An Expert System for Determining Compliance with the Texas Building Energy Design Standard[1]

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ABSTRACT

Demonstration of compliance with the Texas Building Energy Conservation Design Standard involves completion of a summary checklist for each of its sections. This manual checking is tedious. Furthermore, no comprehensive documentation of the user's compliance is provided and the compliance checker must manage the data collected. To assist designers in complying with the Standard and to reduce the time required, the Center for Energy Studies (CES) at the University of Texas at Austin has developed an expert system to serve as both the compliance procedure and its documentation. This expert system directs the user with queries (screen menus), prompting the user for all relevant information. A graphical user interface has been developed to facilitate quick navigation through the Standard, easy data entry, and identification of compliance failures. This paper describes the research approach to the expert system, the system features, current status of project, and the benefits to be derived from this innovative compliance tool.

1.0 INTRODUCTION

The Texas Energy Conservation Design Standard for New State Buildings provides architects, designers, and builders with guidelines for designing more energy efficient nonresidential buildings (14). The Standard applies to state-owned facilities and contains criteria for the building envelope and for electrical, mechanical, lighting, and service water heating systems and equipment. The Standard is essentially equivalent to the ASHRAE Standard 90.1 although the envelope design criteria have been particularized for Texas climatic conditions (1).

For compliance, planners must show that designs satisfy the basic requirements and also meet compliance via the system/component method or the building energy cost budget method. Basic requirements are those criteria that must be met for all sections of the Standard and most often relate to sources of technical data or calculations. There are basic criteria for electric power, lighting, other systems/equipment, building envelope, HVAC systems, HVAC equipment, service water heating, and energy management.

For compliance checking, the Standard offers a checklist that summarizes the basic and the prescriptive requirement provisions. The list provides a straightforward way of keeping track of which provisions have been complied with and which have not. Once the compliance check is complete, the designer submits a signed statement to SECO certifying that the design is in compliance with the Standard. Since no itemized record of the compliance process is delivered to the SECO, no verification is attempted by that office.

To better assure compliance with the Standard, a compliance review process was recently developed by CES in conjunction with the Texas General Services Commission. In this process an advisory team of local energy consultants meets with the design team at key points in the design process to evaluate compliance and to advocate energy efficient design.

However, it is evident that documentation of the process needs improvement. The compliance checklist may be expanded and computerized to reduce the time required to show compliance. This project was undertaken to develop a computerized version of the Standard based on expert systems programming. Such a tool could provide improved management of the information needed for compliance checking, reduce the burden on designers, and automatically document the user's response to the process. Moreover, questions asked in the computer screens of the expert system would guide the user through compliance and tailor questioning to the user's data input or previous responses.

This paper documents the development of the expert system version of the Standard. Because its development is not yet complete, only the HVAC Systems section of the Standard (Section 9) is described here. In addition to the HVAC Systems section, sections on Lighting, Envelope, and HVAC Equipment are complete and are undergoing testing.

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2.0 RESEARCH OBJECTIVES

The central objective of this project is to develop a prototype computerized application which represents the goals of the Standard and reduces the time and resource investment required for compliance checking. Section 9 is the pilot section for initial system development. Experience gained during the development of this section is being applied to transforming other sections of the Standard into the expert system structure.

The computer application documents information provided by the user during consultation sessions. When compliance checking is complete, the entered data and conclusions reached by the application must be retrievable for review by the designers or by state officials. The application's interface should provide a straightforward means for the user to respond to the system and to query the system for explanatory information. Progression through sections of the Standard should be smooth and sufficiently referenced to make clear what sections the user is currently working on, what sections have been completed, and what sections are incomplete.

While helping the user through compliance examination, the application should make recommendations for corrective measures when compliance is not met. Also, recommendations for improvements should be provided when the opportunity to do so arises. The application must provide a straightforward procedure to modify or update previously entered data.

3.0 SOLUTION APPROACH

The solution approach is to develop an expert system to guide the designer through the compliance checking process. Expert systems combine expert-level knowledge and inferencing procedures to create a model of human problem solving capacity within a domain. In this case, the need is for an expert system that mimics an energy efficiency expert who interviews designers regarding a project. The expert would guide the designer through the compliance process and would possess an awareness of what information has been obtained and what information to request next.

During such consultations the expert can supply information, on request, that helps to clarify the question posed. Thus, the expert can tailor the level of detail to match the knowledge of the designer. Figures 1 and 2 illustrate the process that an expert may utilize to determine if a project complies with the Standard.

Figure 1 shows a schematic representation of the procedure used by an expert to determine compliance.

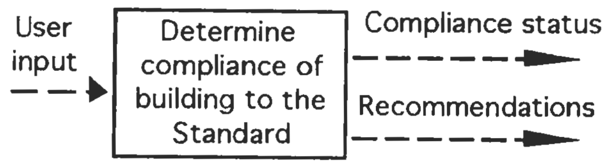

Figure 1: Black box representation of the problem.

The designers provide the information regarding the building to the expert. The information is then processed and conclusions regarding compliance are returned to the designer.

A first-level function structure for an expert system performing the tasks of Figure 1 is shown in Figure 2. Information is passed through the boundary via the "Interface" function. This can be an interview wherein the expert directs the designer through provisions of the Standard. In the "Inference Engine" function, the expert takes information gained from the interview and applies the "Knowledge Base" of the Standard to determine compliance and recommendations. "Working Memory" represents a storage area where the expert keeps information provided by the designers. Results of the consultation are returned to the designer via the "Interface" function. The knowledge base represents a computerized form of human expertise in a domain.

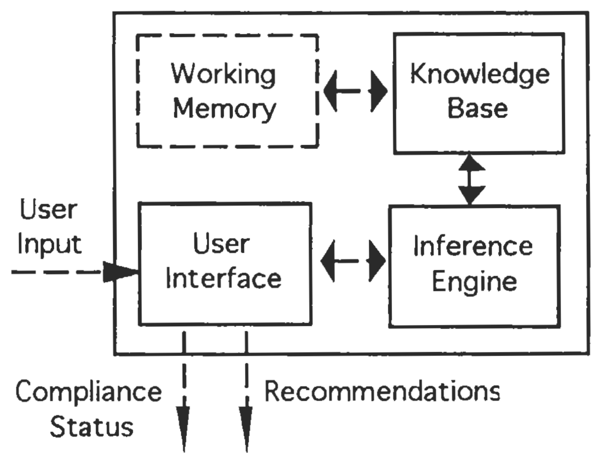

Figure 2: Expert system first-level function structure, parallel to human expert's function structure.

After considerable research on available expert system shells, the EXSYS Professional (development package) was selected as it provides a menu-driven environment allowing for quick and efficient generation of the rules encountered in the Standard (7).

4.0 HVAC-RELATED EXPERT SYSTEMS

Several expert systems have been developed within the HVAC domain, some of which are intended to assist with HVAC system design (5) and selection (13). Other expert systems have been developed to perform diagnostic functions on HVAC equipment (6). One ambitious system was the Knowledge-Aided Design System for Energy-Efficient Buildings (KADE) system, which provides assistance for design with simultaneous consideration of architectural and mechanical aspects (12). Another analysis system was intended to determine the HVAC system retrofit potential of public buildings (8). In the literature search for this project, no HVAC-related compliance checking expert systems were found. However, there is a compliance checking system for local Vancouver, Washington, building codes, which is used to determine appropriate spatial separation between residences (10).

Developers of these systems saw that modularization of the functions and tasks of the expert system were necessary. Camejo and Hittle separated their knowledge bases into three phases of HVAC system design: prefeasibility study, facility design, and system design. The KADE system also had several knowledge bases devoted to specific aspects of a building's design. This modular approach to knowledge representation will be significant when more sections of the standard are transformed into the expert system format.

Heikkila and Blewett showed that even with an accurate knowledge base, end user consideration is a necessity (10). Although Vancouver officials declared that the plan-checking expert system was "remarkably consistent and accurate," their primary focus was the accuracy of the knowledge base. Plan checkers found the data entry interface was cumbersome and complained about the lack of a graphical interface. They concluded that careful consideration must be given to the scope of the application, the impact of the system on the role of the users within the organization, the type of reasoning employed (chaining methods), and the user interface.

5.0 THE DEVELOPMENT PROCESS

As applied to the Standard the expert system development process can be divided into four stages: problem definition, solution justification, system development, and system implementation. The previous sections have identified the need for an alternative to manual compliance checking and have proposed the expert system approach as the solution. The following sections discuss solution justification through system implementation.

5.1 Justifying the Expert System Approach

An expert system is well suited to the Standard's compliance problem. To use an expert system effectively, sources for expert level knowledge must exist. Such knowledge is available in the Standard and its *User's Manual* (2). Furthermore, the function structure for a human expert and that for the expert system have essentially the same functions when applied to compliance-checking issues. Expert systems offer an interactive environment in which the user receives direction and assistance during the compliance-checking process. Shams and his colleagues also indicate that expert systems may be useful for showing compliance to HVAC installation codes (13). Culp envisioned intelligent CAD systems that would remind designers of applicable building codes when considering their design options (6).

Heikkila and Blewett's expert system shows that written standards and codes, including HVAC systems criteria, can be transformed into a knowledge base (a set of if-then rules in this case). According to Ignizio, problems that may be addressable by expert systems are those with a narrow and stable problem domain, a preponderance of heuristic rather than algorithmic procedures, and symbolic rather than numeric values (11).

The Standard fits these expert systems attributes well. It is a relatively stable document. In 1989, the first version of the Texas Standard appeared and the latest release appeared in 1993. Revisions have been few. Furthermore, the knowledge contained in the Standard is generally based on heuristics rather than algorithms. This leads to attribute values that are symbolic rather than numeric.

The expected benefits of a compliance-checking tool also justify the expert systems approach. The Basden Benefits Model identifies three levels into which expert system benefits may be categorized: feature, task level, and role benefits (3). Table 1 lists some of the possible benefits at each level. Task level benefits are derived from feature benefits, and role benefits are derived from task benefits.

According to Basden, realization of the role benefits is key to the success of an expert system application. Availability of expert-level knowledge regarding the Standard certainly increases the chance that a building will be designed in accordance with accepted energy efficiency practices. The expert system will increase designer productivity by reducing the time spent on checking compliance. Productivity is enhanced by the expert system's ability to accommodate users of varying familiarity with the Standard.

The expert system may also improve the relationship between the HVAC system designer and the client. Although improvements in accuracy and thoroughness of compliance checking directly benefit

Table 1. Basden's Benefits Model as applied to an HVAC compliance-checking expert system.

Feature Benefits	Task Benefits	Role Benefits
Efficient input/output	Reduce checking time	Improve building designs
Progress tracking	Reduce costs	Increase designer productivity
Clear on-line help	Improve training/availability of knowledge	Improve designer/client relationship
Accurate failures explanation	Improve checking accuracy	Improve enforcement of Standard
Easy data revision	Improve data management	

the designer, clients gain assurance that the design follows the requirements of the Standard. From the perspective of state officials who review design submittals, this documentation of compliance is a significant improvement over the current checklist method. Finally, enforcement of the Standard is clearly improved because the expert system provides a documented record of the user's compliance process.

5.2. Acquiring the Knowledge

The HVAC section of the Standard has many requirements and the textual format can sometimes hinder understanding of the relationships among sections. Its "Standard-type language" also contributes to confusion. Therefore, a decision tree, which contains text combined with a graphical structure that visually suggest relationships among sections, was developed for Section 9 to help clarify the Standard requirements and its organization. The advantage of such a schematic is that the developer automatically gets a global view of the section before the knowledge representation phase begins.

The decision tree serves as the source for developing the knowledge base. For example, Figure 3 shows a portion of the decision tree that deals with Section 9.5.6 (System Temperature Reset Controls). Section 9.5.6 has subsections for air system and hydronic system temperature resets, both of which must be satisfied before temperature controls are acceptable. In turn, each subsection has one or two requirements that the design must satisfy. Note also that the subsections have possible exceptions. Exceptions sometimes are not independent of other sections of the Standard. The first exception in both subsections requires that the design meet the requirements of Sections 9.5.2 and Sections 9.5.5.2, respectively, without exceptions. The knowledge in the tree diagram form clearly shows the relationship between sections and provides a quick read of what is required of the design.

5.3 Representing the Knowledge

Besides serving as a source for constructing the knowledge base, the decision tree is also a form of knowledge representation. In this case, it is an intermediate step towards compiling an if-then rule set that represents the knowledge for HVAC compliance checking.

As an illustration, the rules for Section 9.5.6 are developed using the tree segment shown in Figure 3. The figure shows that to pass the compliance check, the design must satisfy both Sections 9.5.6.1 and 9.5.6.2, Air Systems and Hydronic Systems, respectively. The rules thus far are:

Rule 1:

IF Section 9.5.6.1 Air Systems *passes*
AND Section 9.5.6.2 Hydronic Systems *passes*
THEN Section 9.5.6 System Temperature Reset Controls *passes*

Rule 2:

IF Section 9.5.6.1 Air Systems *fails*
OR Section 9.5.6.2 Hydronic Systems *fails*
THEN Section 9.5.6 System Temperature Reset Controls *fails*

Rule 3:

IF Systems with supply to multiple zones *include automatic reset for supply air temperature*
AND Temperatures are *capable of being fully reset*
THEN Section 9.5.6.1 Air System *passes*

Rule 4:

IF Systems supplying heated water to comfort conditioning systems *include automatic reset for supply water temperature*
AND Temperatures are *capable of being fully reset*
THEN Section 9.5.6.2 Hydronic System *passes*

Rule 5:

IF Systems with supply to multiple zones *do not include automatic reset for supply air temperature*
AND Air systems exceptions *are acceptable*
THEN Section 9.5.6.1 Air System *passes*

Rule 6:

IF Systems supplying heated water to comfort conditioning systems *do not include automatic reset for supply water temperature*

AND Hydronic system exceptions *are acceptable*

THEN Section 9.5.6.2 Hydronic Systems *passes*

The above rules are considered pseudo rules because they are rule statements in English and therefore are not in the symbolic format required by the inference engine. The pseudo rules are used here for convenience. Rules 1 through 6 consist of object-attribute-value triplets in the premise and conclusion clauses. The italicized text indicates the value portion of a clause, while the normal text represents the object and attribute part of the clause.

This example illustrates how the knowledge tree is used to construct rules. The inference engine determines, through Rules 5 and 6, if the exceptions to the automatic temperature reset requirements are met. The example also shows that production rules can be derived naturally from the knowledge tree. No prior knowledge of expert system development is required to interpret the requirements. The EXSYS Professional rule editor, used as the expert system shell in this project, provides a menu-driven environment that allows for quick and efficient generation of rules (7).

The expert system directs the compliance process through complex relationships among sections of the Standard, relieving the designer of the responsibility for recognizing relationships among sections. This is illustrated above where Section 9.5.6 requirements depend on the requirements of Section 9.5.5.

The structure of the knowledge base influences the rule analysis strategy chosen and the order of the rules. Figure 4 shows that Section 9 has four subsections, of which only Sections 9.4 and 9.5 are divided into subsections. Note that the structure of Section 9 strongly resembles the search space given in Figure 5. In both cases, at all levels the possible outcomes are known and are few in number. For compliance there are only two possible outcomes: the design either passes or fails. For this structure, Harmon suggests using backward-chaining and depth-first searching methods (9).

In backward chaining, the inference engine begins with the conclusions and traces backwards in the knowledge structure in an attempt to validate the conclusion. In depth-first searching, in contrast to breadth-first searching, the inference engine follows a single branch to its greatest depth, rather than searching all branches at the highest level.

5.4 User Interface

The user interface is the information link between the expert system and the user. Systems as recent as the Heikkila system failed to give

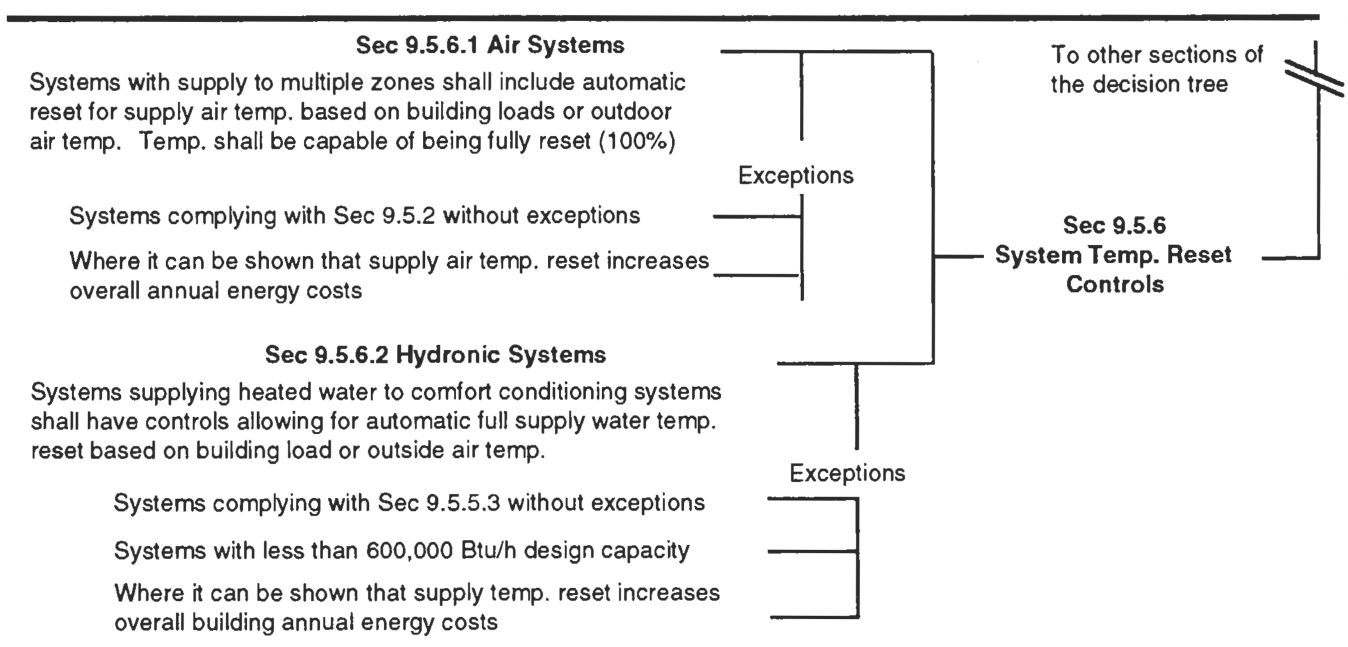

Figure 3: Excerpt from the decision tree for Section 9 HVAC Systems.

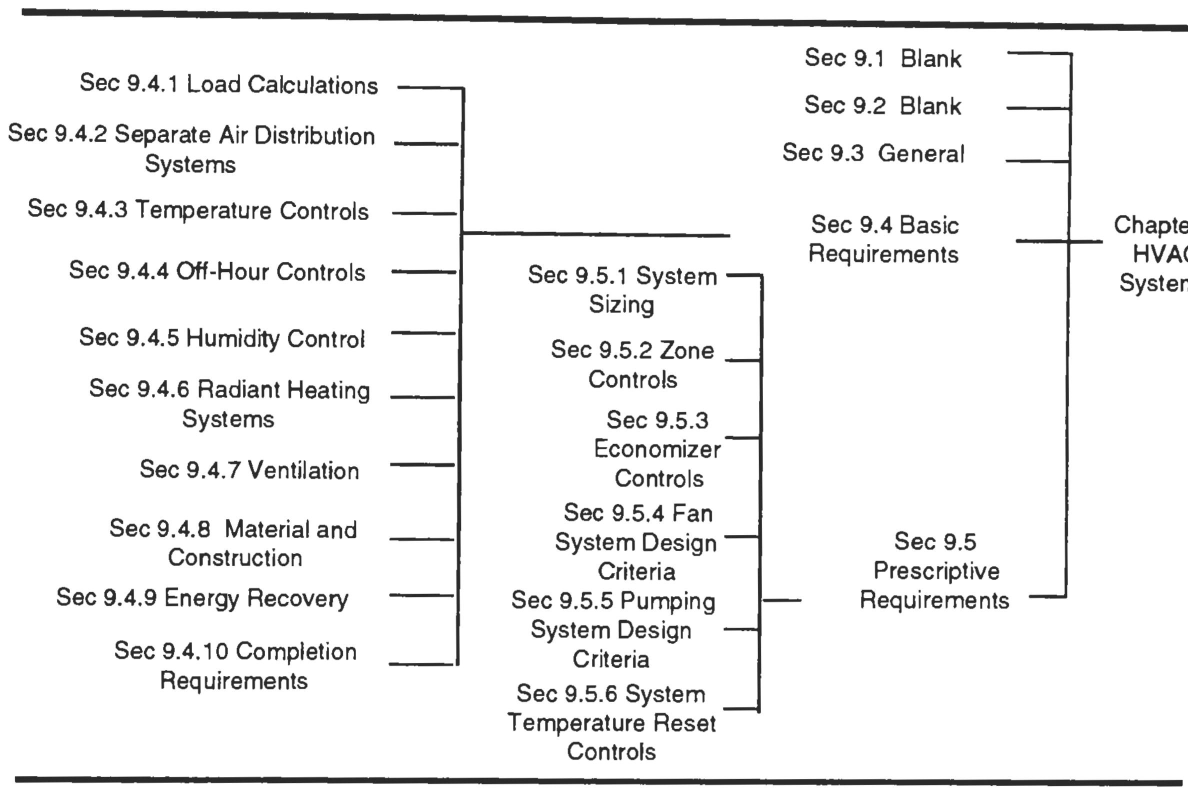

Figure 4: The structure of Section 9.

significant consideration to the user interface only to find that the user interface is indeed critical to the success of the system (10). In the case of building an expert system for HVAC compliance, the development of the user interface is at least as important as knowledge acquisition and knowledge representation. For development of the user interface, Berry considers dialogue control, explanation facilities, user models, and evaluation to be the primary elements (4).

5.4.1 Dialogue Control. During query sessions, the expert system presents the user with a question accompanied by possible choices, which may be as simple as "yes" or "no" or may be a list of design choices. Continuing with the temperature reset controls example, Figure 6 shows a typical query screen where the question is followed by "yes/no" choices which are represented by "radio" buttons that toggle between "yes" and "no." At the top left of the screen is a label showing the current section of the Standard under consideration. Opposite this is one showing whether the user is working on the basic requirements or prescriptive requirements. The "Help" button provides explanations of the question asked or additional information from the Standard.

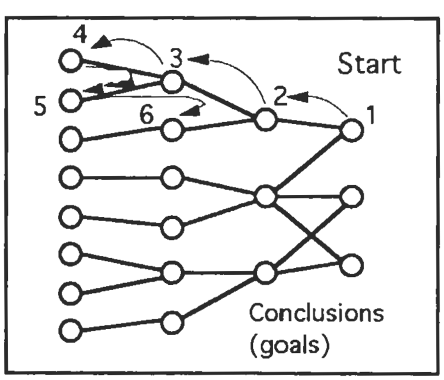

Figure 5: The search space structure suitable for backward-chaining and depth-first searching (9).

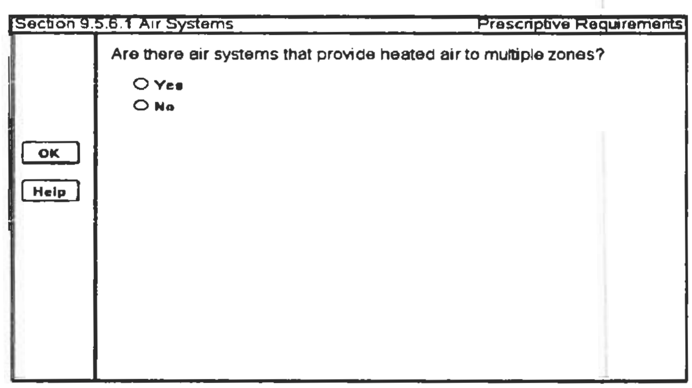

Figure 6: Sample query screen showing yes/no radio buttons.

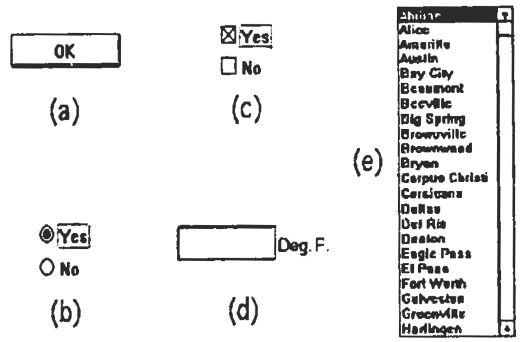

Figure 7: Screen input elements. (a) push button, (b) radio button, (c) check box, (d) edit region, (d) list box.

Other input elements—such as list buttons, check boxes, and edit regions—are used in various screens in the system. Figure 7 shows samples of these screen input elements. List buttons give possible choices from which the user may select, for example, the location of the building that defines the climatic condition. Check boxes are used when a question has multiple valid responses, whereas edit regions are used when the user must type a response.

Berry emphasizes that user initiative during the consultation enhances the acceptability of an expert system. Figure 8 shows a menu in which each push button at the end of a branch represents a section of the Standard. When selected, the "Section 9 HVAC Systems" button displays summary reports generated from Sections 9.4 and 9.5. A hard copy of these reports is generated when the user selects "Print," whereas the "Exit" button ends the consultation session.

Pressing the buttons labeled "Section 9.4" or "Section 9.5" takes the user to those subsections of the Standard, in whatever order the user selects, beginning the consultation. In Figures 9 and 10, which depict the basic and prescriptive criteria subsections, selecting "Main Menu" returns the user to the section-level tree schematic. To view the summary/results of the subsections on screen, the user may select "Section 9.5 Basic Req." or "Section 9.5 Pres. Req."

Three colors are used to show the status of compliance. Initially, the connecting lines that form the branches are black to indicate that a section has not been addressed. Once a section is complete, the result is success (branch is colored green) or failure (branch is colored red).

5.4.2 Change/Rerun Screens. Once a section has been completed, the option exists to change the inputs or to correct errors. To modify the inputs, the user selects the section's button again to display a change/rerun screen. Figure 11 shows such a change/rerun screen for Section 9.5.6.

On the upper region of the screen is a summary of the questions presented by the system and the answers provided by the user during a consultation. All questions posed and answers given are documented, preceded by markers to indicate their

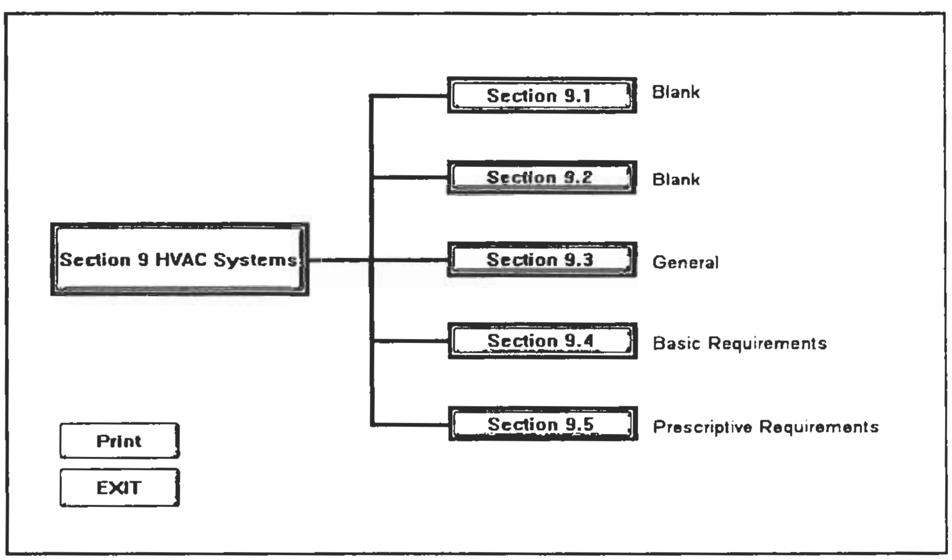

Figure 8: Branch structure for Section 9.

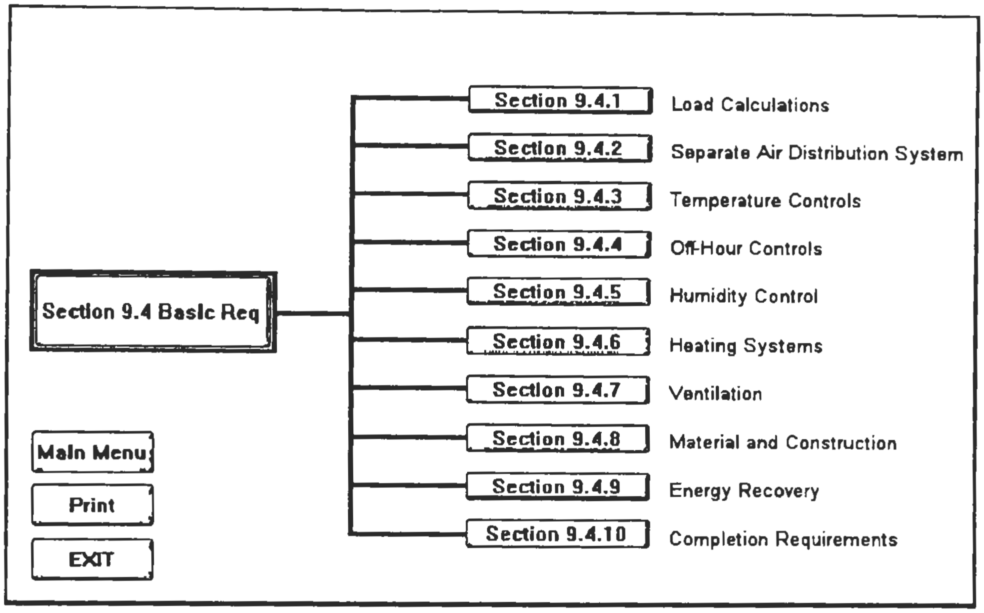

Figure 9: Schematic of basic requirements.

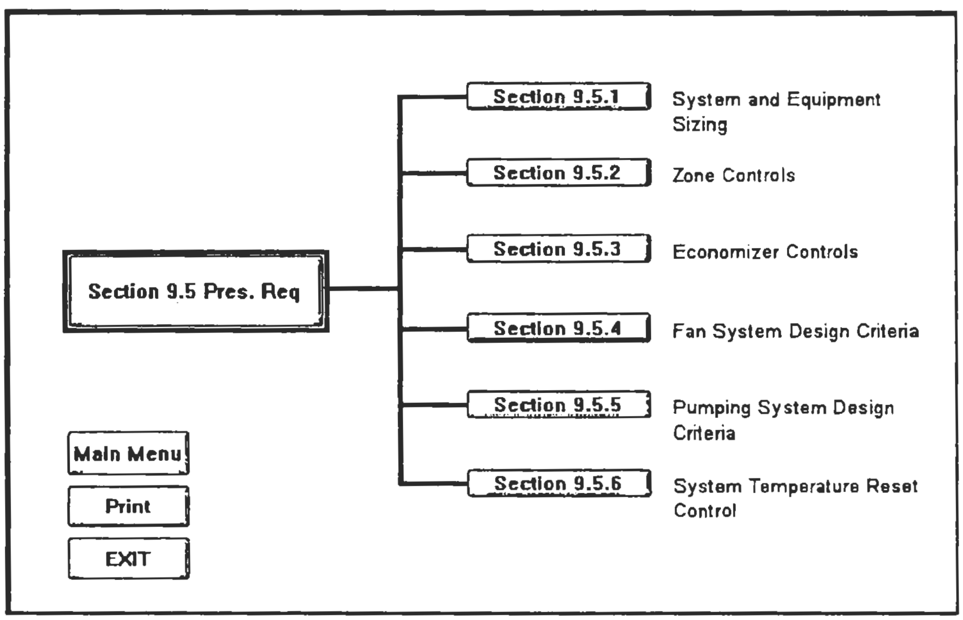

Figure 10: Schematic of prescriptive requirements.

status: "OK," "Pass," or "Fail." "OK" is used for qualifiers and variables that do not directly pass or fail a design but are used to direct the questioning session.

The list box at the lower left of the change/rerun screen lists the first few words from the qualifier and variable text used during the consultation. The user may change a value for any qualifier or variable by selecting the appropriate entry in the list box. Once a selection is made, clicking "Change" will signal the expert system to present the question to the user again, after clearing all rules pertaining to the section and then rerunning the rule with the updated information. The user is then returned to the tree showing the prescriptive requirement branches with updated color indicators.

5.4.3 Explanation/Help Features. The expert system shell includes several features used to provide assistance during consultations. The shell provides for the use of stored information that is linked by

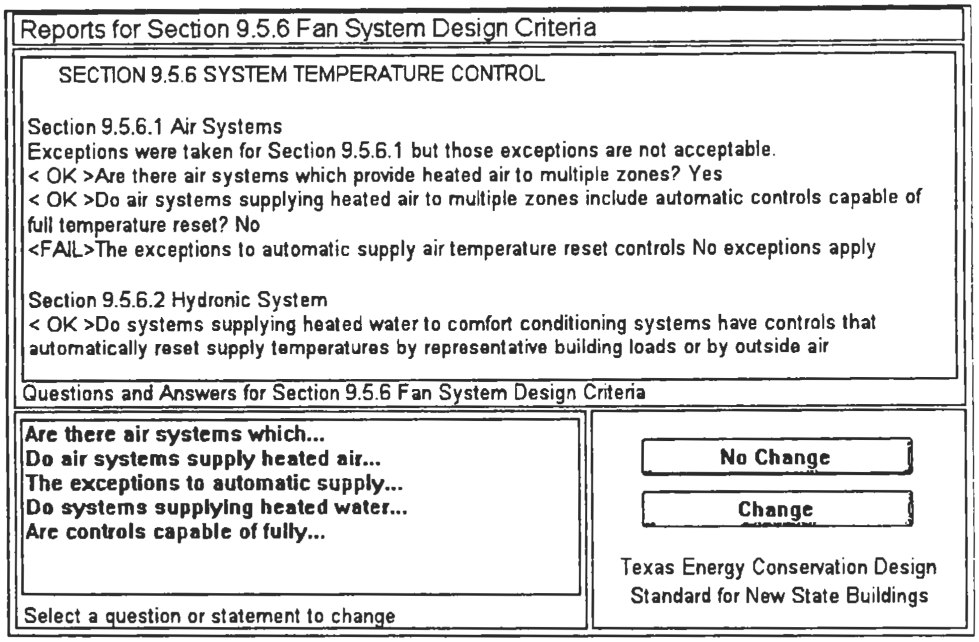

Figure 11: The change and rerun screen for Section 9.5.6.

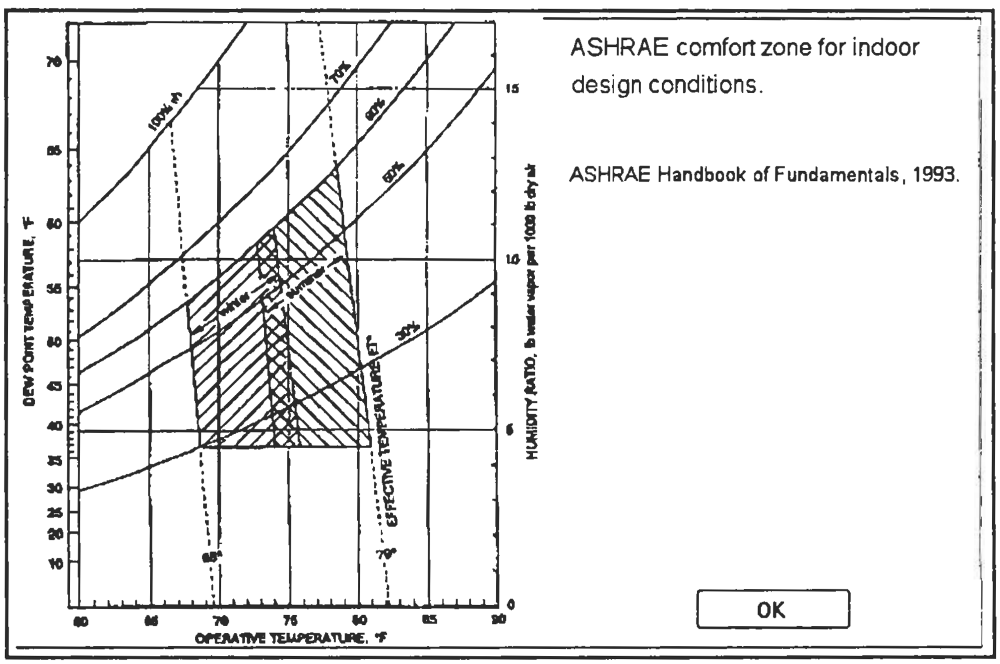

Figure 12: The ASHRAE comfort zone illustrated to help users select the appropriate indoor design conditions.

"Help" buttons and hypertext phrases. Information may be text or graphics compiled from the *Standard User's Manual* or from sources cited by the Standard. Figure 12 shows a sample help screen that provides the ASHRAE comfort chart to assist the user in selecting appropriate indoor design conditions.

5.4.4 Testing and Evaluation. Evaluation of the user interface has been conducted on an informal basis. Weekly demonstrations of the expert system to domain experts yielded discussions not only on the knowledge base but also on the user interface design. Although the system is fully operational, it has undergone only preliminary testing; full testing will await a prototype system that includes multiple sections of the Standard (HVAC Systems, HVAC Equipment, Envelope, and Lighting).

6.0 CONCLUSIONS

This project has demonstrated that an expert system is a highly useful solution to compliance checking of the Texas building energy design Standard. The expert system that has been developed greatly simplifies the determination of compliance with the Standard and provides essential documentation for compliance checking.

Additional benefits include graphical data entry features that make answering the expert system's queries an easy task. Stored text and images accessible via "Help" buttons and hypertext phrases help guide users in understanding the Standard's requirements. Menu screens have labels that keep users aware of the section, question, or requirement being addressed. In addition, colored branches on the tree schematics indicate the progress made during consultation. When failures are indicated, a change/rerun screen, which provides notes describing the nature of the failure, can be called.

7.0 RECOMMENDATIONS

In the development of the expert system, limitations in the interface features of the shell were reached when advanced features were developed. For example, to develop the change/rerun screens we found that the knowledge base and the user interface features had to be integrated. An alternate approach would be to imbed the inference engine within a graphical user interface (GUI) application. With such a structure users could quickly develop new portions of the knowledge base without the complications of user interface elements.

In the expert system shell that we used, each query screen (qualifier or variable) requires code to specify the screen's appearance and operation. Since there are hundreds of qualifiers and variables, screen coding is a major task. If a separate GUI language were to be used to develop suite-general screens to accommodate the varying query types, the screen definitions could be reduced from hundreds to no more than ten.

Our development of Section 10 (HVAC Equipment) of the Standard indicates that such an approach is feasible. Since Section 10 depends heavily on input from tabular data, input is cumbersome using the expert system shell. Therefore, in that section Microsoft Visual Basic 4.0 is being used to develop applications, which are called as subroutines by the expert system, to format large data tables.

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