Expert System for Environmental Quality Evaluation

By Rabee M. Reffat[1] and Edward L. Harkness[2]

Abstract: This paper presents the development of an expert system to evaluate the effects on environmental quality of proposed modifications to an office building following a postoccupancy evaluation. The model presented in this paper has been designated Expert System for Environmental Quality Evaluation (ESEQE). The ESEQE model consists of 200 rules covering 65 performance criteria of environmental quality. These performance criteria cover lighting comfort, acoustic comfort, thermal comfort, and indoor air quality. The performance criteria and the method of evaluation were extracted from a series of interviews with experts in the field of environmental quality in the built environment. The structure and development cycles of the ESEQE model are described. A demonstration of using ESEQE to evaluate the environmental quality in office buildings is presented. The potential benefits of using ESEQE during the design stages are also discussed.

INTRODUCTION

Buildings should provide high quality environments to support the activities of their occupants. This case study is an endeavour to develop a computer-based model with which to evaluate the environmental quality of buildings postoccupancy or during the design process.

Designers could benefit from previous experience of experts' knowledge built into a knowledge base in an expert system model. A detailed and careful postoccupancy evaluation could facilitate the fine-tuning of a recently completed building and could help others learn from the experience (Lushington and Kusack 1990). The Expert System for Environmental Quality Evaluation (ESEQE) model can assist in documenting successes and failures in a building's performance, and it may also assist in trouble-shooting during the commissioning/shakedown period immediately after occupation, thereby identifying unforeseen problems in building use.

This study asserts that there is a need for designers to assess environmental quality and that environmental quality evaluation (EQE) would enable designers to improve a design or completed building to meet the expectations of clients and users. Development of an expert system model for EQE could provide designers with a more efficient evaluation of office buildings.

ENVIRONMENTAL QUALITY CATEGORIES

Environmental quality in office buildings includes provision of lighting comfort, acoustic comfort, thermal comfort, and acceptable indoor air quality (IAQ) for the occupants of buildings (McMullan 1983; Davis 1986; Manning 1987). The evaluation of environmental quality in offices may be broken down into relevant performance criteria. Many criteria may be relevant to achieve the desired comfortable level.

A series of interviews was conducted with experts to extract these performance criteria. Two kinds of experts were selected under certain benchmarks to be interviewed. These benchmarks include experience of at least 15 years in the field of specialization, substantial practical contribution to a related field, and comprehensive understanding of the interdisciplinary relationships with the related fields. A combination of theory and practice was considered while selecting potential experts. The experts interviewed totaled 50. There were 29 professionals and 21 academics. A comprehensive overview of related literature was carried out in which initial ranges of comfort conditions for each performance criterion in the environmental quality categories were established. A structured questionnaire was then developed to collect the necessary knowledge and data.

After the completion of the interviews, 65 performance criteria for evaluating environmental quality were extracted as shown in Reffat and Harkness (2001, Tables 1–4). A method of weighting and integrating the performance criteria obtained from the experts was developed (Reffat and Harkness 2000). This paper presents the model developed for this integration of environmental quality using expert systems techniques.

OVERVIEW OF EXPERT SYSTEMS

Expert systems are computer techniques that can be used to model the expertise of humans in a specific domain. Expertise is that knowledge that has been acquired through experience over a period of time in a specific domain and is heuristic in nature. Expert systems provide a technique to model the reasoning processes of experts and use their knowledge to solve specific problems. Such systems can be used by nonexperts to improve problem-solving capabilities. Expert systems can also be used by experts as knowledgeable assistants. Expert systems are used to propagate scarce knowledge resources for improved consistency of results. Such systems could function better than a single human expert in making value judgements in a specific area of expertise (Turban 1992).

Expert systems are best known as self-contained entities that exist quite separately from other computer-aided design systems. Important is the notion of embedding explicit knowledge of the kind that is encoded in expert systems within more general computer design tools (Krishnamoorthy 1996). The task of the expert system developed in this paper is to communicate, access knowledge, make inferences, arrive at conclusions, and explain its conclusions.

STRUCTURE OF EXPERT SYSTEMS

Expert systems are composed of two major parts: (1) the development environment; and (2) the consultation (run time) environment, as illustrated in Fig. 1. The developmental environment is used to build the components and to introduce knowledge into the system. The consultation environment is used to obtain expert knowledge and advice. The development environment contains components that facilitate the creation of expert systems: knowledge acquisition facility, inference engine, and knowledge base. The knowledge acquisition facility provides a way to store experts' qualitative knowledge to address a given problem. The inference engine controls the rea-

[1]Lect., Dept. of Arch. and Des. Sci., Univ. of Sydney, Sydney, NSW, Australia. E-mail: rabee@arch.usyd.edu.au

[2]Visiting Lect., Facu. of Built Environment, Univ. of New South Wales, NSW, Australia. E-mail: tedh@fbe.unsw.edu.au

Note. Discussion open until January 1, 2002. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 6, 2000; revised April 12, 2001. This paper is part of the ***Journal of Performance of Constructed Facilities***, Vol. 15, No. 3, August, 2001. ©ASCE, ISSN 0887-3828/01/0003-0109–0114/$8.00 + $.50 per page. Paper No. 21975.

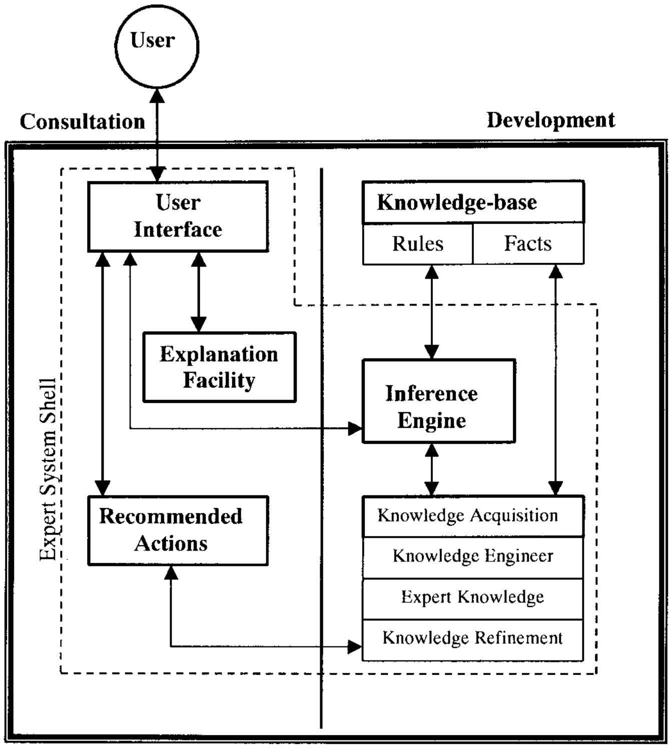

FIG. 1. Expert System Structure [after Turban (1992)]

soning process and decides how the stored knowledge will be implemented (Waterman 1986; Nikolopoulos 1997).

The consultation environment contains components that facilitate the use of the model and provides the users with expert advice and answers their queries. There is an interface, explanation facility, and recommended action facility. The interface allows human-machine and machine-machine communication and interaction. The human-machine interface should be as simple and natural as possible. The machine-machine interface must allow for communication with other computer programs (e.g., databases and graphical interfaces). The explanation facility illustrates why certain knowledge is being applied and why a certain expert system is following a specific line of reasoning. This explains why and how such conclusions were reached (Rosenman 1990). The recommended action facility allows revision of some of the system's reasoning processes by the users who learn to make additions and modifications to the system.

DEVELOPMENT OF ESEQE

This section presents the procedures that were carried out while developing an ESEQE of office buildings. These procedures include knowledge extraction and analysis, weights determination, knowledge-base development, decision trees, production rules, development, and validation of the ESEQE model.

Knowledge Extraction and Analysis

The first step in developing the EQE was to extract the knowledge from the experts. At this stage, concepts, relationships, and control mechanisms are needed to describe problem solving in the EQE of office buildings together with subtasks, strategies, and constraints related to the problem solving. A structured questionnaire was developed and used in the interview sessions with the selected experts: 29 professional and 21 academics. The outcome from these interviews was a list of 65 performance criteria to evaluate the environmental quality of office buildings and determination of the weight of each category of environmental quality and of each performance criterion. Such results are variable because of the experts interviewed, type of building to be evaluated, and region wherein a building may be located. Interviewing different experts or evaluating another type of building (hospitals or schools) may result in a different outcome of performance criteria and weights. However, changing the region would definitely affect the comfort ranges for some of the performance criteria. As such, ESEQE does not present a generalized model that can be used within different regions and does not reflect a globalized experience.

Determination of Weights of Environmental Quality Categories

Data were collected through interviews to determine the weight of each environmental quality category (lighting comfort, acoustic comfort, thermal comfort, and acceptability of IAQ) compared to other environmental quality categories for each office building element. For each office building element such as a reception area, office workplace, and meeting areas, a paired comparison method (David 1988) was used to establish the weights by determining the importance of each environmental quality category compared to each one of the other categories. An evaluation matrix was used to find the row score, assigned weight, and rank of each environmental quality factor in each office building element (Reffat and Harkness 2000).

After collation of assigned weights from the expert inputs, a statistical analysis was carried out. For example, the means of the assigned weights of environmental quality categories in an office workplace indicated that lighting had the highest weight (9.56 on a 10-point scale). Other weights were thermal comfort (6.35), IAQ (6.35), and acoustic comfort (5.56). From the previous results, the final function that integrates the weights of lighting comfort, acoustic comfort, and IAQ was derived to give an overall score of the achievement of environmental quality of the office building under evaluation. This is called the weighted average of EQE and was counted on a 10-point scale (Reffat and Harkness 2000)

$$\text{total EQE} = \{1.89 \cdot (\text{acoustic}) + 2.29 \cdot (\text{thermal}) + 2.38 \cdot (\text{IAQ}) + 3.44 \cdot (\text{lighting})\}$$

Determination of Weights of Performance Criteria

The weight of each performance criterion of an environmental quality category was determined based on its influential effect compared to other performance criteria within the environmental category. For instance, temperature shifts are extremely influential in evaluating thermal comfort (an environmental quality category). Data were collected through interviews with experts to determine this influential effect (extremely influential, of major influence, influential, somewhat influential, and not influential) (Reffat and Harkness 2000). The weighted average for each performance criterion was calculated from a total 100-point scale for each environmental quality factor. For instance, the weighted average of temperature shifts is 8.7 from the 100-point scale including all performance criteria for evaluating thermal comfort.

Development of ESEQE Knowledge Base

The heart of EQE is the knowledge base. It is upon this knowledge base that expert advice can be modeled. The four categories of the ESEQE knowledge base are lighting comfort, acoustics comfort, thermal comfort, and acceptability of IAQ. The knowledge incorporated in the knowledge base was extracted from experts' inputs. Experts' inputs were used to construct the evaluation process and to formulate broad constraints for performance criteria evaluation.

Sets of comfort ranges for each performance criterion of an environmental quality in office building elements were extracted from the experts' inputs. The knowledge extracted was encoded in the formation of production rules in the knowledge base. If a rule-based system starts with a hypothesis and tests, it is called ''backward-chaining.'' One that builds to a conclusion has a structure called ''forward-chaining.'' In this ESEQE model, a forward-chaining was used. The result of using such an approach is derivation of the performance values of environmental quality.

Simulating Evaluation Making Process by Experts

The second step was to simulate the evaluation process and draw the relationships between the extracted knowledge (performance criteria and their weights and environmental quality categories and their weights). Decision trees were used as a means of representing the interrelationships among performance criteria and categories. The aim was to draw how an expert arrives at a decision through looking at different aspects of the task. In a decision tree, each criterion represents a node and the attribute values (reflection of comfort range effects) of each criterion may indicate different paths. In other words, each node can be a question with one or more answers. This concept is helpful in visualizing and explaining how an expert analyzes problems and how an ''inference engine'' searches through its knowledge base.

One may imagine the search space within this decision tree growing an increment at a time, as the inference engine moves from a node to the next looking for a solution. A general decision tree for environmental quality includes categories, performance criteria, and attribute values, as shown in Fig. 2. The decision trees for a search root through lighting comfort, acoustic comfort, thermal comfort, and IAQ are structured similarly.

The relationships established through the previous stages were implemented together in the form of ''production rules.'' From the analysis of the comfort ranges, the weights of environmental quality categories, their performance criteria and attribute values were used to construct the knowledge base on the ESEQE model. The knowledge base was then constructed in the form of production rules, which comprised a set of rules, each consisting of a left side (a pattern that determines the applicability of the rule) and a right side (that describes the action to be performed if the rule is applied). The knowledge base was incorporated directly into an expert systems shell (EXSYS Professional) in the form of IF-THEN rules. EXSYS Professional is a generalized expert system development package with an empty knowledge base and an empty database (*EXSYS* 1995). Expert systems can be developed with EXSYS that involve a selection from a definable group of choices where the decision is based on logical rules. The rules that EXSYS uses are IF-THEN-ELSE rule types. A rule is made up of a list of IF conditions and lists of THEN and ELSE conditions. EXSYS is written in C language for high speed and efficient utilization of memory.

The production rules were developed by creating a series of qualifiers. A qualifier has two parts: an incomplete sentence ending with a verb and associated values representing all the possible situations relevant to the qualifier (Hanna et al. 1992). The IF part of the rule consists of one or more of the ''qualifier'' values and conditions that could occur. The THEN part consists of other qualifier values, variables, or choices (possible solutions to the rule) and represents action that must be taken. NOTE represents any text to explain specific points and the REFERENCES show from where the text was quoted. Both NOTE and REFERENCES represent the explanation facility in the model. The following is an example of constructing a production rule:

RULE No. 1

The component parts are IF, THEN, NOTES, and REFERENCES.

IF:	Background noise level (using noise criteria curve) is <20 dB or greater than or equal to 45 dB through to <60 dB
THEN:	Confidence weight of background noise level = 7 on a 10-point scale and background noise level is given the value $\{(0.068)\cdot 7\}$, where 0.068 is a conversion from the 100-point scale to a 1.0-point scale
NOTE:	For practical measurements of sound strength, it is convenient to use a decibel scale
REFERENCE:	McMullan (1983)

Developing and Validating Demonstration (Portion of Complete Model)

Validating a system requires an understanding of the sequence of rules that must be executed to achieve a goal. The validation is carried out by examining how the system operates at run time (Preece et al. 1996). The demonstration was first developed for testing purposes. It is structurally a complete expert system but on a smaller scale. The purpose of developing a demonstration was to ensure that the system was ca-

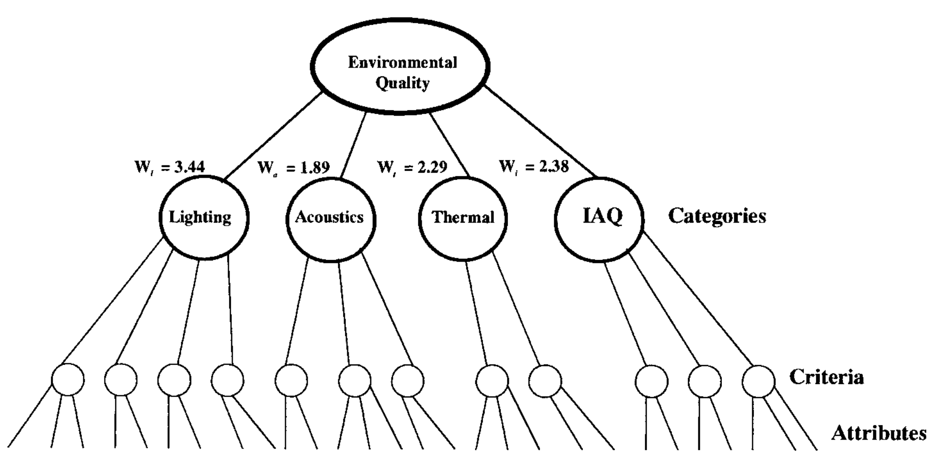

FIG. 2. General Decision Tree for Search Root through Environmental Quality

pable of producing valid results that experts would reach. The demonstration was applied to the acoustic comfort quality of an office building. It consisted of 47 rules covering all of the relevant acoustic performance criteria in acoustics and interrelated performance criteria with other environmental quality categories. The validation of the demonstration was carried out by taking a hypothetical case of an office building and manually calculating the outcome by applying the rules developed from the extracted knowledge of the experts during the interviews.

The computational ESEQE demo was tested and run using the same rules for the same hypothetical case. The computational ESEQE demo provided an evaluation of acoustic comfort identical to the one reached by the manual method.

Development of Complete ESEQE

Model

After the successful demonstration run on the computer, the ESEQE model was similarly completed and validated through the following steps:

1. The number of rules covering the full scope of the ESEQE model was increased.
2. The performance criteria and attribute values of other environmental quality categories were added.
3. The execution rules were added to complete the program.
4. Validation of the complete ESEQE model was similarly carried out as for the demo.

The complete computerized ESEQE model consists of 200 rules covering all aspects of environmental comfort quality evaluation of office buildings in a hot, arid region. The structure of the ESEQE model is summarized and illustrated in Fig. 3. The structure of the ESEQE model indicates the importance of continuous interactions between users and the model as the main stream of data flow to perform the evaluation.

Running ESEQE Model

Users' interactions with the ESEQE model are in the form of selecting one of the available options for each question the model presents. The attribute value for each performance criterion is assigned consequently and internally by the ESEQE model. The assigned value of each performance criterion is an input to the ESEQE's inference engine that guides the execution of corresponding rules in the knowledge base. The ESEQE model commences with a brief introduction of its purposes and provides the user with different alternatives to carry out the evaluation, as illustrated in Fig. 4(a). The ESEQE model presents related questions to users based on their initial selections of certain categories of environmental quality to be evaluated (e.g., lighting comfort). An example of one of the questions in evaluating lighting comfort is shown in Fig. 4(b). The ESEQE model continues with presenting further questions, carrying out the evaluation to the end. During the evaluation process, ESEQE provides users with more explanations about any performance criterion by typing WHY at the COMMAND line. The ESEQE model browses the related rule within which this criterion is executed in addition to other explanations. An example of an explanation screen is shown in Fig. 4(c). Moreover, ESEQE allows users to access the references of the knowledge provided in the explanation section by typing R at the COMMAND line.

At the completion of the evaluation, the ESEQE model displays results in the forms of (1) attribute values for all performance criteria: (2) percentage of acoustical comfort, lighting comfort, thermal comfort, and acceptability of IAQ achievements; and (3) an overall percentage of environmental quality for the office building under evaluation.

The results of the EQE depend on the selection of appropriate attributes that reflect the correct situation of the office

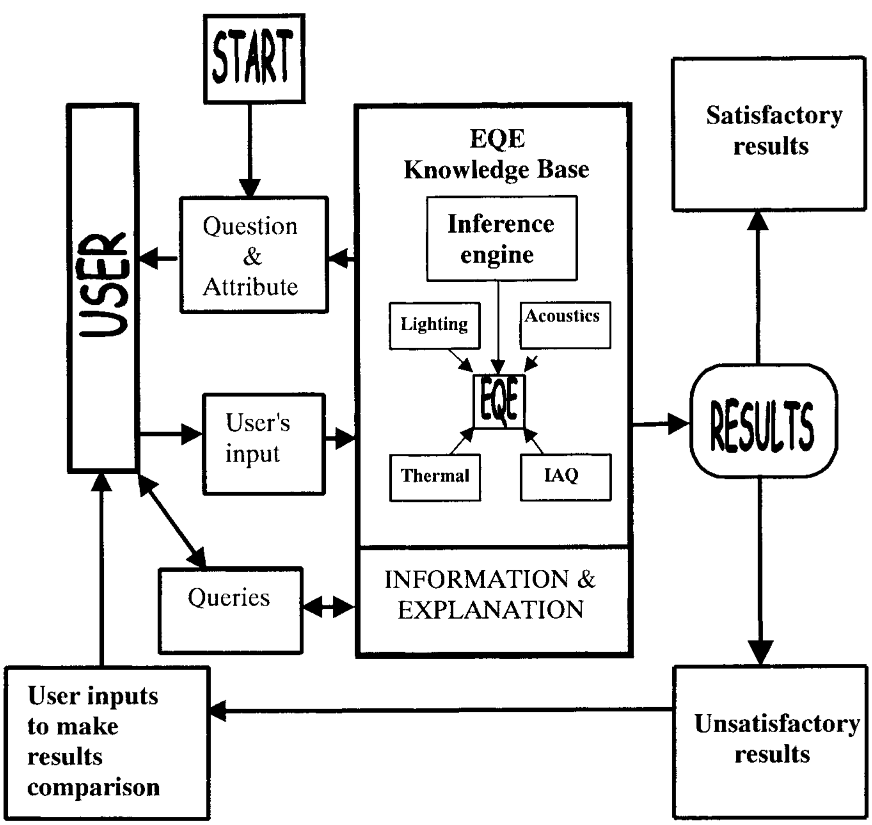

FIG. 3. Structure of Expert System Model to Support Evaluation of Environmental Quality

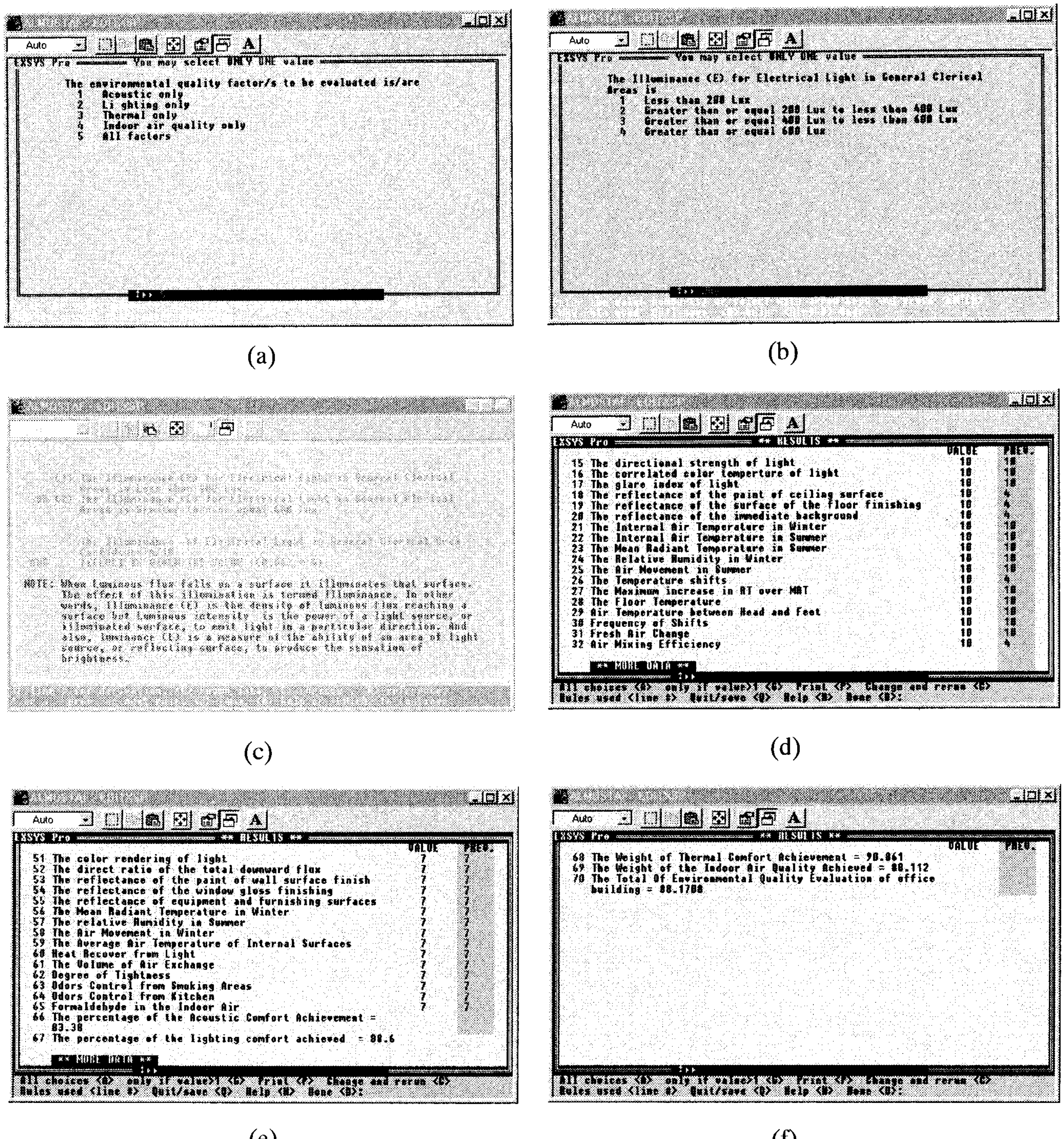

FIG. 4. Running ESEQE Model

building under evaluation. The attribute selection is not a haphazard procedure but demands professional experience to extract the inputs and measurements from a building design or built environment. If the final results of the evaluation are not satisfactory, the ESEQE model provides users with points of deficiency and ways to enhance the level of environmental quality of that building. To do so, necessary changes need to be made in the design of the office building. After carrying out such changes, a reevaluation can be made using ESEQE. The ESEQE model displays the enhanced results as well as the previous results. Examples of enhanced results are shown in Figs. 4(d–f). Figs. 4(d and e) show the improvement of certain performance criteria by changing the surface materials of ceiling, floor, and paint. Fig. 4(f) reflects the effect of such changes on the total environmental quality of the office building under evaluation.

DISCUSSION

On completion of the construction of a building, an evaluation of environmental quality might reveal a response that was not optimal. In deciding which of several criteria to address, it would be helpful to have a means of establishing relative effectiveness in achieving overall environmental quality. The ESEQE model could be run for a variety of possible modifications and the results assessed for cost to the building owner and inconvenience to tenants.

CONCLUSIONS

An ESEQE model was developed and simulated the evaluation and reasoning process carried out by experts in the field of environmental quality. The value for each performance criterion as well as an overall evaluation were computed and displayed. The ESEQE model has the capability to provide explanations of knowledge used in the evaluation and to point out the deficiencies for the user to revisit and enhance, provides comparison of results after such enhancement is made, and would help in providing useful support in evaluating the effects of proposed modifications to a building following a postoccupancy evaluation.

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