns represent the knowledge domain of the application of passive solar energy systems to residential building design. This is a large, complex knowledge domain. An effective method of implementing such a domain into a knowledge-based system is to identify and incrementally encode smaller sub-domains within the larger. This is a modular implementation approach common to both knowledge-based system and traditional computer program development.

There are potentially four modular sub-domains within the Mazria text. These four are: giving the building its shape and location on the building site, choosing the appropriate passive solar system(s), designing the chosen passive system(s), and optimizing the overall efficiency of the designed building. Within the domain of *designing the chosen passive system(s)* are sets of patterns for the design of each system type. These types include: direct gain, thermal storage wall, attached greenhouse, roof pond, and isolated passive collector. The set of patterns for designing an attached greenhouse thus forms a modular knowledge sub-domain within the larger domain of the entire Mazria text. It is this attached greenhouse domain which was selected for implementation as a prototype knowledge-based system, using the expert system shell called EXSYS. Implementation of this domain requires identification of pertinent knowledge-base facts and the subsequent development of a rule-base which defines the knowledge relationships between these facts.

The Knowledge System Facts

Implementation of a knowledge domain requires identification of pertinent facts. These facts must be capable of being represented in one of the forms provided by the expert system shell. EXSYS provides the following three forms described in detail in the previous section: choices, variables, and qualifiers.

Choices are equivalent, in this situation, to final recommendations which the knowledge-based system reaches following a consultation session with a user. For the attached greenhouse domain, recommendations must be given for the type of thermal mass and the heat transfer method prescribed for the selected greenhouse type. Ten possible combinations of mass and transfer method were identified by careful review of the Mazria text. These combinations were built into the knowledge-base as choices. Examples of these choices include: *Concrete common wall with vents, Concrete common wall without vents,* and *Active Storage/Passive Discharge.* A complete listing of the ten choices can be found in appendix A.

Recommendations which give more detailed information related to a selected mass and heat transfer combination must also be displayed following a consultation session. These recommendations include the amount of glazing, the amount of thermal mass, and special instructions such as the inclusion of operable windows between the greenhouse and the heated space. Recommendations such as the amount of glazing require arithmetic calculations and must therefore be implemented in an EXSYS knowledge-base as numeric variables rather than choices. Special instructions such as the one regarding operable windows may be implemented as string or text variables.

To support the decision-making process for a given consultation session, factual knowledge concerning the specific problem at hand must be represented within the knowledge-base. Facts which dynamically store user responses to system queries are required. Numeric variables are used to store those responses which will become part of arithmetic calculations. For the attached greenhouse knowledge-base this includes such facts as the latitude and average winter temperature at the proposed building site and the floor area of the space which the user wishes to heat with the greenhouse. Qualifiers are used to store those responses which can be represented as multiple choice selection of textual facts. An example of this type of fact is *The building space to be* *heated is primarily used during the: 1) day, 2) evening, 3) night.* When the system queries the user about this fact, the response may be one or more of the listed selections.

Certain internal or intermediate facts must also be included in the knowledge-base. Internal or intermediate facts are those used by the system during the decision-making process which need not be displayed to the user either during or following a consultation session. These facts are only used "behind the scenes" and may be either a numeric variable or a qualifier. An example of an internal numeric fact is a glazing multiplier which is based on arithmetic relationships between average winter temperature and building site latitude. An example of an internal qualifier used by the attached greenhouse knowledge-base is *The heat transfer method is: 1) conductive, 2) passive convective, 3) active convective, 4) active convective with thermal storage.* The user will not be queried about this qualifier since the attached greenhouse rule-base is designed in such a way that the appropriate response(s) will be selected internally.

A total of ten choices, five qualifiers, and seventeen variables is used in the *Selecting and Sizing Greenhouse Systems* knowledge-base to represent the pertinent facts within this domain. The process of identifying these facts within the Mazria text is closely integrated with the development of the knowledge-based system rule-base. It is this "fact base" upon which the rule-base will be designed.

The Knowledge System Rule-Base

As discussed previously, a simple listing of pertinent facts within a knowledge domain is not a sufficient means of representing the knowledge-base. Some means of representing relationships between these facts is also required. EXSYS represents factual relationships in the form of production, or logic, rules. For this reason EXSYS is an example of what is known as a rule-based knowledge system shell. The collection, or set of rules, referred to as the rule-base, provides the structure for representing relationships between facts. As a simple example, a rule-base might contain the following two rules: IF A THEN B and IF B THEN C. These two rules represent not only relationships between A and B and between B and C, but also a relationship between A and C. The rule-base also provides the structure for manipulating the knowledge-based system once it has been completely represented. Using the above example, if it is known that A is true, then it can be deduced (using the backward chaining method previously discussed) that C is also true. Development of the rule-base is not independent of the identification of the knowledge domain facts. Facts and rules are divined concurrently. This process is technically referred to as knowledge acquisition.

The acquisition of knowledge suitably framed for a rule-base is best approached in a goal-directed manner. That is, it is often helpful to first identify a list of EXSYS choices, and then work backward to develop the chains of rules which would support each choice. This approach to knowledge acquisition parallels the so-called backward chaining method which EXSYS will employ in its manipulation of the knowledge base. Attempting to think in the same way in which EXSYS will "think" improves the coherence of the system development process. It is significant to note that this approach also parallels the "solution-focussed" approach to design which is employed by architects.

Within the attached greenhouse domain, the list of choices pertain to the type of thermal mass and the method of heat transfer which best match the building to which the greenhouse will be attached. It is these two characteristics which differentiate between the greenhouse solar system types appropriate for the variety of residential situations likely to be encountered. The selection of a particular combination of thermal mass and method of heat transfer is dependent on several situation facts. These facts include: the orientation, occupancy schedule, and floor area of the building space to be heated; the building construction material; and the location of the building site. The rule-base states the logic for selecting the most appropriate greenhouse solar system for any given set of values for these facts. Furthermore, the rule-base provides the structure for EXSYS to determine the value of each of these facts for a given situation. Finally, the rule-base includes the means to determine the value of additional facts related to each greenhouse solar system. These additional facts include: glazing area, amount of thermal mass, and unique system features such as operable windows.

Knowledge acquisition seldom proceeds in a neat linear sequence of identifying choices, identifying required supportive facts, and developing rules which relate these facts to each other and encode an expert's process of reasoning through them. However, a retrospective look at one possible chain of rules incorporated into the attached greenhouse rule-base will better explain both the development process and the backward chaining performed by EXSYS.

One possible choice related to an attached greenhouse is to provide thermal mass and heat transfer with a concrete common wall containing vents. A chain of rules which supports this choice must determine the truth of necessary supportive facts. One example chain of rules is included in the rule-base for dealing with the situation in which: the building is constructed of concrete, the room for which heat is needed has an exterior wall facing within 45 degrees of true south, and this room is primarily used during the day. Extracted from the complete rule-base listing in appendix A, this chain was implemented in the following form.

RULE NUMBER: 5

IF:

The heat transfer method is passive convective

and The common wall material is concrete

THEN:

Concrete wall with vents - Probability=9/10

and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER]

* [HEATED AREA] + 0.5)

and The recommended thickness of the concrete wall is 12 to 18 inches

RULE NUMBER: 13

IF:

The exterior wall of the building space to be heated faces within 45 degrees of true south

and The building space to be heated is primarily used during the day

THEN:

The heat transfer method is passive convective

RULE NUMBER: 15

IF:

The building construction material is concrete

THEN:

The common wall material is concrete

There are additional rules which will be invoked in this chain for evaluation of the numeric variable [GLAZING AREA]. They do not contribute to the basic logic of this chain and are therefore not included in this discussion.

An important observation of the above rules is that this is only one possible chain of rules for dealing with this situation. As in traditional programming, there are always multiple ways of implementing a problem solution. The key is to develop a standard flow of logic which can be used to implement the various chains which make up a single knowledge-base. This example chain illustrates a logic which bases final recommendations on key situation factors. Various values for each of these factors lead to different final recommendations.

A second observation is to note that the sequence of rule numbers within the rule-base has no pertinence. The rules listed above have the numbers: 5, 13, and 15. The placement of rules which make up a single chain within the rule-base need not be in adjacent sequence, nor do they even need to be in any particular order. EXSYS sifts through all rules, correctly identifying each chain, using the logic of backward chaining.

EXSYS manipulation begins by locating a choice as part of the THEN portion of a rule. EXSYS next attempts to prove the premises (statements in the IF portion) of this rule by locating other rules which contain these premises as part of their THEN portion. This backward chaining will be continued until a chain of rules has been fully evaluated. Evaluation of a chain is complete when EXSYS has either proven all premises of all rules in the chain (thus proving the original choice to be true), or a single premise has been disproved (thus disproving the original choice). As discussed earlier, EXSYS will attempt to prove a premise first by checking the currently known facts, then by invoking other rules which might deduce new pertinent facts, and finally by querying the user about pertinent facts which cannot be deduced.

The above example three rule chain demonstrates the logic which EXSYS might use to determine that the most appropriate greenhouse system for a particular situation would use a concrete common wall with vents. This conclusion would be deduced if all premises in the three rules were determined by EXSYS to be true. Similar chains of rules must be devised which will encode the logic for reaching each of the other possible conclusions (choices) within the greenhouse system knowledge domain.

A fully implemented rule-base contains the supportive logic behind each choice. This includes rules which not only determine the final choice, but also guide the interaction with a potential user of the system. The system developer must decide which facts are reasonable to ask of the user and which should be deduced internally by the system.

An Example Consultation Session

The chain of rules discussed above lead to the recommended choice of a concrete common wall with vents. This is one of the more simple chains contained in the attached greenhouse system. It will therefore serve as a straightforward example of a potential consultation session with a system user.

A consultation session begins by starting the EXSYS program. The program prompts the user to enter the name of the knowledge-base which is to be consulted. This attached greenhouse knowledge-base is called MAZRIA2. The program then displays an opening message which the system developer has written to give an overview of the knowledge-base. For this greenhouse knowledge-base, the following text appears: "This program helps select and size attached greenhouse systems. System selection is based on simplified aspects of the following building factors: orientation, time of day of occupancy, and construction material. Once a system type has been selected, sizing recommendations are calculated based on site latitude and average winter outdoor temperature."

EXSYS nexts begins to search the rule-base for a rule which contains a choice as part of its THEN portion. For the purposes of this discussion, it will be assumed that the first such rule located is rule number 5 displayed in the previous section.

The interactive consultation session might proceed as follows. Rule number 5 is invoked since it contains a choice as part of its THEN portion. Rule number 13 is subsequently invoked since it contains the *passive convective* premise of rule number 5 as part of its THEN portion. Since no rule in the knowledge-base allows EXSYS to determine the orientation of the exterior wall of the building space to be heated, the user will be queried for this data. The query will be displayed onscreen as follows:

The exterior wall of the building space to be heated faces

1 within 45 degrees of true south

2 more than 45 degrees off of true south

The user may respond to this prompt by entering a 1 or a 2. If the user entered a 2 in response to this query, then rule number 13 would fail. This would mean that Rule number 5 would also fail unless another rule could be found which proved its passive convective premise. No such rule exists in this rule-base. Therefore, EXSYS would consider the concrete wall with vents choice eliminated and begin searching for another choice to attempt to prove. For this discussion, therefore, the user response is assumed to be a 1.

EXSYS allows the user to enter a combination of the listed responses by entering both numbers separated by a comma. This would be logically impossible for this particular qualifier, but EXSYS is not intelligent enough to determine this on its own. It is ultimately the responsibility of the system developer to enhance the intelligence of the knowledge-base to prevent possible confusion from illogical user responses.

There is no rule in the knowledge-base which allows EXSYS to determine the primary time of use of the space to be heated. In an attempt to evaluate rule number 13, the user must be queried for this value as well. The query will be displayed onscreen as follows.

The building space to be heated is primarily used during

1 the day

2 the evening

3 the night

The user may respond by entering an individual number or, if the space is used during more than one period, any combination of individual responses separated by commas.

The user may also respond to a system query by typing the word WHY. This response is a means of allowing the user to ask EXSYS why the system wants to know the answer to its query. EXSYS will in turn respond to the WHY response of the user, by displaying the rule which it is currently trying to evaluate. At this stage in the example consultation session, rule number 13 would be displayed as follows.

RULE NUMBER: 13

IF:

(1) The exterior wall of the building space to be heated faces within 45 degrees of true south

and (2) The building space to be heated is primarily used during the day

THEN:

The heat transfer method is passive convective

Below this portion of the display, EXSYS will offer a variety of user options which allow the pursuit of the question of why EXSYS is requesting data. For information on the current state of known facts, the user may request lists of known data and currently recommended choices. The user may also look at other rules in the rule-base in any order desired. Most helpfully, the user can ask EXSYS why it considers one of the premises in the displayed rule to be true. Entering the number enclosed in parentheses to the left of a premise will cause EXSYS to respond with information on the origin of this fact. EXSYS may respond by displaying a rule which contains this premise as part of its THEN or ELSE portions. The user can then further pursue the origin of the truth of the premise by asking EXSYS how it knows the newly displayed rule is true. EXSYS may respond by saying that you, the user, had told it that this premise was true. EXSYS may respond that it does not yet know that a premise is true. In the context of this example session, entering a 1 at this point would cause EXSYS to inform the user that it was known that the exterior wall of the building space to be heated faces within 45 degrees of true south because he or she had said so. Entering a 2 at this point in the example consultation session would result in the response that it is not yet known that the building space to be heated is primarily used during the day. Since it was the system's attempt to elicit this fact from the user which initiated this WHY scenario, this is the obvious response from EXSYS.

Once the user has pursued the question of WHY a query has been made, and is satisfied, a response is required. For this discussion assume the user responds with a 1 (the building space to be heated is primarily used during the day). Having now determined the truth of both premises in rule number 13, EXSYS has determined that the heat transfer method is passive convective. This confirms the first premise of rule number 5.

EXSYS must now attempt to determine the truth or falsity of the second premise of rule number 5, that is, the common wall material is concrete. Finding this fact in the THEN portion of rule number 15 causes EXSYS to evaluate this last rule in the example chain. Failing to locate a rule in the knowledge-base which contains the fact "the building construction material is concrete" in its THEN portion, causes EXSYS to query the user for this information. This query will be displayed onscreen as follows:

The building construction material is

1 concrete

2 brick

3 adobe

4 wood frame

Assuming that the user responds to this query by entering 1, EXSYS will now have confirmed both premises of rule number 5. This confirmation will result in the probability of 0.9 (9/10) being assigned to the choice "Concrete wall with vents." Also, the numeric variable [GLAZING AREA] will be assigned the result of the indicated calculation. Finally, the text variable which recommends a thickness of 12 to 18 inches for the concrete mass wall will be identified for display with the other recommendations.

The calculation of a value for [GLAZING AREA] is performed because its formula is included in the THEN portion of a rule whose premises have been confirmed. The formula assigns [GLAZING AREA] a value equal to the integer truncation of the results of 0.5 plus the variable [GLAZING MULTIPLIER] multiplied by the variable [HEATED AREA]. In order to perform this calculation, EXSYS requires values for [GLAZING

MULTIPLIER] and [HEATED AREA]. EXSYS will first attempt to locate rules in the knowledge-base which will allow the system to determine values for these variables without querying the user. If this is not possible, then EXSYS will ultimately require user input. This knowledge-base has been designed so that [HEATED AREA] is the amount of floor space which the homeowner wishes to heat with the greenhouse. For this discussion assume a user entered value of 400. This value will therefore need to be entered by the user when EXSYS displays the following query onscreen:

Please input the floor area of the building space to be heated:

The variable [GLAZING MULTIPLIER] is an internal numeric variable which EXSYS calculates from a formula based on average winter temperature and building site latitude. The user must be queried for these last two values. At some point during the example consultation session, therefore, EXSYS will display the following two queries for user input:

Please input the average December and January outdoor temperature (degrees F):

Please input the latitude of the building site (degrees NL):

For this discussion assume input values of an average winter temperature of 45 and a latitude of 35. Following these last two user input values, EXSYS has elicited all of the information required to formulate its final recommendations. At this point EXSYS displays a statement written by the system developer which indicates that final recommendations have been reached. For the greenhouse system the following text appears: "The following attached greenhouse system has been selected as the most appropriate for your situation. The greenhouse must be attached to a south-facing exterior wall. Sizing recommendations are based on rule of thumb (patterns) from *The*

Passive Solar Energy Book by Edward Mazria."

EXSYS then displays its final recommendations. For the example consultation session, the following recommendations are reached:

Concrete wall with vents 9

The recommended area of south-facing greenhouse glass = 132.00

The recommended thickness of the concrete wall is 12 to 18 inches.

These recommendations indicate that the recommended thermal mass and heat transfer method is a concrete wall with vents. The confidence with which the knowledge-base makes this recommendation is 9 out of 10 (90%). The recommended glazing area is 132 square feet. The recommended thickness of the concrete mass wall is 12 to 18 inches.

The above scenario then, completes the description of an example consultation session with the selecting and sizing greenhouse systems knowledge-based design guide tool. Although the step by step description of the interaction between user and system appears complex on the written page, it proceeds quite smoothly in practice.

This example session can be generalized to state what is usually required for user input and what is usually generated as system output. For most consultation session scenarios, the user is required to input five facts. These facts include the orientation, size, and time of day of occupancy of the building space to be heated. These facts also include the site latitude and building construction material. EXSYS determines recommendations describing the most appropriate greenhouse system for the situation defined by these entered facts and facts deduced from the rule-base. These recommendations include: the type and amount of thermal mass to include in the greenhouse, the method of transferring heat from the greenhouse to the heated space, the glazing area of the greenhouse, and any additional notes for more unique situations. Examples of additional notes are: the inclusion of operable windows, additional thermal mass to avoid freezing in the evening, and the use of an active distribution system for daytime heating.

SMALL OFFICE BUILDING HANDBOOK

The Knowledge Domain

The Small Office Building Handbook (Burt/Hill/Kosar/Rittelmann 1985) is subtitled "Design for Reducing First Costs and Utility Costs." This handbook states that its focus is on energy saving strategies for office buildings with less than 50,000 square feet of floor area. The strategies are intended for use in designing new buildings or substantially remodeling existing buildings. The development of these strategies was based on multiple computer simulation runs cross-checked using professional judgement and the experience of a wide range of building experts. The bulk of the handbook details a complete decision-making process for selecting energy saving strategies in five representative climates of the United States. This decision-making process is subdivided into five levels. Level one is entitled "Start Right." This level attempts to assure that all buildings will at least match the energy efficiency standards set forth by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 90-75). Level two is entitled "Make Initial Choices." This level selects basic building characteristics such as amount of glazing, HVAC system type, and lowest cost heating fuel. Level three is entitled "Select Strategy Set." This level attempts to improve upon the design achieved in levels one and two by selecting a set of lighting, mechanical, and daylighting strategies. Level four is entitled "Add More." This level presents strategies which are unique to specific climate regions or which require a strong commitment to energy conservation. Level five is entitled "Finish Right." This level presents a checklist of responsibilities for design and construction team members to insure that the final operation of the constructed building will be correct.

The five levels of the decision-making process identified above represent the knowledge domain presented in the *Small Office Building Handbook.* Each of these levels is potentially a sub-domain which could be implemented in modular fashion using EXSYS. The text further divides the overall domain by delineating the decision making process for each of the five climate regions of the United States. However, the logic behind all decisions remains the same for each climate region. Once this logic has been implemented, only the data upon which the decisions are based change. It is the data which differentiates between climate regions, not the decision logic.

The prototype knowledge-based system developed as part of this thesis implements the decision logic required for levels one and two. The initial recommendations within level one are reached by referring to a simple checklist of ASHRAE 90-75 good practice recommendations. These recommendations remain the same for all building types in all climate regions. These recommendations have been omitted from the knowledge-based system since they do not involve judgement or logic, but simply checking. Other level one recommendations are dependent on building size and form. These decisions provide the basis for recommendations made in level two and therefore are included in the developed knowledge-base. Level two performs a comparative energy cost analysis of alternative building design decisions. This cost analysis uses relatively simple calculations which manipulate values extracted from a database. The recommendations made in level two are based substantially on these calculations. Although EXSYS is capable of performing arithmetic calculations, it cannot directly access an external database during knowledge manipulation. For this reason, a companion program was developed using the Pascal programming language. This program is executed automatically by EXSYS at the appropriate stages of knowledge-base manipulation. The results of the calculations performed by this program are automatically returned to EXSYS and used to formulate final level two recommendations. Complete listings of the knowledge-based system and the companion Pascal program can be found in appendix B.

The handbook states that levels one and two represent most of the decisions made through the schematic design stage of a building (Burt/ Hill/Kosar/Rittelmann 1985). These decisions can account for up to 50% of the potential first cost savings and energy operating costs savings available in a project.

The Knowledge System Facts

Each of the facts pertinent to the knowledge-based decision-making process must be represented in one of the forms allowed by EXSYS. These forms are: choices, variables, and qualifiers. The *Small Office Building Handbook* decision-making process also includes accessing and manipulating a database which is external to the knowledge-base. The values in this database and in the external program which manipulates them are represented in the traditional programming form of numeric and string variables. Data are transferred between EXSYS and the external program by means of the forms which they have in common, numeric and string variables.

Choices are useful for representing fundamental recommendations which the system reaches. These recommendations are presented by EXSYS at the end of a consultation session, accompanied by their levels of likelihood. The levels of likelihood are calculated internally by EXSYS using values between 0 and +100 combined as independent probabilities in the manner discussed in the previous section of this thesis. Facts within this domain which are appropriately implemented as choices include the heating, ventilating, and air-conditioning (HVAC) system, the heating fuel, and the glazing area represented as a percentage of wall surface. These facts are represented as choices for two specific reasons. The first reason is that these are fundamental decisions which define the energy efficient strategies of level two. The second reason is that these decisions are based on a variety of factors, some of which strongly suggest a particular recommendation, and some of which only weakly suggest a recommendation. Furthermore, decisions regarding the same aspect of the building design (e.g. HVAC system) receive recommendations as part of both level one and level two. The knowledge-based system must be given the capability of assigning relative weights to these decisions which result from a combination of recommendations. This allows the system to make potentially conflicting recommendations which can be ranked by their associated level of likelihood. This capability is only available for choices in EXSYS.

There are 19 choices defined in this prototype. There are ten potential HVAC system types such as a packaged terminal air conditioner and a three deck multi-zone system. There are three possible heating fuel types including: gas, oil, and electricity. There are six potential glazing area percentages ranging from a low of 10% of wall area to a high of 40% of wall area. Despite the fact that these last six recommendations appear to be quantitative in nature, they are six discrete values. Glazing area recommendations are not calculated values which range over a continuous scale. This characteristic of these recommendations, in combination with the desire to associate levels of likelihood with each suggested glazing area, provide the motivation for implementing them as choices. A complete list of these 19 choices is included in appendix B.

There are ten numeric variables and two text variables incorporated in this system. These variables are used to display additional recommendations at the completion of a consultation session. The resistance values of roof and wall insulation are displayed. The ventilation rate for the building during hours when it is unoccupied is displayed. A recommendation as to the type of glazing is also displayed. Additionally, the values which were calculated by the external Pascal program are displayed at the end of a session. The principal value of interest in this set is the annual operating cost of the least expensive combination of glazing area, heating fuel type, and HVAC system (in dollars per square foot of floor area). There are other numeric and string variables which are used internally for purposes of passing data between EXSYS and the Pascal program, and making decisions based on these values.

Four qualifiers have been implemented in this knowledge-based system for representation and manipulation of qualitative information. The facts represented by these qualifiers are: climate region, the size of the building, the number of stories in the building, and the preferred and/or available heating fuel types. These facts have been represented using qualifiers for the express purpose of simplifying system interaction with the user. Each of these facts must be assigned one of a restricted set of values. Even though the size of a building may appear to be numeric, the knowledge-based system recommendations are based on the size categories of small, medium, and large. Likewise, recommendations based on the number of stories in the building are different only for buildings of one, two, or three to five stories. The allowable climate regions are: cold, temperate, hot/cold, hot/humid, and hot/arid. The list of allowable heating fuel types includes only: gas, number 2 fuel oil, and electricity. The most effective method of restricting user input to a discrete list of possible values is to implement these situation facts as qualifiers.

In summary, 35 variations in situation facts are represented by the choices, variables, and qualifiers discussed above. Additional facts are implemented in the companion Pascal program as numeric values. There are eleven critical factors within this collection which must be assigned values during a consultation session with the *Small Office Building Handbook* knowledge-based system. These factors are: climate region, size of the building, number of stories in the building, heating fuel types which are either preferred or available to the building owner, utility fuel rate structures, local fuel costs, HVAC system type, glazing area, glazing type, insulation levels, and ventilation rate.

The Knowledge System Rule-Base

There are 129 rules which make up the *Small Office Building Handbook* rule-base. This number of rules is required to represent the relationships between all possible combinations of variables, qualifiers, and the recommendations which result.

There tend to be subgroups of rules within this rule-base which are similar in format, but which have variations based on the critical knowledge system factors discussed above. For example, recommendations regarding glazing area are generally based on the factors of climate region and building size. Four rules were required in the rule-base to deal with this issue. These rules have the general format of *IF climate C and size S THEN glazing area G.* Individual rules within this subgroup vary only in the values for C, S, and G. Another subgroup uses variations in value for climate region, building size, number of stories, and the results of a comparative cost analysis, to recommend the HVAC type. Individual rules within this subgroup contain one combination of system factors and result in a specific HVAC recommendation. As a group, however, these rules have the same general format. There are 60 rules within this subgroup.

Chains of rules within the rule-base are consequently a combination of individual rules from each subgroup which support recommendations based on a consistent set of system factor values. For example, a manual perusal of the rule-base can identify rules pertinent to the situation of a medium sized building designed for a cold climate. The backward chaining logic which EXSYS applies to a rule-base during a consultation session sorts through all rules to extract chains which can be used to either prove or disprove a conclusion based on known situation facts. One illustrative subset of chains of rules within the rule-base will provide a basis for examining a consultation session in the next sub-section. The list of rules below was extracted for a two story building of medium size, to be constructed in a cold climate region, where gas and oil are the heating fuels of choice.

As discussed previously, there is no knowledge-based information which is encoded by the order in which rules are placed in the rule-base. The rule numbers shown in the following list only indicate the sequence in which these rules were added to the *Small Office Building Handbook* rule-base. These rule numbers will be used to refer to specific rules during the discussion which follows their listing.

RULE NUMBER: 1

IF:

[BEST VALUE] > 0.0

THEN:

[BEST CASE] IS GIVEN THE VALUE INT([BEST VALUE] / 1000.0)

and [BEST FUEL] IS GIVEN THE VALUE INT(([BEST VALUE] - ([BEST CASE] * 1000.0) / 100.0)

and [BEST COST] IS GIVEN THE VALUE (([BEST VALUE] - ([BEST CASE] * 1000.0)) - ([BEST FUEL] * 100.0))

NOTE:

EXSYS may only return a single value from an external program called by the evaluation of a rule. BEST VALUE actually contains 3 values which are extracted by this rule.

RULE NUMBER: 2

IF:

[BEST VALUE] = 1.0

THEN:

GAS is a recommended heating fuel - Probability=75/100

RULE NUMBER: 3

IF:

[BEST VALUE] = 2.0

THEN:

OIL is a recommended heating fuel - Probability=75/100

RULE NUMBER: 11

IF:

The climate region in which the building will be constructed is COLD

and The size of the building based on floor area is Medium (10000 - 25000 sq ft)

and The building will have 2 stories

and [BEST CASE] >= 19

and [BEST CASE] <= 23

THEN:

A glazing area of 15% is recommended - Probability=75/100

RULE NUMBER: 29

IF:

The size of the building based on floor area is Medium (10000 - 25000 sq ft)

and [STORIES] > 1

THEN:

The building will have 2 stories

RULE NUMBER: 50

IF:

The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD

and The size of the building based on floor area is Medium (10000 - 25000 sq ft)

and The building will have 2 stories

and [BEST CASE] >= 19

and [BEST CASE] <= 20

THEN:

Medium Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 51

IF:

The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD

and The size of the building based on floor area is Medium (10000 - 25000 sq ft)

and The building will have 2 stories

and [BEST CASE] >= 21

and [BEST CASE] <= 22

THEN:

Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 52

IF:

The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD

and The size of the building based on floor area is Medium (10000 - 25000 sq ft)

and The building will have 2 stories

and [BEST CASE] = 23

THEN:

Split Heat Pump HVAC System - Probability=75/100

RULE NUMBER: 92

IF:

The preferred and/or available heating fuel type(s) are gas

THEN:

GAS is a recommended heating fuel - Probability=33/100

RULE NUMBER: 93

IF:

The preferred and/or available heating fuel type(s) are no. 2 fuel oil

THEN:

OIL is a recommended heating fuel - Probability=33/100

RULE NUMBER: 95

IF:

The climate region in which the building will be constructed is COLD

THEN:

[CLIMATE] IS GIVEN THE VALUE 1.0

RULE NUMBER: 101

IF:

The size of the building based on floor area is Medium (10000 - 25000 sq ft)

THEN:

[BLDG SIZE] IS GIVEN THE VALUE "M"

RULE NUMBER: 103

IF:

The preferred and/or available heating fuel type(s) are gas

THEN:

[PREF FUELS] IS GIVEN THE VALUE [PREF FUELS] + 100.0

RULE NUMBER: 104

IF:

The preferred and/or available heating fuel type(s) are no. 2 fuel oil

THEN:

[PREF FUELS] IS GIVEN THE VALUE [PREF FUELS] + 10.0

RULE NUMBER: 107

IF:

The climate region in which the building will be constructed is COLD

and The size of the building based on floor area is Medium (10000 - 25000 sq ft)

THEN:

A glazing area of 15% is recommended - Probability=50/100

and A glazing area of 30% is recommended - Probability=50/100

RULE NUMBER: 111

IF:

The climate region in which the building will be constructed is COLD

and The size of the building based on floor area is Medium (10000 - 25000 sq ft)

THEN:

Medium Building Constant Volume DX HVAC System - Probability=33/100

and Medium Building Variable Air Volume DX HVAC System - Probability=33/100

and Split Heat Pump HVAC System - Probability=33/100

RULE NUMBER: 115

IF:

The climate region in which the building will be constructed is COLD

THEN:

[ROOF R] IS GIVEN THE VALUE 14.3

and [WALL R] IS GIVEN THE VALUE 7.5

RULE NUMBER: 123

IF:

The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD

and The size of the building based on floor area is Medium (10000 - 25000 sq ft) or Large (25000 - 50000 sq ft)

THEN:

[GLAZING] IS GIVEN THE VALUE "DOUBLE GLAZED WITH TINTED GLASS"

RULE NUMBER: 129

IF:

The size of the building based on floor area is Medium (10000 - 25000 sq ft) or Large (25000 - 50000 sq ft)

THEN:

[UNOCCUP AC] IS GIVEN THE VALUE 0.33

The subset of rules listed above will be discussed within the context of a consultation session in the next subsection of this thesis. There are numerous characteristics of individual rules within this subset which warrant mention here. There are also observations to be made concerning this subset as a whole which illustrate certain aspects of rule-base implementation.

Rule number 1 is a unique rule within this rule-base. The purpose of rule number 1 is to execute the companion Pascal program at the proper point in a consultation session, and to extract the desired data values from the single value returned by this program. This rule will be invoked (i.e., EXSYS will attempt to evaluate it) when backward chaining requires a value for any of the variables contained in the THEN portion of this rule. For example, if EXSYS requires a value for the variable BEST FUEL, rule number 1 would be invoked. When EXSYS attempts to evaluate the premise of rule number 1 (the IF portion), the external Pascal program will be executed. This action takes place because of the definition of the variable BEST VALUE. As listed in appendix B, BEST VALUE has a verbal description associated with it which begins with the phrase RUN(CASECOST ...). This description informs EXSYS that a value can be assigned to this variable by running (executing) the external program called CASECOST. The interaction and calculations performed by the program CASECOST will be discussed later. If BEST VALUE has been assigned a value greater than 0.0, then values for BEST CASE, BEST FUEL, and BEST COST will be arithmetically extracted from it.

Rules numbered 2 and 3 contain choices in the THEN portions of each rule. For this reason, EXSYS will backward chain beginning at each of these rules, in the effort to evaluate them. Using the logic of backward chaining, either rule requires a pursuit of a value for the variable BEST FUEL which appears in the premise of each rule. If rule number 1 has not already been evaluated during a consultation session, by the time that either rule number 2 or 3 is invoked, then the external program CASECOST will be executed as a result. The program CASECOST performs a comparative annual energy operating cost evaluation of a variety of building design options and returns a numeric value which fully represents the least expensive design option. If the variable BEST FUEL has been assigned a numeric value of 1.0, then EXSYS uses this information in rule number 2 to assign a likelihood of 75/100 to the choice of GAS as a recommended heating fuel. If the variable BEST FUEL has been assigned a numeric value of 2.0, then rule number 3 will assign a likelihood of 75/100 to the choice of OIL as a recommended heating fuel.

Rules numbered 11 and 107 both assign levels of likelihood to glazing area choices based on a COLD climate region and a building size of MEDIUM. Rule number 11 uses the additional critical factors of number of stories, and results from the comparative operating cost analysis in the formulation of a recommended glazing area. These rules are an example of complementary recommendations resulting from the different levels within the decision-making process presented in the *Small Office Building Handbook* text. The resulting levels of likelihood associated with these complementary recommendations are combined as independent probabilities. Thus, if both rules are proven true, and no other rules recommend a choice of 15% glazing area, then the final degree of likelihood for this choice would be 87.5/100 (i.e. 1 - ((1 - 0.75) * (1 - 0.50))). The method of combining multiple degrees of likelihood is chosen by the system developer from the options of: averages, dependent probabilities, and independent probabilities. The method selected depends on the manner in which the system developer chooses to assign degrees of likelihood within individual rules.

For this system, individual rules assign levels of likelihood to choices based solely on the premises contained in that rule. For example, rule number 11 assigns a level of likelihood of 75/100 to a choice of 15% glazing area based only on the premises of rule number of 11. This value is independent of any level of likelihood assigned to this same choice by any other rule in the rule-base. For this reason multiple levels of likelihood are combined as independent probabilities. The fact that both rules numbered 11 and 107 assign levels of likelihood to a choice of 15% glazing area is interpreted as meaning that two independent combinations of critical design factors suggest this recommendation. Rule number 11 is based on a recommendation made in level one of the *Small Office Building Handbook* decision-making process while rule number 107 is based on a level two recommendation.

Rules numbered 50, 51, and 52 contain only slight variations related to the comparative operating cost analysis which aid in the decision between recommended HVAC system types. These rules are an example of the system development need for somewhat redundant premises to be included in multiple rules. To a traditional programmer this might appear to be an inefficient means of encoding system decisions. The way in which EXSYS structures rules, however, requires this approach.

Rules numbered 92 and 93 are rules which make recommendations based directly on user input. At some point in a consultation session, the user will be asked to select from among a list of heating fuel types which includes: gas, number 2 fuel oil, and electricity. This user selection is based either on the fuels available at the building site, or the fuel types preferred by the user for some reason. The fuel types which are input by the user are consequently assigned a uniform level of likelihood based on this preference.

Rules numbered 95, 101, 103, and 104 all convert user responses to qualifier based queries into a form which can be communicated (passed) to the companion Pascal program. Again, the only mutual forms of data values between EXSYS and the companion program are numeric and string variables. Therefore, values assigned to qualifiers within EXSYS must be converted to one of these forms before they can be passed to the Pascal program.

Rule number 111 implements a level one recommendation which assigns equal levels of likelihood to each of three HVAC system types. These recommendations are based solely on the climate region and size of the building. Rules numbered 50, 51, and 52 incorporate the additional design factor of number of stories and the results of the comparative operating cost analysis to recommend a specific HVAC system type.

Rules numbered 115, 123, and 129 make recommendations as to insulation levels, glazing type, and unoccupied ventilation rates based on various design factors. These recommendations do not require levels of likelihood because there is only one possible recommended value for each of these design factors. Therefore, the system does not need the capability to rank order conflicting recommendations. This is the reason for implementing these factors as variables instead of choices.

This completes a discussion of individual rules within this subset of the *Small Office Building Handbook* rule-base. As with all computer implementations, these rules represent only one of many possible rule-bases which might be developed to encode the decision making process presented in this knowledge domain. This complete rule-base, which contains the subset of rules listed above, has been tested for its accuracy in matching recommendations reached by following the manual method presented in the text. An example of this validation will be illustrated in the following section. The rule-base has not been optimized for its efficiency in reaching these recommendations. One of the problems associated with this technology is the potentially long execution time of knowledge-based processing performed on a "traditional" numeric processing hardware platform. For a rule-base of this relatively small size, efficiency of execution is not a problem.

An Example Consultation Session

The set of selected rules discussed in the previous section are an illustrative subset of the rule-base created for implementation of the *Small Office Building Handbook* knowledge domain. This prototype knowledge-based system displays several advantages over the manual process presented in the text. A user of this system does not need to read and assimilate the entire process presented in the text. The interaction of EXSYS during a consultation session eases access to this process by presenting the user with a series of non-technical queries which are automatically taken into consideration in the decision-making process. The companion Pascal program automates the database lookup and arithmetic calculations required to perform the comparative operating cost analysis and automatically folds these results into the decision-making process.

The set of rules discussed above have been selected because collectively they deal with the potential design situation for a medium sized, two story building, constructed in a cold climate region, in which the designer wishes to only consider either natural gas or fuel oil as possible heating fuels. To simplify the discussion of an example consultation session, utility rates for this design site will be assumed to be relatively uniform throughout the year. This means that annual averages can be entered for electricity, gas, and oil rates. This prototype system is also capable of dealing with the situation in which fuel consumption rates vary from month to month. For fuel rate structures more complex than this, the decision-making process presented in the text requires a response from the local utility. For this reason, this most complex utility rate situation has not been implemented.

A consultation session begins with an opening message which briefly describes the purpose of this expert system. For the *Small Office Building Handbook* system, the following text appears: "This expert system is an implementation of the Level 2 decision-making process described in the *Small Office Building Handbook* compiled by Burt Hill Kosar Rittelmann Associates. The system incorporates criteria for making initial choices regarding HVAC system, heating fuel type, and the amount of glass which can substantially reduce operating energy costs in the constructed building. This tool is meant to be used very early in the architectural design process."

EXSYS next searches the rule-base for any rule which contains a choice as part of the THEN portion. EXSYS will eventually consider all such rules. The order in which these rules are identified is therefore not critically important to the final conclusions drawn by the system. However, a consequence of some importance is that changes in this order might subsequently alter the sequence in which EXSYS presents queries to the system user. In practice, it is difficult, even when familiar with the entire rule-base, to recreate the order in which EXSYS attempts to evaluate individual rules during a given consultation session. The rule-base must first be implemented and then modified after consultation experience demonstrates the sequence of queries.

The following discussion lists system queries and user responses as they occurred during an actual consultation session. A running commentary will suggest a possible order in which rules are being invoked by the system. This session is representative of most interactions with the Small Office Building Handbook expert system.

The first query presented by the system is displayed onscreen as follows:

The size of the building based on floor area is

1 Small (2000 - 10000 sq ft)

2 Medium (10000 - 25000 sq ft)

3 Large (25000 - 50000 sq ft)

For purposes of this discussion, the user response to this query is assumed to be option 2 indicating a Medium sized building.

The second query presented by the system is displayed onscreen as follows:

The climate region in which the building will be constructed is

1 COLD

2 TEMPERATE

3 HOT/COLD

4 HOT/HUMID

5 HOT/ARID

The user response to this query is option number 1 for COLD. This climate region includes most of the northern latitudes in the United States except for the northwest coastal area. The representative city for this climate is Madison, Wisconsin.

These first two queries are based on the need for EXSYS to determine values for two qualifiers, building size and climate region. The necessity of determining these values may have been prompted by the attempt to evaluate any rule which contains a choice in its THEN portion and these qualifiers in its premise (i.e. the IF portion). This includes several rules within the subset discussed in the preceding section. Rules numbered 11, 50, 51, 52, 107, and 111 all fit this characterization. The backward chaining process which EXSYS employs would lead from any of these rules to the search for rules which contain an assignment to the necessary qualifiers as part of their THEN portion. There are no rules in the rule-base which assign values to these qualifiers. This situation consequently results in the need to directly query the user for values.

A third query presented by the system pertains to a second characteristic of the size of the building, the number of stories. Instead of being based on a qualifier, however, this query derives its form from a numeric variable and is displayed as follows:

Please input the number of stories in the building:

The motivation for this query may have derived from an attempt to evaluate any of rules numbered 11, 50, 51, or 52. The reason for the query taking the form of a request for a numeric value instead of the system qualifier defining the number of stories is the backward chaining of any one of these rules to rule number 29. In the attempt to determine if the building will have 2 stories (a premise for rules 11, 50, 51, and 52), rule number 29 is invoked. This is caused by the presence of the building story qualifier in the THEN portion of rule 29. To fully evaluate rule 29, a value is required for the numeric variable STORIES, prompting the above query. The user response to this query is assumed to be the numeric value 2. The result of this response, combined with the previously entered building size of Medium, is the completed evaluation of rule number 29. The system now "knows" that the qualifier *the building will have* can be assigned the value of *2 stories.*

A fourth query presented by the system is displayed onscreen as follows:

The preferred and/or available heating fuel type(s) are

1 gas

2 no. 2 fuel oil

3 electricity

The motivation for this query may have come from an attempt to evaluate either of rules numbered 92 or 93. These rules both contain choices in their THEN portions and require an assignment to the qualifier *the preferred and/or available heating fuel* *type(s)*. Since no rules exist which assign values to this qualifier by means of backward chaining, EXSYS is forced to directly query the user. The response to the above query is assumed to be 1,2 indicating that both gas and number 2 fuel oil are either preferred or available at the building site.

A review of all rules in the example subset at this stage in the consultation session, reveals that EXSYS now has derived values for all premises necessary for evaluating these rules, with the exception of a collection of numeric variables. These numeric variables include: BEST FUEL, BEST CASE, and BEST VALUE. The variable BEST FUEL is required for evaluation of rules numbered 2 and 3. The variable BEST CASE is required for evaluation of rules numbered 11, 50, 51, and 52. Backward chaining from any of these rules would invoke rule number 1 since this rule contains assignments to the two variables BEST FUEL and BEST CASE in its THEN portion.

In an attempt to evaluate rule number 1, EXSYS requires a value for the variable BEST VALUE. This variable was uniquely defined during implementation of this expert system. The definition of this numeric variable informs EXSYS that a numeric value will be assigned to BEST VALUE by executing the companion Pascal program. The definition also informs EXSYS that it must pass (i.e. communicate) values to this external program for the variables: CLIMATE, BLDG SIZE, STORIES, and PREF FUELS.

These four variables exist primarily for the purpose of passing values, derived by backward chaining during a consultation session, to the external program. Only numeric and string values may be passed between EXSYS and an external program. Consequently, rule number 95 converts the climate region qualifier value of COLD to the numeric CLIMATE variable value of 1.0. Similarly, rule number 101 converts the building size qualifier value of Medium to the string BLDG SIZE variable value of "M." The numeric variable PREF FUELS is a three digit number in which each digit takes on a value of either 0 or 1 indicating the preferred fuel types entered by the user. The hundreds digit represents the user preference regarding gas, the tens digit represents oil, and the ones digit represents electricity. For example, a value of 100 indicates that gas is preferred while oil and electricity are not. A value of 110 indicates that gas and oil are preferred while electricity is not. The purpose of rules numbered 103 and 104 is to assign a value to PREF FUELS based on the user entered preference for fuel types.

The evaluation of rule number 1 causes EXSYS to execute the companion Pascal program. This program performs the comparative operating costs analysis required to complete the consultation session. This program first queries the user as to the utility rate structure. The rate structures for which the comparative costs analysis can be performed are relatively uniform demand and consumption charges throughout the year, or relatively uniform demand charges throughout the year with no "ratchet" charges and consumption rates with only seasonal (in fact, monthly) changes. For this example consultation session the simplest rate structure was selected.

The comparative costs analysis subsequently queries the user for annual average utility rates for each preferred or available fuel type. For this analysis, an annual average of $0.10 per therm is entered for gas, and $0.50 per gallon for fuel oil.

Rates for electricity are also entered. Although electricity is not a preferred heating fuel in this situation, it is always assumed to be used for lighting and equipment. Therefore, electricity always contributes to the operating costs of a building. A consumption rate of $0.02 and a demand rate of $1.00 are entered for this analysis.

The comparative costs analysis now searches an external database containing energy use values for various combinations of HVAC system type, heating fuel type, and percent glazing. These database values were calculated by performing hundreds of parametric computer simulations using DOE 2.1B and a computer version of the ASHRAE TC 4.7 method (Burt/Hill/Kosar/Rittelmann 1985, p.2). The energy use values are given for each heating fuel type per square foot of building floor area per year. The database search locates energy use values for each combination for the climate region, building size, and number of building stories which were passed from

EXSYS.

The database values are next multiplied by the user entered utility rates to calculate the annual energy costs per square foot of floor area for each combination of HVAC system, heating fuel type, and percent glazing option. The least cost combination along with the calculated least cost is now passed back to EXSYS for inclusion in the decision-making process. Since only a single value can be passed to EXSYS from an external program, this information must all be represented in one number which is returned to EXSYS as the variable BEST VALUE.

Upon return to EXSYS control, rule number 1 can be fully evaluated. Values for BEST CASE, BEST FUEL, and BEST COST are calculated from BEST VALUE. It is this value for BEST FUEL which is used in rules numbered 2 and 3 to assign levels of likelihood to recommended heating fuel choices. The value for BEST CASE is used in rules numbered 11, 50, 51, and 52 to complete their evaluation. The variable BEST COST will be reported to the user as part of the summary report following the consultation session.

EXSYS fully evaluates all rules in the system to reach the final recommendations for a given situation. Consequently, despite the fact that rules numbered 115, 123, and 129 do not contain choices in their THEN portions, values will be assigned to the numeric and string variables which make up the conclusions of these rules.

This completes the evaluation of all rules in this subset for this example consultation session. This subset is representative of all rules in the rule-base and it may therefore be assumed that the entire rule-base has been fully evaluated. At this point in the session, a message is displayed onscreen informing the user that processing has been completed. This message appears as follows: "The following recommendations regarding HVAC system, heating fuel type, and amount of glass are based on your responses to the preceding questions and a comparative analysis of operating costs. For further detail related to these recommendations refer to the *Small Office Building Handbook.*"

Finally, the recommendations which have been reached for this consultation session are displayed onscreen. Recommendations based on choices are accompanied by their final calculated values of level of likelihood. The following display omits several internal values which are displayed for system debugging purposes only. Choices which receive levels of likelihood are ranked in descending level. All numeric and string variables which have been marked for display by the system developer are then also listed. Although this prototype system displays these values without units of measure, EXSYS provides additional report formatting capabilities which could be used to eliminate this omission in a polished software product. The pertinent recommendations resulting from the above consultation session are as follows:

1	A glazing area of 15% is recommended	88
2	Medium Building Variable Air Volume DX HVAC System	84
3	GAS is a recommended heating fuel	84
4	A glazing area of 30% is recommended	50
5	Medium Building Constant Volume DX HVAC System	33
6	Slit Heat Pump HVAC System	33
7	OIL is a recommended heating fuel	33
8	The preferred heating fuel type which results in the lowest operating cost (1=GAS, 2=OIL, 3=ELEC) =	1
9	The lowest operating cost which uses a preferred fuel =	0.72
10	The recommended R value of roof insulation =	14.3
11	The recommended R value of wall insulation =	7.5
12	The recommended number of air changes per hour during unoccupied hours =	0.33
13	Recommended type of glazing = dbl glazed w/ tinted glass	

The Burt/Hill/Kosar/Rittelmann decision-making process leaves some design considerations to the design team. For example, in selecting an HVAC system, it is important to consider system flexibility, maintainability, fuel availability, manufacturer or dealer service, and previous professional experience (Burt/Hill/Kosar/Rittelmann 1985, p.7). Considerations such as these must be taken into account when deciding between the various recommendations listed above. The above recommendations nonetheless match those which would be reached by manually proceeding through the process presented in the text, but with much greater ease and reliability.

The above scenario completes the description of an example consultation session with the *Small Office Building Handbook* level one and level two knowledge-based system. This example session can be generalized to state the usual requirements for user input and the usually generated system output. For each situation, the following data are required: the climate region (cold, temperate, hot/cold, hot/humid, or hot/arid), the size of the building (small, medium, or large), the number of stories, the user preferred heating fuel types (gas, oil, or electricity), and utility rate data (annual or monthly). The resulting recommendations include: level of likelihood ranking of HVAC system types, level of likelihood ranking of glazing area, level of likelihood ranking of fuel type, the least cost fuel type, the annual operating cost per square foot for this fuel type, insulation levels for roof and wall, the type of glazing, and the ventilation rate for unoccupied hours. Consultation sessions using variations in each of the input values have been performed to validate correspondence between recommendations reached by the prototype system and by the manual method. Given this validation, the computer system can be used to generate recommendations without having to first assimilate the method presented in the text. Furthermore, this computerized generation process requires much less user effort and a fraction of the time.

CHAPTER V

DESIGN TOOL INTEGRATION AND CONCLUSIONS

It was stated in the introduction to this thesis that to be both useful and used, a design tool must fulfill a need in an easily applied fashion. The development of architectural design tools must therefore begin with the identification of some aspect of the design process which might be enhanced by the use of a new tool. The product of this enhancement might be improved process efficiency, improved decision-making reliability, or improved product quality.

A discussion of improving process efficiency requires a review of the design process. Jane Darke's (1979) analysis of interviews with architects supports a design process model of generator-conjecture-analysis. To review, a generator is a set of one or more key objectives for a designed building which forms a starting point for the development of design solutions. The purpose of a generator is to aid the designer in prestructuring the design problem. That is, the need is to reduce the number of potential design solutions to a manageable set of alternatives. The generator is considered, in the light of the designer's knowledge of solution types, to produce a conjecture. This conjecture is an approximate design solution which can be subjected to an analysis of its fulfillment of the collective design criteria. This is an iterative process which continually generates more refined definitions of the building design. The primary agent in the generator-conjecture cycle, according to Darke, is the designer's own cognitive structure. Again, this is the designer's knowledge regarding potential solutions to aspects of the design problem.

Yehuda E. Kalay (1985, p.5) observes that the single most difficult problem of architectural design is the generation of new design states from existing ones. That is, given an incomplete set of design parameters, the difficulty lies in generating a more complete design solution. This process of generation depends in great part on the designer's access to, and understanding of, information regarding building technologies. Kalay notes that the design of increasingly complex buildings requires the application of increasing amounts of informational resources.

Feigenbaum and McCorduck (1983, p.55) refer to a common problem encountered during complex kinds of engineering. A natural capacity of humans is the ability to attend consciously and simultaneously to about four different items. Beyond this limit, humans are overwhelmed by information. Feigenbaum and McCorduck propose a method of alleviating this overload. This method is to compile the "details, data points, and ever-changing information" on an intelligent machine. This would allow some information processing to be "subcontracted out to the machine." Humans would then be freed to use their "processing power to attend to more important matters." In both engineering and architecture, these more important matters tend to be the creative aspects of design.

The views presented above indicate a general need for a tool which can support the designer during the generation phase of design. This support would take the form of supplemental information processing and presentation of potential alternative combinations of design solutions prescribed according to acceptable and pertinent criteria. Consultation with this tool could considerably aid access to state of the art knowledge regarding building technologies. The consultation capabilities described for the *Small Office Building Handbook* knowledge-based system exhibit the required aid. A consultation session elicits preliminary design factors and generates design solution recommendations. This interaction employs a machine based cognitive structure to appropriately reduce the number of potential design solutions and generate a refined building design state. At the same time, the designer's creative freedom is not unduly restricted since the system lists alternative recommendations, rank ordered by level of likelihood.

The knowledge-based system is therefore most appropriately integrated into the design process during phases of generator-conjecture. These generator-conjecture phases occur within the larger context of the architectural design project. As discussed earlier, the sequential stages of an architectural design project are: predesign analysis, schematic design, design development, construction documents, and construction observation (see figure 3). Generator-conjecture phases begin to occur very early in this sequence. Predesign analysis begins the determination of general building characteristics. These characteristics often become the initial parameters of design generators. Conjectures relating to fundamental design parameters begin to be formed here. Schematic design involves the most intense application of the generator-conjecture process resulting in selection of most, if not all, fundamental design parameters not set in predesign analysis. Here, consultation again with the knowledge-based system can provide a check of internal consistency of design decisions made to this point. Design development includes design refinement and material specification. Both of these activities might also be enhanced by consultation with a knowledge-based system developed specifically for each activity. These first *three* stages of the architectural design project, therefore, could be made more efficient by integrating use of these systems into each process.

Improving the quality of the product of architectural design is perhaps a more subjective proposition than improving efficiency or reliability within the design process. A supposition of the following discussion is that reducing the energy consumption of a building without negatively impacting occupant comfort is an improvement in quality.

Darke notes that the greatest variety reduction, or narrowing down of the range of design solutions, occurs during early iterations of the generator-conjecture-analysis process (1979, p.180). This implies that fundamental building parameters will be set or restricted during beginning stages of design, based on the designer's knowledge set. Treado, Holland, Remmert, and Pierpoint (1986, p.3) state that many critical design decisions must be made very early in the design process. These authors further emphasize that major decisions which must be made early in predesign analysis and schematic design cannot easily be changed later during design development. It is generally agreed that at least half of the potential energy savings due to building design result from decisions made by the end of the schematic design stage. These decisions also form the basis for equipment selection decisions made during the design development stage.

Burt, Hill, Kosar, and Rittelmann suggest that fewer than one in ten architects or engineers can correctly guess, unaided by an analysis tool, the annual utility bill of a small commercial office building (1985, p.256). Claude Robbins, in reference to the design decision regarding the desirability of using daylighting, remarks that few designers have a sufficient intuitive understanding of this issue to make the decision with confidence (1986, p.14). The use of daylighting in a building design is only one of a wide variety of energy related design decisions. If few designers have assimilated knowledge concerning energy objectives, then these objectives have little chance of becoming part of a design generator.

As this thesis demonstrates, knowledge-based systems can provide critical decision-making support during predesign analysis and schematic design. Furthermore, equipment selection knowledge-based systems, which are consistent with the systems employed during these early design stages, can help to optimize the remainder of the potential for design based energy savings. The use of knowledge-based systems can therefore enhance the process of generating conjectures within each of the first three stages of an architectural design project. If these systems are consistently developed, they can also enhance the efficiency of the overall project by reducing the need to reiterate early stages to correct uninformed decisions.

The example consultation sessions in the preceding section presented details of specific interactions with each knowledge-based system prototype. A few summary comments regarding the interface between the computer system and the user may further illustrate the potential benefits of these interactions.

Knowledge-based systems can be developed in such a way as to hide technical detail from the user. An example of this drawn from the greenhouse selection and sizing system relates to the heat transfer method of the greenhouse. Possible methods of transferring heat from the greenhouse to the building space to be heated include: conductive, passive convective, active convective, and active convective with thermal storage. This is a key parameter in the decision-making process of this system. Although not overly technical, this aspect of design need never be considered by the system user. The method of heat transfer can instead be deduced by the system from other parameters such as time of day of building occupancy and the building orientation. These other parameters are more apt to be known and understood by all users of the system than is the heat transfer method. The system can be developed so that only these more familiar parameters are elicited from the user. In similar manner, access to other technical information can be provided using non-technical user queries. This characteristic of well designed knowledge-based systems can greatly enhance technology transfer. Up-to-date knowledge can be disseminated and efficiently accessed by users without having to assimilate detailed technical data. This can be especially useful for equipment specification during the design development stage.

Although technical detail can be hidden within the system, the logic behind system recommendations can be fully explored by the user. At any point in a consultation session, the user may query the system regarding its status. The system is capable of responding to such a query by displaying the currently known situation facts and the chain of rules which are presently being evaluated. These capabilities are important for two reasons. First, providing access to internal logic reduces the black box (i.e. mysterious) nature of the decision-making process. This tends either to increase the user's confidence in the resulting recommendations, or to help identify errors in the system. Second, after repeated exposure to the system logic, users begin to develop their own mental model of this decision-making process. They learn the new material by assimilating it during interaction with the knowledge-based system. For certain aspects of design this may allow users to wean themselves from the system and to further improve design process efficiency by reducing the need for the computer.

A capability more familiar to users of computer building energy analysis tools is also provided by a knowledge-based system shell such as EXSYS. This is the capability of performing sensitivity or parametric analyses of a building design. This type of analysis involves changing one or more key design parameters in an attempt to assess the impact on other design parameters. This allows the user to evaluate the relative importance of certain critical design decisions. EXSYS provides this capability by allowing the user to save all data associated with a completed consultation session. One or more of the answers entered by the user to system queries can then be modified, the session can be rerun, and the new recommendations compared with the original. This is another way in which experienced users can develop an intuitive understanding of the design logic encoded in the system. Again, this allows them ultimately to make informed decisions efficiently with less interaction with the knowledge-based system.

Another characteristic of the interaction with knowledge-based systems which argues for their use relates to the results of a consultation session. Recommendations are listed in rank order of their level of likelihood. This means that the output of such a session is not a black or white, take it or leave it, recommendation. The user is presented with a list of alternative recommendations which is not restrictive. This output is truly similar to what Darke refers to as "variety reduction" as opposed to design restriction. This allows creative freedom from hard and fast decisions. It also reduces the chances of reaching exclusively conflicting decisions at different stages in the design project.

Knowledge-based design guide tools should be designed for integration into an overall design project at very specific stages. These tools are seen as most useful in the generator-conjecture phases of predesign analysis, schematic design, and design development. The prototype tools discussed in the previous section of this thesis were designed to illustrate predesign analysis and early schematic design aids. This same technology might usefully be applied to more sophisticated tools for use in any of these project stages.

The majority of computerized design tools currently available are tools of *analysis.* These tools require detailed input describing a proposed building design before they can produce any output at all. Parametric simulations using these tools are required for effective evaluation of alternative design decisions. After performing many parametric simulations of a variety of building types, a designer may develop a cognitive model of this decision-making process. This would then allow the designer to generate design solutions based on an acquired intuitive sense of "correct" building design. This cumbersome process of learning, though, by no means guarantees success. Even experienced research scientists have difficulty establishing rules for "correct" building design which are both reliable and flexible.

The existence of published design guide handbooks such as *The Passive Solar Design Book* (Mazria 1979) and the *Small Office Building Handbook* (Burt, Hill, Kosar, and Rittelmann 1985) reflect the need for design *guide* tools as opposed to tools of analysis. These design guides generally have their foundations in the type of parametric building studies mentioned above. The handbooks are distillations of the results of these parametric studies which have been "correlated" into rules of thumb. The author of the handbook develops the cognitive model and transfers this information by means of the written page. By necessity, though, these rules are limited to a few discretely grouped sets of parameters, which may not accurately reflect the conditions of a particular proposed design.

There is continuous, though poorly funded, research into the development of the next generation of design tools. The majority of these tools remain analytical in nature. The algorithms which model the complex physical processes related to building energy use are being improved. The user interfaces which allow access to the detailed building descriptions required for input to this type of tool are being enhanced.

There are also a few tools being developed which are aimed at aiding the generative phase of design. One such tool proposed by Kalay combines knowledge engineering techniques for generating and testing design decisions, geometric modeling for object representation, and interactive graphic user interfaces (1985, p.11). This tool is meant to encompass the entire design process. It is a highly complex tool which applies graphics, drafting, object oriented database management, and traditional algorithmic and knowledge-based systems technologies in its development.

The prototype tools developed for this thesis are much smaller in scale than these more ambitious tools. These prototypes are more equivalent to the manuals and handbooks which architects and architectural engineers currently use for simplified early reference. These tools, developed using knowledge-based systems technology and a minimum of traditional programming, demonstrate several promising qualities. They do not require years to design and implement. They do not force the end user to climb a steep learning curve before they can be operated. They can be used simply to generate design parameter recommendations. They can also be used to provide access to the decision-making logic behind these recommendations. This second use aids in the transfer of cognitive models of this design process phase.

These prototypes also expose certain limitations of the application of knowledge-based technology to the development of architectural design tools. This type of tool does not provide an environment in which the entire design process can be performed. The prototypes are not integrated with computerized drafting, and include only in a simplified fashion, database management and energy analysis tools. This is not to imply that such integration could not be accomplished more thoroughly. Indeed, the promising results of these simplified prototypes suggest that more complete knowledge-based system design tool development is warranted.

It is not clear, however, that one computerized tool which "does it all" is the most appropriate or useful type of tool. The domains of knowledge encoded in the prototype tools are specialized sets of rules of thumb which represent a current state of knowledge. Knowledge of this type is constantly being updated and revised by experience. Tools which incorporate knowledge-based system technology must be capable of similar updating and revision. Simple specialized tools which can be quickly and easily developed would allow for this type of revision, suggesting a possible trade-off of complexity for adaptability.

The predominant software applications in use in the world today are computerized versions of earlier manual methods. This is true for word processing, database management, and spreadsheet applications. Each of these arenas has been improved, enhanced, enlarged, and more widely disseminated by computerization. In similar fashion, the types of tools illustrated by this thesis and its prototypes are computerized versions of manual design guide handbooks. If the handbook is deemed useful, then the computerized equivalent should be deemed at least equally useful. The computer system has the advantage of easing access to the knowledge being transmitted and helping to assure greater reliability and consistency in the early design decisions that result. These prototype tools are nascent examples of the potential for encoding decision-making knowledge in an easily developed, disseminated, and accessed form.

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APPENDIX A

SELECTING AND SIZING GREENHOUSE SYSTEMS PRINTOUT

Subject: Selecting and Sizing Greenhouse Systems

Author: Rob Hitchcock

Starting text:

This program helps select and size attached greenhouse systems. System selection is based on simplified aspects of the following building factors: orientation, time of day of occupancy, and construction material. Once a system type has been selected, sizing recommendations are calculated based on site latitude and average winter outdoor temperature.

Ending text:

The following attached greenhouse system has been selected as the most appropriate for your situation. The greenhouse must be attached to a south-facing exterior wall. Sizing recommendations are based on rules of thumb (patterns) from 'The Passive Solar Energy Book' by Edward Mazria.

RULES:

RULE NUMBER: 1
IF:
The heat transfer method is conductive
and The heat transfer method is NOT passive convective or active convective
and The common wall material is concrete
THEN:
Concrete wall without vents - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and The recommended thickness of the concrete wall is 12 to 18 inches.

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', p.181

RULE NUMBER: 2
IF:
The heat transfer method is conductive
and The heat transfer method is NOT passive convective or active convective
and The common wall material is brick
THEN:
Brick wall without vents - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and The recommended thickness of the brick wall is 10 to 14 inches.

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', p.181

RULE NUMBER: 3

IF:
The heat transfer method is conductive
and The heat transfer method is NOT passive convective or active convective
and The common wall material is adobe
THEN:
Adobe wall without vents - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and The recommended thickness of the adobe wall is 8 to 12 inches.

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', p.181

RULE NUMBER: 4
IF:
The heat transfer method is conductive
and The common wall material is water
THEN:
Water wall - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and [WATER WALL VOLUME] IS GIVEN THE VALUE [GLAZING AREA] * 0.67

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', p.183

RULE NUMBER: 5
IF:
The heat transfer method is passive convective
and The common wall material is concrete
THEN:
Concrete wall with vents - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and The recommended thickness of the concrete wall is 12 to 18 inches.

RULE NUMBER: 6
IF:
The heat transfer method is passive convective
and The common wall material is brick
THEN:
Brick wall with vents - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and The recommended thickness of the brick wall is 10 to 14 inches.

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', p.181

RULE NUMBER: 7
IF:
The heat transfer method is passive convective
and The common wall material is adobe
THEN:
Adobe wall with vents - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] *

[HEATED AREA]) + 0.5)
and The recommended thickness of the adobe wall is 8 to 12 inches.

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', p.181

RULE NUMBER: 8
IF:
The heat transfer method is passive convective
and The common wall material is wood frame
THEN:
Wood frame wall with vents - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and For this system, additional thermal mass should be added to the interior of the greenhouse to dampen temperature swings.

RULE NUMBER: 9
IF:
The heat transfer method is active convective
THEN:
Active distribution - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and This system uses an active distribution system to supply the required heat during the daytime only.

RULE NUMBER: 10
IF:
The heat transfer method is active convective with thermal storage
and [WINTER TEMP] <= 32
THEN:
Active storage/ Passive discharge - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and [ROCK STORAGE VOLUME] IS GIVEN THE VALUE [GLAZING AREA] * 1.0
and For adequate heat transfer (passive) from the rock bed to the heated space, 75 to 100% of the floor's surface area should act as the heating source.
and Operable windows or a door should be placed between the greenhouse and a heated space to assure that during periods of extreme cold the greenhouse can be kept from freezing.
and Additional thermal mass should be located in the greenhouse to supply heat to the greenhouse in the evening to keep it above freezing.

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', pp.184,185

RULE NUMBER: 11
IF:
The exterior wall of the building space to be heated faces more than 45 degrees off of true south
and The building space to be heated is primarily used during the day
and The building space to be heated is primarily used during NOT the evening or the night
THEN:

The heat transfer method is active convective

RULE NUMBER: 12
IF:
The exterior wall of the building space to be heated faces more than 45 degrees off of true south
and The building space to be heated is primarily used during the evening or the night
THEN:
The heat transfer method is active convective with thermal storage

----

The exterior wall of the building space to be heated faces within 45 degrees of true south
and The building space to be heated is primarily used during the day
THEN:
The heat transfer method is passive convective

RULE NUMBER: 14
IF:
The exterior wall of the building space to be heated faces within 45 degrees of true south
and The building space to be heated is primarily used during the evening or the night
THEN:
The heat transfer method is conductive

RULE NUMBER: 15
IF:
The building construction material is concrete
THEN:
The common wall material is concrete

RULE NUMBER: 16
IF:
The building construction material is brick
THEN:
The common wall material is brick

RULE NUMBER: 17
IF:
The building construction material is adobe
THEN:
The common wall material is adobe

RULE NUMBER: 18
IF:
The building construction material is wood frame
and The heat transfer method is conductive
THEN:
The common wall material is water

RULE NUMBER: 19
IF:
The building construction material is wood frame

and The heat transfer method is passive convective or active convective or active convective with thermal storage
and The heat transfer method is NOT conductive
THEN:
The common wall material is wood frame

RULE NUMBER: 20
IF:
[WINTER TEMP] <= 32
and The common wall material is concrete or brick or adobe or wood frame
and The common wall material is NOT water
THEN:
[GLAZING MULTIPLIER] IS GIVEN THE VALUE 1.5 - ((48 - [LATITUDE]) / 13 * 0.85)

REFERENCE:
E. Mazria. The Passive Solar Energy Book, p.173

RULE NUMBER: 21
IF:
[WINTER TEMP] > 32
and The common wall material is concrete or brick or adobe or wood frame
and The common wall material is NOT water
THEN:
[GLAZING MULTIPLIER] IS GIVEN THE VALUE 0.9 - ((48 - [LATITUDE]) / 13 * 0.57)

REFERENCE:
E. Mazria. The passive Solar Energy Book, p.173

RULE NUMBER: 22
IF:
The common wall material is water
and [WINTER TEMP] <= 32
THEN:
[GLAZING MULTIPLIER] IS GIVEN THE VALUE 1.27 - ((48 - [LATITUDE]) / 13 * 0.8)

REFERENCE:
E. Mazria, The Passive Solar Energy Book, p.173

RULE NUMBER: 23
IF:
The common wall material is water
and [WINTER TEMP] > 32
THEN:
[GLAZING MULTIPLIER] IS GIVEN THE VALUE 0.65 - ((48 - [LATITUDE]) / 13 * 0.41)

REFERENCE:
E. Mazria, The Passive Solar Energy Book, p.173

RULE NUMBER: 24
IF:
The heat transfer method is active convective with thermal storage
and [WINTER TEMP] > 32

THEN:
Active storage/ Passive discharge - Probability=9/10
and [GLAZING AREA] IS GIVEN THE VALUE INT(([GLAZING MULTIPLIER] * [HEATED AREA]) + 0.5)
and [ROCK STORAGE VOLUME] IS GIVEN THE VALUE [HEATED AREA] * 2.25
and For adequate heat transfer (passive) from the rock bed to the heated space, 50 to 75% of the floor space should act as the heating source.

REFERENCE:
E. Mazria. 'The Passive Solar Energy Book', pp.184,185

RULE NUMBER: 25
IF:
[LATITUDE] < 35
THEN:
[LATITUDE] IS GIVEN THE VALUE 35

RULE NUMBER: 26
IF:
[LATITUDE] > 48
THEN:
[LATITUDE] IS GIVEN THE VALUE 48

QUALIFIERS:

1 The heat transfer method is

conductive
passive convective
active convective
active convective with thermal storage

Used in rule(s): 1 2 3 4 5 6
7 8 9 10 (11) (12)
(13) (14) 18 19 24

2 The common wall material is

concrete
brick
adobe
wood frame
water

Used in rule(s): 1 2 3 4 5 6
7 8 (15) (16) (17) (18)
(19) 20 21 22 23

3 The exterior wall of the building space to be heated faces

within 45 degrees of true south
more than 45 degrees off of true south

Used in rule(s): 11 12 13 14

4 The building space to be heated is primarily used during

the day
the evening

Used in rule(s): 11 12 13 14

5 The building construction material is

concrete
brick
adobe
wood frame

Used in rule(s): 15 16 17 18 19

CHOICES:

1 Concrete wall with vents

Used in rule(s): (5)

2 Concrete wall without vents

Used in rule(s): (1)

3 Brick wall with vents

Used in rule(s): (6)

4 Brick wall without vents

Used in rule(s): (2)

5 Adobe wall with vents

Used in rule(s): (7)

6 Adobe wall without vents

Used in rule(s): (3)

7 Wood frame wall with vents

Used in rule(s): (8)

8 Water wall

Used in rule(s): (4)

9 Active storage/ Passive discharge

Used in rule(s): (10) (24)

10 Active distribution

Used in rule(s): (9)

VARIABLES:

1 WINTER TEMP
the average December and January outdoor temperature (degrees F).
Numeric variable

2 GLAZING MULTIPLIER
The multiplier for calculating glazing area
Numeric variable

3 LATITUDE
the latitude of the building site (degrees NL).
Numeric variable

4 GLAZING AREA
The recommended area of south-facing greenhouse glass
Numeric variable
Displayed at the end of a run

5 HEATED AREA
the floor area of the building space to be heated.
Numeric variable

6 ROCK STORAGE VOLUME
The recommended volume in cubic feet of fist-sized rock used for storage
Numeric variable
Displayed at the end of a run

7 ROCK STORAGE NOTE
percentage of heated space floor area used for passive discharge
Displayed at the end of a run as text only

8 PASSIVE DISCHARGE CO
For adequate heat transfer (passive) from the rock bed to the heated space, 75 to 100% of the floor's surface area should act as the heating source.
Displayed at the end of a run as text only
Displayed at the end of a run

9 PASSIVE DISCHARGE HO
For adequate heat transfer (passive) from the rock bed to the heated space, 50 to 75% of the floor space should act as the heating source.
Displayed at the end of a run as text only
Displayed at the end of a run

10 OPERABLE WINDOWS
Operable windows or a door should be placed between the greenhouse and

a heated space to assure that during periods of extreme cold the greenhouse can be kept from freezing.
Displayed at the end of a run as text only
Displayed at the end of a run

11 ADDITIONAL MASS
Additional thermal mass should be located in the greenhouse to supply heat to the greenhouse in the evening to keep it above freezing.
Displayed at the end of a run as text only
Displayed at the end of a run

12 CONCRETE THICKNESS
The recommended thickness of the concrete wall is 12 to 18 inches.
Displayed at the end of a run as text only
Displayed at the end of a run

13 BRICK THICKNESS
The recommended thickness of the brick wall is 10 to 14 inches.
Displayed at the end of a run as text only
Displayed at the end of a run

14 ADOBE THICKNESS
The recommended thickness of the adobe wall is 8 to 12 inches.
Displayed at the end of a run as text only
Displayed at the end of a run

15 WATER WALL VOLUME
The recommended volume of water in the water wall in cubic feet
Numeric variable
Displayed at the end of a run

16 MASS NOTE
For this system, additional thermal mass should be added to the interior of the greenhouse to dampen temperature swings.
Displayed at the end of a run as text only
Displayed at the end of a run

17 DISTRIBUTION NOTE
This system uses an active distribution system to supply the required heat during the daytime only.
Displayed at the end of a run as text only
Displayed at the end of a run

APPENDIX B

SMALL OFFICE BUILDING HANDBOOK PRINTOUT

KNOWLEDGE-BASED SYSTEM PRINTOUT

Subject: Small Office Building Handbook Level 2

Author: Rob Hitchcock

Starting text:

This expert system is an implementation of the Level 2 decision making process described in the Small Office Building Handbook compiled by Burt Hill Kosar Rittelmann Associates. The system incorporates criteria for making initial choices regarding HVAC system, heating fuel type, and the amount of glass which can substantially reduce operating energy costs in the constructed building. This tool is meant to be used very early in the architectural design process.

Ending text:

The following recommendations regarding HVAC system, heating fuel type, and amount of glass are based on your responses to the preceding questions and a comparative analysis of operating costs. For further detail related to these recommendations refer to the Small Office Building Handbook.

```
RULES:
-------------------------------------
RULE NUMBER: 1
IF:
     [BEST VALUE] > 0.0
THEN:
     [BEST CASE] IS GIVEN THE VALUE
      INT([BEST VALUE] / 1000.0)
  and [BEST FUEL] IS GIVEN THE VALUE
      INT(([BEST VALUE]-[BEST CASE] * 1000.0) / 100.0)
  and [BEST COST] IS GIVEN THE VALUE
      (([BEST VALUE]-([BEST CASE] * 1000.0))-([BEST FUEL] * 100.0))
NOTE:
EXSYS may only return a single value from an external program called by
the evaluation of a rule. BEST VALUE actually contains 3 values which are
extracted by this rule.
-------------------------------------
RULE NUMBER: 2
IF:
     [BEST FUEL] = 1.0
THEN:
     GAS is a recommended heating fuel - Probability=75/100
-------------------------------------
RULE NUMBER: 3
IF:
     [BEST FUEL] = 2.0
THEN:
```

OIL is a recommended heating fuel - Probability=75/100

RULE NUMBER: 4
IF:
    [BEST FUEL] = 3.0
THEN:
    ELECTRICITY is a recommended heating fuel - Probability=75/100

RULE NUMBER: 5
IF:
    The climate region in which the building will be constructed is COLD
  and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
  and The building will have 1 story
  and [BEST CASE] >= 9
  and [BEST CASE] <= 13
THEN:
    A glazing area of 15% is recommended - Probability=75/100

RULE NUMBER: 6
IF:
    The climate region in which the building will be constructed is COLD
  and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
  and The building will have 1 story
  and [BEST CASE] >= 14
  and [BEST CASE] <= 18
THEN:
    A glazing area of 30% is recommended - Probability=75/100

RULE NUMBER: 7
IF:
    The climate region in which the building will be constructed is NOT COLD
  and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
  and The building will have 1 story
  and [BEST CASE] >= 9
  and [BEST CASE] <= 13
THEN:
    A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 8
IF:
    The climate region in which the building will be constructed is NOT COLD
  and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
  and The building will have 1 story
  and [BEST CASE] >= 14
  and [BEST CASE] <= 18
THEN:
    A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 9
IF:
    The climate region in which the building will be constructed is NOT COLD
  and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
  and The building will have 2 stories

and [BEST CASE] >= 19
and [BEST CASE] <= 23
THEN:
A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 10
IF:
The climate region in which the building will be constructed is NOT COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 24
and [BEST CASE] <= 28
THEN:
A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 11
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 19
and [BEST CASE] <= 23
THEN:
A glazing area of 15% is recommended - Probability=75/100

RULE NUMBER: 12
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 24
and [BEST CASE] <= 28
THEN:
A glazing area of 30% is recommended - Probability=75/100

RULE NUMBER: 13
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 29
and [BEST CASE] <= 34
THEN:
A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 14
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 35
and [BEST CASE] <= 40
THEN:
A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 15
IF:
The climate region in which the building will be constructed is TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 29
and [BEST CASE] <= 33
THEN:
A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 16
IF:
The climate region in which the building will be constructed is TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 34
and [BEST CASE] <= 38
THEN:
A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 17
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 29
and [BEST CASE] <= 31
THEN:
A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 18
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 32
and [BEST CASE] <= 34
THEN:
A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 19
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 41
and [BEST CASE] <= 46
THEN:
A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 20
IF:

The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 47
and [BEST CASE] <= 52
THEN:
A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 21
IF:
The climate region in which the building will be constructed is TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 39
and [BEST CASE] <= 43
THEN:
A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 22
IF:
The climate region in which the building will be constructed is TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 44
and [BEST CASE] <= 48
THEN:
A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 23
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 35
and [BEST CASE] <= 37
THEN:
A glazing area of 20% is recommended - Probability=75/100

RULE NUMBER: 24
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 38
and [BEST CASE] <= 40
THEN:
A glazing area of 40% is recommended - Probability=75/100

RULE NUMBER: 25
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
and [BEST CASE] >= 1

and [BEST CASE] <= 4
THEN:
A glazing area of 10% is recommended - Probability=75/100

RULE NUMBER: 26
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
and [BEST CASE] >= 5
and [BEST CASE] <= 8
THEN:
A glazing area of 25% is recommended - Probability=75/100

RULE NUMBER: 27
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
THEN:
The building will have 1 story

RULE NUMBER: 28
IF:
The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and [STORIES] <= 1
THEN:
The building will have 1 story

RULE NUMBER: 29
IF:
The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and [STORIES] > 1
THEN:
The building will have 2 stories

RULE NUMBER: 30
IF:
The size of the building based on floor area is Large (25000 - 50000 sq ft)
and [STORIES] <= 2
THEN:
The building will have 2 stories

RULE NUMBER: 31
IF:
The size of the building based on floor area is Large (25000 - 50000 sq ft)
and [STORIES] > 2
THEN:
The building will have 3 to 5 stories

RULE NUMBER: 32
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
and [BEST CASE] = 1
THEN:
Packaged Terminal Air Conditioner HVAC System - Probability=75/100

RULE NUMBER: 33
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)

and [BEST CASE] >= 2
and [BEST CASE] <= 3
THEN:
Packaged Rooftop DX HVAC System - Probability=75/100

RULE NUMBER: 34
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
and [BEST CASE] = 4
THEN:
Packaged Terminal Heat Pump HVAC System - Probability=75/100

RULE NUMBER: 35
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
and [BEST CASE] = 5
THEN:
Packaged Terminal Air Conditioner HVAC System - Probability=75/100

RULE NUMBER: 36
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
and [BEST CASE] >= 6
and [BEST CASE] <= 7
THEN:
Packaged Rooftop DX HVAC System - Probability=75/100

RULE NUMBER: 37
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
and [BEST CASE] = 8
THEN:
Packaged Terminal Heat Pump HVAC System - Probability=75/100

RULE NUMBER: 38
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 9
and [BEST CASE] <= 10
THEN:
Medium Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 39
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 11
and [BEST CASE] <= 12
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 40
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] = 13
THEN:
Split Heat Pump HVAC System - Probability=75/100

RULE NUMBER: 41
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 14
and [BEST CASE] <= 15
THEN:
Medium Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 42
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 16
and [BEST CASE] <= 17
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 43
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] = 18
THEN:
Split Heat Pump HVAC System - Probability=75/100

RULE NUMBER: 44
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 9
and [BEST CASE] <= 10
THEN:
Three Deck Multi-Zone HVAC System - Probability=75/100

RULE NUMBER: 45
IF:
The climate region in which the building will be constructed is

HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 11
and [BEST CASE] <= 12
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 46
IF:
The climate region in which the building will be constructed is
HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] = 13
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 47
IF:
The climate region in which the building will be constructed is
HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 14
and [BEST CASE] <= 15
THEN:
Three Deck Multi-Zone HVAC System - Probability=75/100

RULE NUMBER: 48
IF:
The climate region in which the building will be constructed is
HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] >= 16
and [BEST CASE] <= 17
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 49
IF:
The climate region in which the building will be constructed is
HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 1 story
and [BEST CASE] = 18
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 50
IF:
The climate region in which the building will be constructed is COLD or
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories

and [BEST CASE] >= 19
and [BEST CASE] <= 20
THEN:
Medium Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 51
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 21
and [BEST CASE] <= 22
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 52
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 23
THEN:
Split Heat Pump HVAC System - Probability=75/100

RULE NUMBER: 53
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 24
and [BEST CASE] <= 25
THEN:
Medium Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 54
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 26
and [BEST CASE] <= 27
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 55
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 28
THEN:

Split Heat Pump HVAC System - Probability=75/100

RULE NUMBER: 56
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 19
and [BEST CASE] <= 20
THEN:
Three Deck Multi-Zone HVAC System - Probability=75/100

RULE NUMBER: 57
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 21
and [BEST CASE] <= 22
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 58
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 23
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 59
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 24
and [BEST CASE] <= 25
THEN:
Three Deck Multi-Zone HVAC System - Probability=75/100

RULE NUMBER: 60
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 26
and [BEST CASE] <= 27
THEN:
Medium Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 61
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 28
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 62
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 29
and [BEST CASE] <= 30
THEN:
Large Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 63
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 31
and [BEST CASE] <= 32
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 64
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 33
and [BEST CASE] <= 34
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 65
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 35
and [BEST CASE] <= 36
THEN:
Large Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 66
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)

and The building will have 2 stories
and [BEST CASE] >= 37
and [BEST CASE] <= 38
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 67
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 39
and [BEST CASE] <= 40
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 68
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 33
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 69
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 34
and [BEST CASE] <= 35
THEN:
Large Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 70
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 36
and [BEST CASE] <= 37
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 71
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 38
THEN:

Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 72
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 29
and [BEST CASE] <= 30
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 73
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 31
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 74
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] >= 32
and [BEST CASE] <= 33
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 75
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 2 stories
and [BEST CASE] = 34
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 76
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 41
and [BEST CASE] <= 42
THEN:
Large Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 77
IF:

The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 43
and [BEST CASE] <= 44
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 78
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 45
and [BEST CASE] <= 46
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 79
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 47
and [BEST CASE] <= 48
THEN:
Large Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 80
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 49
and [BEST CASE] <= 50
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 81
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 51
and [BEST CASE] <= 52
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 82
IF:
The climate region in which the building will be constructed is TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 39
and [BEST CASE] <= 40

THEN:
Large Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 83
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 41
and [BEST CASE] <= 42
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 84
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] = 43
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 85
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 44
and [BEST CASE] <= 45
THEN:
Large Building Constant Volume DX HVAC System - Probability=75/100

RULE NUMBER: 86
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 46
and [BEST CASE] <= 47
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 87
IF:
The climate region in which the building will be constructed is
TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] = 48
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 88
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 35
and [BEST CASE] <= 36
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 89
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] = 37
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 90
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] >= 38
and [BEST CASE] <= 39
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=75/100

RULE NUMBER: 91
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
and The building will have 3 to 5 stories
and [BEST CASE] = 40
THEN:
Hydronic Heat Pump Loop HVAC System - Probability=75/100

RULE NUMBER: 92
IF:
The preferred and/or available heating fuel type(s) are gas
THEN:
GAS is a recommended heating fuel - Probability=33/100

RULE NUMBER: 93
IF:
The preferred and/or available heating fuel type(s) are no. 2 fuel oil
THEN:
OIL is a recommended heating fuel - Probability=33/100

RULE NUMBER: 94
IF:

The preferred and/or available heating fuel type(s) are electricity
THEN:
ELECTRICITY is a recommended heating fuel - Probability=33/100

RULE NUMBER: 95
IF:
The climate region in which the building will be constructed is COLD
THEN:
[CLIMATE] IS GIVEN THE VALUE 1.0

RULE NUMBER: 96
IF:
The climate region in which the building will be constructed is TEMPERATE
THEN:
[CLIMATE] IS GIVEN THE VALUE 2.0

RULE NUMBER: 97
IF:
The climate region in which the building will be constructed is HOT/COLD
THEN:
[CLIMATE] IS GIVEN THE VALUE 3.0

RULE NUMBER: 98
IF:
The climate region in which the building will be constructed is HOT/HUMID
THEN:
[CLIMATE] IS GIVEN THE VALUE 4.0

RULE NUMBER: 99
IF:
The climate region in which the building will be constructed is HOT/ARID
THEN:
[CLIMATE] IS GIVEN THE VALUE 5.0

RULE NUMBER: 100
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
THEN:
[BLDG SIZE] IS GIVEN THE VALUE "S"

RULE NUMBER: 101
IF:
The size of the building based on floor area is Medium (10000 - 25000 sq ft)
THEN:
[BLDG SIZE] IS GIVEN THE VALUE "M"

RULE NUMBER: 102
IF:
The size of the building based on floor area is Large (25000 - 50000 sq ft)
THEN:
[BLDG SIZE] IS GIVEN THE VALUE "L"

RULE NUMBER: 103
IF:
The preferred and/or available heating fuel type(s) are gas
THEN:
[PREF FUELS] IS GIVEN THE VALUE [PREF FUELS] + 100.0

RULE NUMBER: 104
IF:
The preferred and/or available heating fuel type(s) are no. 2 fuel oil
THEN:
[PREF FUELS] IS GIVEN THE VALUE [PREF FUELS] + 10.0

RULE NUMBER: 105
IF:
The preferred and/or available heating fuel type(s) are electricity
THEN:
[PREF FUELS] IS GIVEN THE VALUE [PREF FUELS] + 1.0

RULE NUMBER: 106
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
THEN:
A glazing area of 10% is recommended - Probability=50/100
and A glazing area of 25% is recommended - Probability=50/100

RULE NUMBER: 107
IF:
The climate region in which the building will be constructed is COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
THEN:
A glazing area of 15% is recommended - Probability=50/100
and A glazing area of 30% is recommended - Probability=50/100

RULE NUMBER: 108
IF:
The climate region in which the building will be constructed is NOT COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
THEN:
A glazing area of 20% is recommended - Probability=50/100
and A glazing area of 40% is recommended - Probability=50/100

RULE NUMBER: 109
IF:
The size of the building based on floor area is Large (25000 - 50000 sq ft)
THEN:
A glazing area of 20% is recommended - Probability=50/100
and A glazing area of 40% is recommended - Probability=50/100

RULE NUMBER: 110
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
THEN:
Packaged Terminal Air Conditioner HVAC System - Probability=33/100
and Packaged Rooftop DX HVAC System - Probability=33/100
and Packaged Terminal Heat Pump HVAC System - Probability=33/100

RULE NUMBER: 111
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
THEN:
Medium Building Constant Volume DX HVAC System - Probability=33/100
and Medium Building Variable Air Volume DX HVAC System - Probability=33/100
and Split Heat Pump HVAC System - Probability=33/100

RULE NUMBER: 112
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
THEN:
Medium Building Constant Volume DX HVAC System - Probability=33/100
and Medium Building Variable Air Volume DX HVAC System - Probability=33/100
and Hydronic Heat Pump Loop HVAC System - Probability=33/100

RULE NUMBER: 113
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000 sq ft)
THEN:
Large Building Constant Volume DX HVAC System - Probability=33/100
and Large Building Variable Air Volume DX HVAC System - Probability=33/100
and Hydronic Heat Pump Loop HVAC System - Probability=33/100

RULE NUMBER: 114
IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
THEN:
Large Building Variable Air Volume DX HVAC System - Probability=50/100
and Hydronic Heat Pump Loop HVAC System - Probability=50/100

RULE NUMBER: 115
IF:
The climate region in which the building will be constructed is COLD
THEN:
[ROOF R] IS GIVEN THE VALUE 14.3
and [WALL R] IS GIVEN THE VALUE 7.5

RULE NUMBER: 116
IF:
The climate region in which the building will be constructed is TEMPERATE or HOT/COLD
THEN:
[ROOF R] IS GIVEN THE VALUE 8.3
and [WALL R] IS GIVEN THE VALUE 7.5

RULE NUMBER: 117

IF:
The climate region in which the building will be constructed is HOT/HUMID or HOT/ARID
THEN:
[ROOF R] IS GIVEN THE VALUE 8.3

RULE NUMBER: 118
IF:
The climate region in which the building will be constructed is HOT/HUMID
and The size of the building based on floor area is Small (2000 - 10000 sq ft)
and A glazing area of 10% is recommended > 50/100
THEN:
[WALL R] IS GIVEN THE VALUE 3.8

RULE NUMBER: 119
IF:
The climate region in which the building will be constructed is HOT/HUMID
and The size of the building based on floor area is Small (2000 - 10000 sq ft)
and A glazing area of 25% is recommended > 50/100
THEN:
[WALL R] IS GIVEN THE VALUE 0.0

RULE NUMBER: 120
IF:
The climate region in which the building will be constructed is HOT/ARID
and The size of the building based on floor area is Small (2000 - 10000 sq ft) or Medium (10000 - 25000 sq ft)
THEN:
[WALL R] IS GIVEN THE VALUE 7.5

RULE NUMBER: 121
IF:
The climate region in which the building will be constructed is HOT/ARID
and The size of the building based on floor area is Large (25000 - 50000 sq ft)
THEN:
[WALL R] IS GIVEN THE VALUE 0.0

RULE NUMBER: 122
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Small (2000 - 10000 sq ft)
[GLAZING] IS GIVEN THE VALUE "DOUBLE GLAZED WITH TINTED GLASS"

RULE NUMBER: 123
IF:
The climate region in which the building will be constructed is COLD or TEMPERATE or HOT/COLD
and The size of the building based on floor area is Medium (10000 - 25000 sq ft) or Large (25000 - 50000 sq ft)

THEN:
[GLAZING] IS GIVEN THE VALUE
"DOUBLE GLAZED WITH TINTED GLASS"

RULE NUMBER: 124
IF:
The climate region in which the building will be constructed is
HOT/HUMID
and The size of the building based on floor area is Small (2000 - 10000 sq ft)
THEN:
[GLAZING] IS GIVEN THE VALUE
"SINGLE GLAZED WITH TINTED OR REFLECTIVE GLASS"

RULE NUMBER: 125
IF:
The climate region in which the building will be constructed is
HOT/HUMID
and The size of the building based on floor area is Medium (10000 - 25000
sq ft) or Large (25000 - 50000 sq ft)
THEN:
[GLAZING] IS GIVEN THE VALUE
"DOUBLE GLAZED WITH TINTED GLASS OR
SINGLE GLAZED WITH REFLECTIVE GLASS"

RULE NUMBER: 126
IF:
The climate region in which the building will be constructed is
HOT/ARID
and The size of the building based on floor area is Small (2000 - 10000 sq ft)
THEN:
[GLAZING] IS GIVEN THE VALUE
"SINGLE GLAZED WITH TINTED GLASS"

RULE NUMBER: 127
IF:
The climate region in which the building will be constructed is
HOT/ARID
and The size of the building based on floor area is Medium (10000 - 25000
sq ft) or Large (25000 - 50000 sq ft)
THEN:
[GLAZING] IS GIVEN THE VALUE
"DOUBLE GLAZED WITH TINTED GLASS"

RULE NUMBER: 128
IF:
The size of the building based on floor area is Small (2000 - 10000 sq ft)
THEN:
[UNOCCUP AC] IS GIVEN THE VALUE 0.5

RULE NUMBER: 129
IF:
The size of the building based on floor area is Medium (10000 - 25000
sq ft) or Large (25000 - 50000 sq ft)
THEN:
[UNOCCUP AC] IS GIVEN THE VALUE 0.33

QUALIFIERS:

1 The climate region in which the building will be constructed is

COLD
TEMPERATE
HOT/COLD
HOT/HUMID
HOT/ARID

Used in rule(s):	5	6	7	8	9	10
	11	12	13	14	15	16
	17	18	19	20	21	22
	23	24	38	39	40	41
	42	43	44	45	46	47
	48	49	50	51	52	53
	54	55	56	57	58	59
	60	61	62	63	64	65
	66	67	68	69	70	71
	72	73	74	75	76	77
	78	79	80	81	82	83
	84	85	86	87	88	89
	90	91	95	96	97	98
	99	107	108	111	112	113
	114	115	116	117	118	119
	120	121	122	123	124	125
	126	127				

2 The size of the building based on floor area is

Small (2000 - 10000 sq ft)
Medium (10000 - 25000 sq ft)
Large (25000 - 50000 sq ft)

Used in rule(s):	5	6	7	8	9	10
	11	12	13	14	15	16
	17	18	19	20	21	22
	23	24	25	26	27	28
	29	30	31	32	33	34
	35	36	37	38	39	40
	41	42	43	44	45	46
	47	48	49	50	51	52
	53	54	55	56	57	58
	59	60	61	62	63	64
	65	66	67	68	69	70
	71	72	73	74	75	76
	77	78	79	80	81	82
	83	84	85	86	87	88
	89	90	91	100	101	102
	106	107	108	109	110	111
	112	113	114	118	119	120
	121	122	123	124	125	126
	127	128	129			

3 The building will have

1 story
2 stories
3 to 5 stories

Used in rule(s):

5	6	7	8	9	10
11	12	13	14	15	16
17	18	19	20	21	22
23	24	(27)	(28)	(29)	(30)
(31)	38	39	40	41	42
43	44	45	46	47	48
49	50	51	52	53	54
55	56	57	58	59	60
61	62	63	64	65	66
67	68	69	70	71	72
73	74	75	76	77	78
79	80	81	82	83	84
85	86	87	88	89	90
91					

4 The preferred and/or available heating fuel type(s) are

gas
no. 2 fuel oil
electricity

Used in rule(s): 92 93 94 103 104 105

CHOICES:

1 Packaged Terminal Air Conditioner HVAC System

Used in rule(s): (32) (35) (110)

2 Packaged Rooftop DX HVAC System

Used in rule(s): (33) (36) (110)

3 Packaged Terminal Heat Pump HVAC System

Used in rule(s): (34) (37) (110)

4 Medium Building Constant Volume DX HVAC System

Used in rule(s): (38) (41) (50) (53) (111) (112)

5 Medium Building Variable Air Volume DX HVAC System

Used in rule(s): (39) (42) (45) (48) (51) (54) (57) (60) (111) (112)

6 Split Heat Pump HVAC System

Used in rule(s): (40) (43) (52) (55) (111)

7 Three Deck Multi-Zone HVAC System

Used in rule(s): (44) (47) (56) (59)

8 Large Building Constant Volume DX HVAC System

Used in rule(s): (62) (65) (69) (76) (79) (82)
(85) (113)

9 Large Building Variable Air Volume DX HVAC System

Used in rule(s): (63) (66) (70) (72) (74) (77)
(80) (83) (86) (88) (90) (113)
(114)

10 Hydronic Heat Pump Loop HVAC System

Used in rule(s): (46) (49) (58) (61) (64) (67)
(68) (71) (73) (75) (78) (81)
(84) (87) (89) (91) (112) (113)
(114)

11 GAS is a recommended heating fuel

Used in rule(s): (2) (92)

12 OIL is a recommended heating fuel

Used in rule(s): (3) (93)

13 ELECTRICITY is a recommended heating fuel

Used in rule(s): (4) (94)

14 A glazing area of 10% is recommended

Used in rule(s): (25) (106) 118

15 A glazing area of 15% is recommended

Used in rule(s): (5) (11) (107)

16 A glazing area of 20% is recommended

Used in rule(s): (7) (9) (13) (15) (17) (19)
(21) (23) (108) (109)

17 A glazing area of 25% is recommended

Used in rule(s): (26) (106) 119

18 A glazing area of 30% is recommended

Used in rule(s): (6) (12) (107)

19 A glazing area of 40% is recommended

Used in rule(s): (8) (10) (14) (16) (18) (20)
(22) (24) (108) (109)

VARIABLES:

1 BEST VALUE
RUN(CASECOST [BEST CASE] [CLIMATE] [BLDG SIZE] [STORIES]
[PREF FUELS])
the value returned to SOBH2 by the external program CASECOST
Numeric variable
Displayed at the end of a run

2 BEST CASE
the base case option with the lowest operating cost using a preferred fuel
Numeric variable
Displayed at the end of a run
Initialized to 0.000000

3 BEST FUEL
the preferred heating fuel type which results in the lowest operating cost (1=GAS, 2=OIL, 3=ELEC)
Numeric variable
Displayed at the end of a run

4 BEST COST
The lowest operating cost which uses a preferred fuel
Numeric variable
Displayed at the end of a run

5 STORIES
the number of stories in the building
Numeric variable

6 CLIMATE
the climate region in which the building is constructed (1=COLD, 2=TEMP, 3=HOT/COLD, 4=HOT/HUM, 5=HOT/ARID)
Numeric variable

7 BLDG SIZE
the size of the building (S=SMALL, M=MEDIUM, L=LARGE)
String variable

8 PREF FUELS
the four digit binary code representing user preferred heating fuel types
Numeric variable
Displayed at the end of a run
Initialized to 1000.000000

9 ROOF R
the recommended R value of roof insulation

Displayed at the end of a run

10 WALL R
the recommended R value of wall insulation
Numeric variable
Displayed at the end of a run

11 GLAZING
the recommended type of glazing
String variable
Displayed at the end of a run

12 UNOCCUP AC
the recommended number of air changes per hour during unoccupied hours
Numeric variable
Displayed at the end of a run

COMPANION PASCAL PROGRAM SOURCE CODE PRINTOUT

```
program casecost;
{ This program is called from an EXSYS run of SOBHn.
  The program reads PASS.DAT written by EXSYS which contains values for:

  BESTCASE     : 0/>0 = casecost has not/has been previously called
  CLIMATE      : 1-5 climate regions (temperate = 2)
  BLDG SIZE    : S/M/L = small/medium/large
  STORIES      : 1/2/4 = number of stories
  PREF FUELS   : 4 binary digit code ; elec/gas/oil ; 0/1 = F/T preferred

  The program then calculates the appropriate base case operating costs,
  determines the lowest cost base case, creates a single value containing
  base case number, fuel type, and operating cost; writes this value to a
  holding file, and returns the value to EXSYS via RETURN.DAT.
}
var
 m : array[1..12] of string[9];
 passfile, returnfile, holdingfile, basecasefile : text;
 rclimate, rstories : real;
 climate, stories : integer;
 bldgsize : char;
 preffuels : string[4];
 basecase, currentcase, lowcase, highcase : integer;
 casereal : real;
 bestcost, bestfuel, bestcase, bestvalue : real;
 worksheet : char;
 cost : real;
 gas, oil, elec : boolean;
 gasrate, oilrate, elecrate, demandrate : array[1..12] of real;
 gasuse, elecuse, demanduse : array[1..13] of real;
{ ******************** LOGO ************************* }
procedure Logo;
{ This procedure writes a message to the screen to let the user know that
  an external program has been called.
}
begin
 ClrScr;
 writeln;writeln;writeln;writeln;
 writeln('COMPARATIVE OPERATING COSTS ANALYSIS');
 writeln;writeln;
end;
{ ********************** READPASS ******************** }
procedure ReadPass;
{ This procedure reads the data written to PASS.DAT by EXSYS. }
begin
 assign(passfile,'PASS.DAT');
 reset(passfile);
 readln(passfile,bestcase);
 readln(passfile,rclimate);
 climate:= trunc(rclimate);
 readln(passfile,bldgsize);
 readln(passfile,rstories);
 stories:= trunc(rstories);
 readln(passfile,preffuels);
```

```
close(passfile);
end;
{ ************************ INIT MONTHS ****************** }
procedure InitMonths;
{ This procedure initializes the m array with string months of the year. }
begin
 m[1]:= 'January';
 m[2]:= 'February';
 m[3]:= 'March';
 m[4]:= 'April';
 m[5]:= 'May';
 m[6]:= 'June';
 m[7]:= 'July';
 m[8]:= 'August';
 m[9]:= 'September';
 m[10]:= 'October';
 m[11]:= 'November';
 m[12]:= 'December';
end;
{ *********************** INITBEST ********************* }
procedure InitBest;
{ This procedure initializes bestcost for determining minimum
  cost value, corresponding case number, and fuel type. }
begin
 bestcost:= 999.0;
end;
{ ************************ SETGOE ********************** }
procedure SetGOE;
{ This procedure sets gas, oil, and elec boolean variables to indicate user
  designated preferred fuels. The string values of characters 2-4 of preffuels
  are used for this purpose. }
begin
 if copy(preffuels,2,1) = '1' then
  gas:= TRUE
 else
  gas:= FALSE;
 if copy(preffuels,3,1) = '1' then
  oil:= TRUE
 else
  oil:= FALSE;
 if copy(preffuels,4,1) = '1' then
  elec:= TRUE
 else
  elec:= FALSE;
end;
{ ******************** DETERMINE WORKSHEET ******************** }
procedure DetermineWorksheet;
{ This procedure determines which SOBH worksheet to use based on user entered
  utility rate characteristics.
  The appropriate utility rates are then requested. }
var
 i : integer;
begin
writeln('Please select an analysis worksheet type based on your utility characteristics');
writeln;
writeln('Type A : 1. relatively uniform demand AND consumption charges
```

```
throughout the');
writeln('         year.');
writeln('Type B : 1. relatively uniform demand charges throughout the year with no');
writeln('         "ratchet" charges.');
writeln('       2. consumption rates with only seasonal changes.');
writeln('Type C : 1. complicated "rachet" clauses for demand.');
writeln('       2. consumption rates that depend on level of demand.');
writeln('       3. seasonal changes in demand and consumption rates.');
writeln('       4. separate heating and general service rates that require many');
writeln('          calculations.');
writeln('       AND Your HVAC system can be wired and metered to use these rates.');
writeln('                         *** WARNING ***');
writeln('       Selecting type C means having your utility company perform this');
writeln('       analysis instead of the program you are currently running.');
writeln;
write('Enter A, B, or C to indicate your choice: ');
readln(worksheet);
worksheet:= UpCase(worksheet);
writeln;
case worksheet of
 'A' : begin
       writeln('Please enter your annual utility rate for:');
       if gas then
        begin
         write('NATURAL GAS ($/therm): ');
         readln(gasrate[1]);
        end;
       if oil then
        begin
         write('NO.2 FUEL OIL ($/gallon): ');
         readln(oilrate[1]);
        end;
       write('ELECTRICITY  ($/kWh): ');
       readln(elecrate[1]);
       write('DEMAND RATE FOR ELECTRICITY ($/kW): ');
       readln(demandrate[1]);
      end;
 'B' : begin
       for i:= 1 to 12 do
        begin
         writeln('Please enter your utility rate for ',m[i],' for: ');
         if gas then
          begin
           write('NATURAL GAS  ($/therm): ');
           readln(gasrate[i]);
          end;
         if oil then
          begin
           write('NO.2 FUEL OIL ($/gallon): ');
           readln(oilrate[i]);
          end;
         write('ELECTRICITY ($/kWh): ');
         readln(elecrate[i]);
         write('DEMAND RATE FOR ELECTRICITY ($/kW): ');
         readln(demandrate[i]);
         writeln;
```

```
      end;
     end;
 'C' : begin
      writeln('I warned you about selecting type C !!!');
      writeln('I take no responsibility for the results of this program.');
      bestcost:= 0.0;
      bestfuel:= 0;
      bestcase:= 99;
     end;
end;
end;
{ ****************** SET CASE LOW AND HIGH ******************* }
procedure SetCaseLowHigh;
{ This procedure sets the range of prospective case numbers for a given
  building based on: climate, size, and number of stories. }
begin
lowcase:= climate * 100;
highcase:= climate * 100;
case bldgsize of
 'S' : begin
       lowcase:= lowcase + 1;
       highcase:= highcase + 8;
      end;
 'M' : begin
       if stories = 1 then
        begin
         lowcase:= lowcase + 9;
         highcase:= highcase + 18;
        end
       else
        begin
         lowcase:= lowcase + 19;
         highcase:= highcase + 28;
        end;
      end;
 'L' : begin
       if stories = 2 then
        begin
         lowcase:= lowcase + 29;
         case climate of
          1 : highcase:= highcase + 40;
          2..3 : highcase:= highcase + 38;
          4..5 : highcase:= highcase + 34;
         end;
        end
       else
        begin
         case climate of
          1 : begin
               lowcase:= lowcase + 41;
               highcase:= highcase + 52;
              end;
          2..3 : begin
                  lowcase:= lowcase + 39;
                  highcase:= highcase + 48;
                 end;
```

```
        4..5 : begin
               lowcase:= lowcase + 35;
               highcase:= highcase + 40;
              end;
        end;
       end;
      end;
end;
end;
{ ********************** CALCULATE COSTS ******************** }
procedure CalculateCosts;
{ This procedure calculates the operating cost for each qualifying base case.
  A base case qualifies if a preferred fuel is used for operation.
  Operating costs are calculated using user entered utility rates and base
  case usage levels listed in the SOBH base case database.
  The lowest base case operating cost is determined along with its base case
  number and fuel type. }
var
 mo : integer;
begin
 assign(basecasefile,'BASECASE.PRN');
 reset(basecasefile);
 repeat
  readln(basecasefile,casereal);
  basecase:= trunc(casereal);
 until basecase = lowcase;
 for currentcase:= lowcase to highcase do
  begin
   { read SOBH database values for the current basecase }
   for mo:= 1 to 13 do
    read(basecasefile,gasuse[mo]);
   readln(basecasefile);
   for mo:= 1 to 13 do
    read(basecasefile,elecuse[mo]);
   readln(basecasefile);
   for mo:= 1 to 13 do
    read(basecasefile,demanduse[mo]);
   readln(basecasefile);
   readln(basecasefile);
   { determine whether or not this basecase uses gas/oil as a heating fuel }
   if gasuse[13] <> 0.0 then
    begin
     { calculate gas/oil operating cost if gas or oil is a preferred fuel }
     { if operating cost is lower than current best cost then replace best cost }
     if gas then
      begin
       case worksheet of
        'A' : cost:= gasuse[13]*gasrate[1]+elecuse[13]*elecrate[1]+demanduse[13]
                     *demandrate[1];
        'B' : begin
               cost:= 0.0;
               for mo:= 1 to 12 do
                cost:= cost + gasuse[mo]*gasrate[mo]+elecuse[mo]*elecrate[mo]
                        +demanduse[mo]*demandrate[mo];
              end;
       end;
```

```
      if cost < bestcost then
       begin
        bestcost:= cost;
        bestfuel:= 1;
        bestcase:= currentcase - (int(currentcase / 100.0) * 100.0);
       end;
     end;
    if oil then
     begin
      case worksheet of
       'A' : cost:= gasuse[13]*0.77*oilrate[1]+elecuse[13]*elecrate[1]
                              +demanduse[13]*demandrate[1];
       'B' : begin
              cost:= 0.0;
              for mo:= 1 to 12 do
               cost:= cost + gasuse[mo]*0.77*oilrate[mo]+elecuse[mo]
                                  *elecrate[mo]+demanduse[mo]*demandrate[mo];
             end;
      end;
      if cost < bestcost then
       begin
        bestcost:= cost;
        bestfuel:= 2;
        bestcase:= currentcase - (int(currentcase / 100.0) * 100.0);
       end;
     end;
   end
  else
   { electricity is the heating fuel for this base case, if electricity is a
     preferred fuel than calculate operating cost and see if this is the new
     best cost, if best cost then replace all bests }
   if elec then
    begin
     case worksheet of
      'A' : cost:= elecuse[13]*elecrate[1]+demanduse[13]*demandrate[1];
      'B' : begin
             cost:= 0.0;
             for mo:= 1 to 12 do
              cost:= cost + elecuse[mo]*elecrate[mo]+demanduse[mo]*demandrate[mo];
            end;
     end;
     if cost < bestcost then
      begin
       bestcost:= cost;
       bestfuel:= 3;
       bestcase:= currentcase - (int(currentcase / 100.0) * 100.0);
      end;
    end;
  end;
 close(basecasefile);
end;
{ ******************** WRITE HOLDING FILE ********************** }
procedure WriteHoldingFile;
{ This procedure combines bestcost, bestfuel, and bestcase into a single
  value. This single value is written to a holding file in case EXSYS calls
  this program again. The value is returned to EXSYS via RETURN.DAT.
```

```
 BEST CASE NUMBER = INT(VALUE / 1000)
 BEST FUEL = INT((VALUE - BEST CASE # * 1000) / 100)
 BEST COST = VALUE - BEST CASE # * 1000 - BEST FUEL * 100 }
begin
 bestcase:= bestcase - int(bestcase / 100.0) * 100.0;
 bestvalue:= bestcase * 1000.0 + bestfuel * 100.0 + bestcost;
 assign(holdingfile,'HOLDING.DAT');
 rewrite(holdingfile);
 writeln(holdingfile,bestvalue:8:2);
 close(holdingfile);
end;
{ ********************** READ HOLDING FILE ********************** }
procedure ReadHoldingFile;
{ This procedure reads bestvalue from the holding file. }
begin
 assign(holdingfile,'HOLDING.DAT');
 reset(holdingfile);
 readln(holdingfile,bestvalue);
 close(holdingfile);
end;
{ ********************** WRITE RETURN FILE ******************** }
procedure WriteReturnFile;
{ This procedure writes bestvalue to RETURN.DAT for return to EXSYS. }
begin
 assign(returnfile,'RETURN.DAT');
 rewrite(returnfile);
 writeln(returnfile,bestvalue:8:2);
 close(returnfile);
end;
{ ********************* MAIN PROGRAM ************************ }
begin
 Logo;
 ReadPass;
 if bestcase = 0.0 then
  begin
   InitMonths;
   InitBest;
   SetGOE;
   DetermineWorksheet; { and request appropriate utility rates }
   SetCaseLowHigh;
   CalculateCosts;     { and determine best cost }
   WriteHoldingFile;
  end
 else
  ReadHoldingFile;
 WriteReturnFile;
end.
```