NBSIR 86-3323

Outline of an Expert System Approach to Residential Air Infiltration

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

Abstract

As a demonstration of the appropriateness and usefulness of expert systems to the field of building construction and maintenance, an application to residential air infiltration is considered. This particular problem area appears to be particularly well-suited to an expert system approach due to the uncertainties associated with infiltration and ventilation in buildings and the large amount of experience that has been obtained by energy auditors, "house doctors," designers, and builders. This report presents the results of an effort to identify an appropriate expert system approach to residential air infiltration for use in the subsequent development of a working system. The intended approach and goals of the expert system are presented, along with the structure of the knowledge base. Resources for developing the knowledge base are also identified and discussed.

Key Words: Air infiltration; artificial intelligence; energy auditing; expert systems; residential buildings

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1. INTRODUCTION

Expert systems have been receiving increasing attention as a means of applying the techniques of artificial intelligence to real-world problems. The building construction field has considered the application of expert systems to some of its particular problems (Lansdown 1982, Clifton et al 1985). Several features of expert systems determine their applicability to a particular domain (Forsyth 1984, Hayes-Roth et al 1984). These features include the ability to provide useful solutions to problems with uncertain data and incomplete information, to "explain" this reasoning, and to expand incrementally as new knowledge is identified. In addition, expert systems are generally restricted to specific domains in which human expertise exists. For these reasons air infiltration in residential buildings was selected as a problem area for demonstrating the applicability of expert systems to the building construction field.

Expert systems are most appropriate to domains characterized by uncertain data and incomplete information. A computational computer approach to analyzing building infiltration would calculate the quantities of interest by applying computational algorithms to a numerical model of a house. While there is sufficient physical understanding to determine infiltration rates, airflow rates into and out of specific locations, and interior contaminant concentrations, moisture levels and temperatures in this manner, the calculation of these quantities is prevented by the inability to determine all of the required inputs. One must know the location and leakage characteristics of every opening in the building envelope and in interior partitions. In addition, wind pressure coefficients must be known over the building envelope as a function of wind direction. The determination of indoor contaminant and moisture levels requires values for interior source strengths and outdoor concentrations as a function of time. Such detailed knowledge about a specific building is generally unobtainable without intensive instrumentation and study. Even if all such information is available, it is not clear whether a detailed computational approach is required to deal with the types of problems that are encountered in the real world. Alternatively, an expert system can deal with the more realistic situation in which there is incomplete knowledge of a home's detailed infiltration characteristics, but valuable nonquantitative information is available.

The air leakage problems that the expert system is intended to deal with concern several aspects of building performance including heat loss and gain, thermal comfort, moisture levels and condensation, and indoor air quality. Although insufficient information is generally available to precisely quantify these factors for any given house, existing expert knowledge does exist to take an incomplete and somewhat uncertain characterization of the home and draw valuable conclusions regarding these air leakage issues. The domain of the proposed system is restricted to residential buildings, specifically single family units and rowhouses, because there is more knowledge and experience concerning these building types than for larger residential and commercial buildings. In recent years, efforts to conserve energy in homes has resulted in a body of knowledge regarding design and construction defects in existing buildings, retrofit strategies for their repair, and alternative design details to avoid such problems in new construction. Most of this knowledge has been developed through detailed energy audits and retrofits in existing buildings and successful attempts to prevent air leakage problems in new construction.

The expert system described in this report is intended to be used by nonexpert auditors, familiar with basic home construction. In the past such auditors have generally employed "pencil-and-paper" approaches, lasting about one hour, to evaluate a home's energy performance. These audits consider only general attributes of the house without recognizing the complexity of building thermal characteristics and the importance of unexpected leakage sites or "anomalies." Such audits generally involve surveys of insulation levels, condition of windows and doors, mechanical equipment type, and other factors, but neglect other important factors such as leaks in attic floors, convective loops within the building, basement air leakage and other obscure air leakage sites. Based on various guidelines these audits produce suggestions regarding retrofit actions, but due to the limited scope of the audits, the suggestions do not include many important air leaks and are generally not designed to diagnose the causes of existing air leakage problems.

On the other hand, a more extensive audit procedure, often referred to as "house doctoring," involves the use of instrumentation to examine the building envelope and equipment in detail (Diamond et al 1982, Energy Resources Center 1983, Harrje et al 1979 and 1980). In addition to suggesting retrofits, simple defects are actually repaired at the time of the audit. House doctoring is not a standardized procedure, and different individuals and organizations have developed their own approaches. A house doctor visit generally involves two person-days. In order to find air leakage sites, a house doctor employs fan pressurization, infrared thermography, and other techniques to locate air leakage sites (ASTM 1985, Harrje et al 1979 and 1980, Keast 1978, Socolow 1978). The use of these procedures enables one to locate unexpected air leakage sites and other thermal defects in the building envelope. These unanticipated defects can constitute a more significant portion of the energy loss of a home than the more mundane leaks considered by "pencil-and-paper" audits. The latter variety of leaks, such as those associated with windows and doors, generally account for only a small percentage of the total leakage of a house (ASHRAE 1985). Most of the leaks are due to a variety of other, less obvious and often elusive, sources.

House doctors have inspected thousands of homes in North America and obtained a great deal of experience regarding the location and significance of air leakage sites. In some cases, extremely experienced house doctors can anticipate construction defects and other leakage problems without the use of instrumentation from knowledge of a house's age, construction style and geographic location. In addition to thermal defects in the building envelope, expert house doctors have experience with, and a general understanding of, other air leakage related issues such as thermal comfort, condensation and moisture damage, and indoor air quality. The experience of these expert house doctors and other building performance experts constitutes a valuable and useful resource for analyzing air leakage problems in homes without the use of instrumentation and calculation models.

The basic goal of this expert system is to structure the knowledge of house doctors and other building performance experts regarding air leakage related problems in order to improve the effectiveness of procedures employed by less experienced auditors. Rather than employing a detailed, computational approach, the knowledge base obtained from experts and other sources will be combined with a description of a specific house, which is both incomplete and somewhat qualitative, to identify air leakage problems and their causes.

2. DESCRIPTION OF THE EXPERT SYSTEM APPROACH

2.1 Goals

The proposed expert system is intended to be used by on-site auditors familiar with home construction and building energy conservation, but not experts in the field. In the past such auditors have employed "pencil-and-paper" approaches to evaluating a home's energy performance. Such audits have been limited in the variety of leakage sites that they consider and have not taken advantage of the existing experience regarding heat loss sites, moisture issues, and indoor air quality. By providing such auditors with the benefits of this experience, the expert system will improve the effectiveness of their procedures and expand their scope to more than just retrofit recommendations.

The expert system is intended to deal with three basic situations or questions regarding air leakage as shown in table 1. The first is the diagnosis of the causes of existing air leakage problems. In this situation, the house has problems such as drafts, cold rooms, lingering odors, and moisture damage. The system will then be able to determine why these are occurring and suggest corrective action. For example, a severe draft in a second floor bedroom may be traced to air leakage sites associated with a second-story overhang. The second problem type in table 1 concerns the identification of air leakage related problems that are presently unknown to the user but which may be potentially serious in the future. These problems might involve the potential for moisture damage, excessive heat loss, or poor indoor air quality. For example, there may be significant, but undetected, air leakage from the occupied space to the attic through interior partitions. The final situation that the expert system is expected to address is retrofit planning. Given that the homeowner is contemplating air leakage and/or other retrofits to the building, the system determines the most appropriate and effective retrofits and anticipates potentially adverse side effects of the proposed retrofits. The expert system under consideration is intended to be able to explore the three questions in table 1 for existing homes, but the potential exists for expanding the system to include the anticipation of air leakage problems in new buildings at the design stage.

Table 1 Problem Types of the Expert System

Diagnosis of Air Leakage Problems - Determining the physical causes of existing symptoms

Identification of Unknown Problems - Anticipating problems based on house characteristics

Retrofit Planning - Determining appropriate retrofit strategies based on the current state of the structure

2.2 Content

The types of air leakage problems that the expert system will deal with concern heat loss and gain, thermal comfort, moisture, and indoor air quality, and several specific examples are listed in table 2. These are general problems types, as opposed to their specific causes and the symptoms which reveal their presence. For example, the cause of a cold interior surface of an outside wall may be air leaking into the wall system at a second-story overhang and flowing up within the wall. The symptoms of this problem may include occupant discomfort, and perhaps some condensation or mildew on that wall. To further explain the content of the expert system, this example is considered in relation to the three problem types in table 1. In the diagnosis mode, the symptoms of the cold room will be input, along with other house information such as the existence of an overhang, and the expert system will suggest a leak into the wall as a potential cause. The system may specify additional inspections to the auditor in order to support the diagnosis. Appropriate techniques for verifying the existence of the leak, and repairing it, will than be provided. In the identification mode the expert system will consider the fact that the house has an overhanging second floor, and based on experience regarding this house style and its construction, will suggest the possibility that such a leak exists. Again, appropriate verification and repair techniques will be provided. Finally, if the user is planning to retrofit the house, including the installation of wall insulation, the expert system will identify this leakage site as an envelope tightening retrofit and as a means of making the proposed insulation more effective.

Table 2 Air Leakage Problems

Heat Loss/Gain:
- Excessive infiltration rates
- Air leakage decreasing the effectiveness of insulation systems

Thermal Comfort:
- Air leakage causing cold/warm interior surfaces
- Air leakage causing drafts in the living space

Moisture:
- Exfiltrating air contacting cold surfaces within the building envelope and condensing (winter)
- Infiltrating air contacting cold surfaces within the building envelope or living space and condensing (summer)
- Inadequate attic ventilation
- Excessive moisture transport from the occupied space to the attic
- Excessive moisture generation and inadequate removal within the space

Indoor Air Quality:
- Excessive pollutant sources strengths
- Inadequate ventilation - whole building and local, and as a function of time

The problems in table 2 are based on the author's experience and a preliminary review of the resources obtained to develop the knowledge base. As the knowledge base resources are examined further, and as the performance of prototype systems are analyzed, the list will be expanded and restructured. However, the basic division into these four categories and the nature of the individual problems are expected to remain useful.

Table 3 Outline of the Knowledge Base

<u>Factual Information</u>

Generic:
- Housing styles
- Floor plans
- Roofs and foundations
- Unheated spaces - basements, attics, crawlspaces

Construction:
- Envelope systems - framing, foundations, insulation
- Details - joints, seams, interfaces
- Accessories - doors, windows, dormers, overhangs
- Mechanical equipment

Problems: Table 2

Symptoms:
- Heat Loss/Gain - Excessive utility bills
- Comfort - Drafts
- Moisture - Condensation, Mildew
- Air Quality - Stuffiness, Lingering Odors, Chronic Respiratory Complaints

<u>Heuristics</u>

Problem Specific:
- Associations between building types and construction details
- Associations between building types and air leakage problems
- Associations between construction details and air leakage problems
- Associations between air leakage problems and symptoms
- Associations between air leakage problems and appropriate retrofits

Strategic:
- Problem solving approaches

In addition to the types of problems listed in table 2, the knowledge base will contain other materials. Table 3 presents an outline of the content of the knowledge base. There are two basic types of information that will be included in the knowledge base, factual and heuristic. The factual information consists of descriptive information regarding houses, their construction, and air leakage problems. The so-called generic subgroup of this factual information concerns basic housing characteristics such as style, layout, roof and foundation types, and the existence of unheated spaces. The second type of factual information includes more detailed information on construction. The air leakage problems listed in table 2 is another type of factual information. Finally, the various symptoms associated with such air leakage problems is the final type. All of this factual information serves as the components for developing a useful characterization of a house within the expert system.

The second type of expert knowledge to be included in the knowledge base, referred to as heuristic, is divided into problem specific and strategic. Heuristics are generally acquired from experts and are used in attacking and solving the problems in the expert system's domain. The heuristic knowledge consists of if-then statements relating building characteristics and air leakage problems to other building characteristics, problems, and retrofit procedures, as noted in table 3. An example of such a rule might be, "If the house has a dropped ceiling over a stairway, then their may be air exchange between the attic and this ceiling space." In many expert systems, these rules are associated with numerical values indicating the degree of uncertainty regarding the rules' conclusions. There are several schemes for quantifying the uncertainty, and combining uncertainties as multiple rules are applied. The strategic heuristics refer to more general rules that embody the problem solving approaches of the system. These approaches are based on the strategies employed by expert house doctors and will serve to guide the selection of rules as the expert system progresses. The information for the knowledge base will be obtained from a variety of sources as discussed in a later section.

2.3 Structure

The system is envisioned as an interactive program in which information provided by the auditor will be used to create an "image" of the house under consideration. This image will be a combination of characteristics, varying in degree of detail and quantification, and will include information provided by the auditor and default values supplied by the expert system. Based on the application of the rules discussed above, and additional information supplied by the user, the house image will be progressively refined and made more useful.

A session will begin with the auditor providing preliminary information on the home. These initial inputs will include exactly which of the three situations in table 1 are relevant, however potential problems will be identified even if they are not requested. In addition, available information regarding the home's physical description, age, mechanical equipment, and other features may be added at this stage. The system will interact with the user/auditor as this information is being input, for instance requesting additional explanation of the inputs. At the conclusion of this initial session, the system will produce a tentative list of conclusions (i.e. problems, causes, and retrofits), plus a list of requests to the auditor for further information. These requests may involve visual inspection ("Go to the kitchen and determine whether the exhaust fan exhausts to the outside or recirculates"), or discussion with the building occupants ("Ask the homeowner if they have experienced eye irritation since obtaining the new furniture"). The auditor will then obtain the additional information and return to the terminal. The interaction with the system will continue and the new information will be input as appropriate. The system will then produce a list of conclusions that is more detailed and building specific, and possibly additional requests for information. The appropriate number of iterations and length of the session will need to be considered in developing the system. The system may suggest more involved study of the building, such as pollutant concentration measurements with commercially available passive pollutant samplers, and then another session with the system at a later date.

As mentioned above, the information provided by the user will be used by the system to create an image of the home. This image will not be a detailed, physical model of the home for use in a calculation of infiltration involving exact descriptions of every leakage site and of the building geometry. Instead it will be a descriptive characterization of the building including both quantitative information (e.g. size, number of occupants, age) and more qualitative information (e.g., existence of a basement, geographic location, construction style). The rules contained in the expert system knowledge base will be used to convert the current set of attributes of the home to a more specific and useful set of attributes. As the system employs these rules and as additional information is provided by the user, the working image of the home will ultimately provide the desired information to the user.

Such a forward-chaining, rule-based system is most appropriate to the two problems of identification and retrofit planning listed in table 1. Such an approach will be employed first in the development of the expert system, but other knowledge representation methods may be found to be more appropriate. Assuming the use of a production system, a control mechanism for determining which rules will be "fired" must be developed. This control mechanism should be based on the problem solving strategies that are actually employed by experts in the field, and is referred to as "strategic heuristics" in table 3. The acquisition of expert knowledge for providing guidance in selecting rules, sometimes referred to as "metaknowledge," will be discussed below.

Alternatively, the diagnosis of air leakage problems lends itself to a backward-chaining approach. As in medical diagnosis expert systems, one starts with symptoms and attempts to determine their causes. In a rule-based system the rules, and their antecedents, necessary to induce the symptoms are considered. Again, a control mechanism is required to proceed with this backward search, and the approaches employed by experts should be useful in developing such a mechanism.

3. KNOWLEDGE BASE RESOURCES

Several different sources have been identified for use in developing the knowledge base for the expert system. These sources include both written documents and human experts, as outlined in table 4. Examples of all the sources have been identified and several have been subjected to preliminary reviews in order to determine their applicability to the system.

3.1 Documents

The documents that will be used in developing the knowledge base of the expert system are listed first in table 4. They include both audit and retrofit manuals which have been developed for specific retrofit programs or as general guides for retrofit planning (Diamond et al 1982, Energy Resources Center 1983, Knight 1981, Marbek 1984, Marshall and Argue 1981). These documents provide both general and specific information for locating and repairing air leakage sites in houses. They will be useful for identifying specific air leakage sites in existing buildings and determining appropriate retrofit measures for their repair. They will also provide more general information regarding the detection of air leakage sites and the physical principles which relate air leakage to factors such as heat flow, moisture transport, and air quality.

Table 4 Knowledge Base Resources

Documents
- Auditing and Retrofit Manuals
- Technical Reports on Retrofit Techniques and Demonstration Projects
- Energy-Efficient Construction Guides
- Home Construction Manuals
- Architectural Guides

Human Experts
- House Doctors and Other Expert Auditors
- Energy-Efficient Housing Designers
- Energy-Efficient Housing Builders
- Home Inspectors

There are many other publications concerning the retrofitting of houses that will be used in the knowledge base. These documents include reports on specific retrofit demonstration projects (Socolow 1978), discussions of energy auditing techniques (Harrje et al 1979 and 1980), and informational pamphlets for the general public (Lawrence Berkeley Laboratory 1981). These publications will also be useful in identifying air leakage sites and in suggesting appropriate measures for their repair.

A report by Rowse and Harrje (1977) concerning retrofit potential in U.S. housing provides information on the characteristics of U.S. housing stock such as distributions over style and age. Descriptions of house construction techniques and materials, as well as classifications of architectural styles, is also included. The information in this report will be helpful in developing descriptive classifications of houses and in developing probabilistic relations between geographic location, house age, and construction style.

There are also many recently developed guides to energy-efficient house construction which supply a great detail of specific information for building houses with high levels of thermal integrity (Alberta Agriculture 1983, Alberta Energy and Natural Resources 1982, CHBA 1980, CMHC 1982, Carlsson et al 1980, Dutt and Harrje 1981, Elmroth and Levin 1983, Erye and Jennings 1983, Nisson and Dutt 1985). Many sketches of construction details are included to enable construction of building envelopes which are extremely well-insulated and airtight. In many cases it may be assumed that these details have been redesigned with so much attention because they have been the source of problems in past construction. Therefore these energy-efficient construction guides may be sources of air leakage sites in existing buildings and in some cases retrofit measures for their repair. These guides also contain discussions of the general principles of heat loss, moisture control, and indoor air quality. There are also house construction guides that describe the techniques used for building more typical U.S. homes (Frankl 1950, U.S. Department of Agriculture 1970, Warland 1969). These documents provide much useful information on the techniques and materials used in building houses, as well as many of the details that have led to today's air leakage problems.

There are also various architectural guides to houses which will be useful for the general classification of houses and for supplying useful terminology for the expert system (Macsai et al 1976, McAlester and McAlester 1984, Ramsey and Sleeper 1970). These guides provide a wide range of information regarding house construction, ranging from construction materials and techniques to specific detailing. They also provide general classifications of building types which may be useful in associating various building features with particular architectural styles.

3.2 Human Experts

There are a variety of human experts available for developing the knowledge base of the expert system, as listed in table 4. House doctors and other expert auditors are sources of both the factual information and the heuristics discussed earlier. These auditors have a great deal of experience in inspecting and retrofitting houses. They know of many air leakage sites, their causes and effects, and appropriate retrofit measures for their repair. They also have observed many relations between housing style and construction, and the existence of specific air leakage sites, which will be used in developing the problem solving heuristics listed in table 3. The approaches that they use in conducting their audits will provide the so-called strategic heuristics.

Energy-efficient housing designers and builders are sources of general knowledge on how to build houses properly, thereby avoiding the problems which are the domain of this system. They understand the general principles of air leakage and its effects on heat and moisture transfer, and issues of indoor air quality. Another source of human expertise, generally untapped in the area of home energy auditing, are home inspectors that are used by prospective purchasers of homes to determine the general condition of the home in question. These inspectors are familiar with many aspects of construction and the types of defects which occur in houses. Their experience, and the approaches they use to inspect houses, may be useful in developing the knowledge base of the expert system.

4. FUTURE WORK

The work to date has been primarily concerned with developing an appropriate expert system approach to the problems of residential air infiltration, and with identifying resources for inclusion in the system's knowledge base. A great deal of work remains to produce a working expert system. This section briefly outlines the work that remains to be done in this project.

A great deal of written material has been identified in this report as resources for the development of the system's knowledge base. Some of these documents will certainly be useful, while the appropriateness of others remains to be determined. The various reports, guides, and manuals must be studied in detail to determine their usefulness and to extract from them the specific information for inclusion in the knowledge base. The review of the written material will be affected by the interaction with the human experts and by the performance of the prototype expert system. Based on these other efforts, additional documents will be included, others will dropped, and the information requirements will be altered.

The knowledge base will draw heavily on the human experts identified earlier.

Their expertise will be acquired through interviews and discussions about air leakage in houses in order to catalog their experience regarding air leakage problems and their repair. In addition, these expert auditors will be accompanied on walk-throughs of houses to observe the protocols they employ in investigating leaks, analyzing existing problems, and recommending retrofits. This approach of observing an expert at work in order to determine their problem solving approaches has been suggested in many discussions of expert system development (Hayes-Roth et al 1983). Another recommended technique for employing human experts is in the evaluation of prototype systems. This includes both static examinations of the knowledge base and dynamic evaluations in which the experts test the system with several prototypical problems. By observing how the system approaches these problems, and the conclusions it reaches, the human expert can test the system's accuracy and utility.

In the development of an expert system, it is generally recommended that one produce a working prototype as soon as possible. This prototype system need only deal with a very limited domain, but the process is quite useful in investigating the appropriateness of the approaches being used. It is very likely that the initial prototypes, and some of the presently anticipated characteristics of the system, will be abandoned as the system is developed, but the process of the construction and testing of prototype systems is extremely useful in the development of the final system. Therefore, a working prototype system will be built and tested, even as the knowledge acquisition procedure is in progress.

5. CONCLUSIONS

The problem of residential air infiltration has been identified as an appropriate domain for an expert system. The inherent uncertainty in diagnosing and correcting air leakage sites, the inappropriateness of calculation approaches in many cases, and the existence of human expertise justify the use of an expert system approach. The proposed expert system was described, along with the resources that have been identified for inclusion in the knowledge base. The future efforts required for the development of the system were also discussed. It is anticipated that based on the resources available a useful expert system for the identification, diagnosis, and retrofit of air leakage problems in houses will be produced.

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FORM NBS-114A (REV.11-84)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET *(See instructions)*	1. PUBLICATION OR REPORT NO. NBSIR 86-3323	2. Performing Organ. Report No.	3. Publication Date FEBRUARY 1986

4. TITLE AND SUBTITLE

Outline of an Expert System Approach to Residential Air Infiltration

5. AUTHOR(S)

Andrew K. Persily

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

10. SUPPLEMENTARY NOTES

[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

As a demonstration of the appropriateness and usefulness of expert systems to the field of building construction and maintenance, an application to residential air infiltration is considered. This particular problem area appears to be particularly well-suited to an expert system approach due to the uncertainties associated with infiltration and ventilation in buildings and the large amount of experience that has been obtained by energy auditors, "house doctors," designers, and builders. This report presents the results of an effort to identify an appropriate expert system approach to residential air infiltration for use in the subsequent development of a working system. The intended approach and goals of the expert system are presented, along with the structure of the knowledge base. Resources for developing the knowledge base are also identified and discussed.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

air infiltration; artificial intelligence; energy auditing; expert systems; residential buildings

13. AVAILABILITY

[X] Unlimited
[ ] For Official Distribution. Do Not Release to NTIS
[ ] Order From Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.
[X] Order From National Technical Information Service (NTIS), Springfield, VA 22161

14. NO. OF PRINTED PAGES

17

15. Price

$9.95

USCOMM-DC 85-6006