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ABSTRACT

A model of the design process and related knowledge and expertise is applied to develop an advanced, computer-based, Building Design Support Environment (BDSE). The BDSE will support building design from the initial schematic phases, through working drawings and specifications, to a building's construction, occupancy, and use. The BDSE will consist of imaging, simulation, and expert systems software, linked in a multimedia environment containing handbooks, product catalogs, and case studies. The structure of the BDSE is presented with emphasis on modeling the building design process and related knowledge. All BDSE modules will operate on three common hierarchical data structures that describe the building, its context, and its performance. The inter-relations among the BDSE modules are compatible with the iterative nature of the design process. An issue based information system (IBIS) will be used to fully record the design process so that it will be transparent and retraceable. Presentation of the structure of the expert system module emphasizes the identification, organization, and application of appropriate building design knowledge. Finally, methodology for acquiring knowledge to develop a prototype knowledge base for designing fenestration systems is presented, along with preliminary findings and future plans.

INTRODUCTION

Continuously decreasing cost has brought computers into most architectural and engineering offices, most commonly for activities such as drafting, accounting, and word processing. Computers are used less often to assess the performance of design solutions; simulation software packages, most of which are simplified versions of main-frame analytical tools originally developed for research purposes, are used for this purpose. Unfortunately, such packages usually require a detailed description of the building, which is possible only at the latest phases of the design process, when most of the design decisions have already been made, and drastic modifications are undesirable. Moreover, the building description input formats for these simulation packages are complicated and incompatible with each other, and the output data are usually specialized and difficult to interpret.

Recently, a major effort has been made to encode building design expertise through the application of expert or knowledge-based systems (ES or KBS) techniques, which emerged from the field of Artificial Intelligence. Prototype expert systems are currently available to *diagnose* problems with various types of building equipment (Haberl et al. 1989; Ruberg and Cornick 1988) and *select* building components and systems (Degelman and Kim 1988; Tuluca et al. 1989).

Initial attempts at encoding building design expertise have identified problems in knowledge acquisition and representation, as well as integration with existing software (Hall and Deringer 1989).

During the past few years, researchers at a national laboratory have been designing and developing an advanced, computer-based building-design support environment (BDSE) (Selkowitz et al. 1986). The BDSE is intended to support building design from the initial schematic phases through working drawings and specifications to a building's construction, occupancy, and use. The BDSE will include imaging, simulation, and expert systems software, linked in a multimedia[1] environment containing handbooks, product catalogs, and case studies. All software modules of the BDSE are designed to operate on three, shared, hierarchical representations of the building's description, context, and performance. The entire design process will be recorded using an issue based information system (IBIS), also linked to the multimedia environment for reference purposes. Prototypes of the various modules of the BDSE will be developed independently, using various types of hardware/software combinations (Figure 1).

In this paper, we present the structure of the BDSE, with emphasis on modeling of the building design process and related knowledge and expertise. We also report on the development of a prototype knowledge base for designing fenestration systems.

MODELING THE BUILDING DESIGN PROCESS

Appropriate modeling of the design process requires an understanding of design activities and their interrelations, so that appropriate data representation and processing can be developed.

The Design Process

Design presupposes a discrepancy between a situation *as is* and a situation *as it ought to be*. The design process is intended to create a plan, which, if executed, will result in a situation with specific properties and without undesired side- and after-effects (Rittel 1972). Designers have to perform three main activities:

1. Specify the "ought-to-be" situation.
2. Generate a plan that will lead to it.
3. Check for undesired side- and after-effects.

These three activities are interdependent. In the early phases of the process, the specifications of the ought-to-be situation are vague and minimal. Plans are generated, evaluated, and checked for undesired side- and after-effects, which contribute to development of the specifications of the ought-to-be situation. The initial plans are modified to meet the updated image of the ought-to-be situation and are again evaluated for undesired side- and after-effects, in a continuous, *iterative* process. Since checking for side- and after-effects contributes to specifying the ought-to-be situation, the two activities can be seen as one, a formulation of the *value system* for rating potential design solutions. The iterative activities of the design process can then be distinguished as:

[1]The term "multimedia" is used to indicate the integration of graphics, animation, sound, and video.

1. Formulation of the value system.

2. Generation of potential solutions.

3. Evaluation of potential solutions.

Each of these activities is analyzed independently with respect to the data and the processes involved in modeling.

Formulation of the Value System. The formulation of the value system is the most difficult and critical activity because the system is used to evaluate potential solutions. A "good" value system is necessary for a "good" design solution; what is "good," however, can only be determined after the building is built. If the building is well received, it is the product of a "good" value system.

When facing a building design problem, designers develop a set of *design criteria*, i.e., considerations for decision making. The initial criteria are formulated from the specifications of the design program and are usually limited to spatial requirements, economic constraints, and, occasionally, a vaguely defined building image. This initial set of design criteria is expanded through specific *building type/site* and general *space/time* considerations to include concerns such as human comfort, safety, and energy requirements.

A design criterion must somehow be considered during evaluation of potential design solutions. A design criterion may be considered either *directly* or *indirectly* through the establishment of more specific criteria. The human comfort criterion, for example, is usually considered through establishment of more specific criteria, such as indoor air quality and thermal, luminous, and acoustic comfort. This results in a tree structure, where each node represents a design criterion that is considered indirectly through the criteria represented by its branches. The terminal branches of the tree represent the design criteria that are considered directly, and the root represents overall consideration of the building's performance (Figure 2). Design criteria that are considered directly are usually classified into two categories:

1. *Quantitative criteria*, such as energy requirements, which are considered through a specific calculated or measured single quantity.

2. *Qualitative criteria*, such as esthetics, which are considered through the human senses and feelings.

In practice, the value system is never explicitly specified nor is it considered in any orderly fashion. Moreover, the value system is flexible, especially with respect to the relative importance of the various design criteria.

Generation of Potential Design Solutions. When the initial design criteria have been formulated, the designer seeks ways to transform the as-is situation into the loosely defined ought-to-be situation. Past experience and creativity are employed to generate plans. The designer develops or selects strategies, prototypes, or specific products, depending on how far the design process has progressed. *Promising* potential design solutions are specified and evaluated until questionable performance with respect to one or more design criteria is identified. Slight or drastic modifications are then considered in order to remove identified discrepancies and maintain desired features.

The progressive specification of design solutions follows a hierarchical conceptualization of the building and its components in a tree-like structure, where objects have attributes and may be *children* or *parents* of other objects (Figure 3). At the initial, schematic design phases, the attributes of the building and its main components are considered, for example the building's shape and structure, its positioning on the site, and the arrangement of required spaces. When results appear promising, the attributes of the main building components and their components are considered, including shape and dimensions of spaces and locations of openings on walls. This progressive consideration continues until it covers the components represented by the terminal branches of the tree, at the level of working drawings and specifications.

Because values of a building component's attributes (e.g., wall thickness) may affect the possible values of its subcomponents' attributes (e.g., thickness of window system within wall), the importance of design decisions increases from the terminal branches to the root of the tree. Decisions about formulation of the value system are concurrent with the generation of potential solutions and their evaluation, which indicates the impact of initial design decisions on design efficiency. Compliance with design criteria that are formulated during the late phases of the process may require drastic modifications toward the root of the tree, repeating the initial phases of the design process.

Evaluation of Design Solutions. The evaluation of potential design solutions requires knowledge of each specific design solution's performance with respect to each of the design criteria. This knowledge is either part of the designer's experience or it is obtained through *simulation* of performance, using a modeling process that provides results similar to the actual building's performance. Esthetic appeal, for example, is evaluated by simulating the visual appearance of the potential design solution through drawings or scale models; energy requirements are evaluated by simulating building operation through calculation procedures.

Single-criterion evaluations contribute to *multi-criteria* ones through consideration of relative importance among criteria and, eventually, to the evaluation of the overall performance of the potential design solution. Trade-offs among the large number of criteria considered in building design result in design solutions that are usually compromises that favor the most important criteria but keep the performance of the rest within acceptable limits.

Design as the Assignment of Values to Variables

If computers are to assist building designers with decision making, an appropriate representation scheme should be used to encode the building design knowledge. This knowledge includes not only the building's description but its context and performance as well. Knowledge is expressed using a particular vocabulary, which includes words such as "room," "wall," "height," "temperature," and "cost." In contrast, the currently available computer-aided drafting (CAD) systems cover only the building description, in terms of points, lines, and polygons, which are intended to suit a market much broader than building designers. The terminology that building designers use during the design process includes three types of variables (Rittel 1973):

1. *Design variables*, whose values are controlled by the designer and refer to building components and their attributes, such as room width, wall color, and glazing type.

2. *Context variables*, whose values are not controlled by the designer and include surrounding variables, such as height of people, cost of utilities, and wind direction.

3. *Performance variables*, which are functions of design and context variables and are used by the designer to evaluate design solutions, such as work-plane illuminance, annual energy requirements, and life-cycle cost.

These three types of variables will be used to represent the building design knowledge of the BDSE. Design variables describe design solutions and performance variables describe value systems following the hierarchical data structures indicated (Figures 2 and 3). Context variables describe the context of a design problem and can also be organized hierarchically, based on building type and site (Figure 4).

The design process can be redefined as the assignment of values to design variables, which will lead to *specific* values of performance variables. However, performance variables can be specified only for quantitative criteria. Moreover, designers do not usually try to meet *specific* values for performance variables. Rather, they try to either *minimize*, *maximize*, or *optimize* them, defining *ranges* of acceptable values. These ranges are defined either by one boundary, as a maximum or minimum acceptable value, or by two boundaries, minimum and maximum acceptable values, which include the optimum value. However, the boundaries of these ranges are usually loosely defined, and no corresponding "scale of goodness" is specified for intermediate values.

Context variables help determine the values of performance variables. Values are assigned to design variables as they are introduced and/or considered throughout the design process. When new design variables are considered for value assignment, ones defined earlier may play the role of context variables. The design process continues until a specific value is assigned to each design variable. In addition to assigning values to design variables, designers also determine the values of performance variables, either through experience or through simulation procedures. They also often review either the status of the design project or general building-related data. These three activities are performed *iteratively* throughout the design process and will be the main *actions* supported by the BDSE (Figure 5). Their iterative engagement is supported through interrelations among the various BDSE modules, as shown in the linked Figures 5 through 10.

When assigning values to variables, designers may make *off-hand decisions*, based on their experience, or *informed decisions*, based on information obtained from sources including building-related magazines and periodicals and specialized handbooks and product catalogs. Based on time and cost considerations, designers occasionally use the experience of others by employing *consultants* with particular specialties. The current, rapid increase in technological development, the better understanding of the operation of buildings, and the demand for better buildings, all mean a designer probably does not know everything about all aspects of a building, so consultants are more important now than in the past. The BDSE will help with off-hand, informed, and consultant's decisions (Figure 6). Informed decisions will be supported using a multimedia-based environment that contains case studies, handbooks, and product catalogs (Figure 7), which will be indexed according to design, context, and performance variables (Shuman et al. 1988). The consultation option will be supported through the use of knowledge-based systems and is discussed in the next section.

Design as an Argumentative Process

Design decisions involve specification of building components and their attributes and the formulation of the value system for judging these. The iterative process of evaluating and modifying potential design solutions means considering several values for building components and their attributes. Some of these values are rejected because of unacceptable performance with respect to one or more design criteria. Although the rest may perform acceptably, each has advantages and disadvantages that are considered for decision making. Moreover, when a design decision is reconsidered for modifications to a design solution, it is critical to know *when*, *why*, and *how* it was made. Such information is important, even after completing the design process, because modifications are usually considered during the construction and occupancy of the building as well. It is critical to maintain decision-making records, so the design process is transparent and retraceable, and modifications are compatible with the designer's original intentions.

Assigning a value to a variable can be seen as an *issue* to be *resolved*, i.e., as a question to be answered. The values considered for the specific variable may be seen as *positions*, i.e., as potential answers to the question or candidates for the resolution of the issue. The advantages and disadvantages of each value may be seen as *arguments* to support and to negate each position, i.e., reasons to accept or reject it. Issues, positions, and arguments may occasionally include *references*, such as case studies, research findings, simulation results, and product catalogs. The design process can then be considered an argumentative process, through which a large number of issues are resolved by considering supporting and negating arguments for the various positions taken.

The BDSE will include an issue-based information system (IBIS) (Dehlinger and Protzen 1972; Kunz and Rittel 1970) to assist in the decision-making process and to record the design process in terms of issues, positions, and arguments. The IBIS will be linked to the multimedia environment for reference purposes. Each variable will be represented as an issue. The values considered will be represented as positions and may refer to drawings, as well as to the product catalogs of the multimedia environment. The supporting and negating arguments for each position may refer to simulation results, as well as to case studies and handbooks in the multimedia environment (Figure 8).

MODELING BUILDING DESIGN EXPERTISE

"Expertise" is a synonym for "experience." The theoretical uniqueness of each design problem calls into question the usefulness of design experience. However, we know that experienced designers are usually better and more efficient than inexperienced ones, so expertise must count, especially in specialized categories, such as building types (e.g., shopping malls, schools, and hospitals), building components and systems (e.g., fenestration, HVAC, and lighting), and specific design criteria (e.g., fire-safety, acoustics, and energy). In practice, experts exist for each of these recognized categories.

Design Expertise

Design expertise can be seen as the ability to treat specific, unique design problems in addition to the mastery of the general design process as it is taught in design schools. All designers share expertise in how to approach design problems in general; this expertise is equivalent to the model of the design process we have described so far in this paper, in which the designer establishes a value system, generates design solutions, and evaluates them. But this knowledge alone does not make an expert. In addition to this general knowledge, each designer knows about specific design problems on which s/he has been involved. Design expertise is then the body of reapplicable knowledge gained through repeated involvement in each of the three general design activities for specific design problems.

Formulation of the Value System. A building design's success is realized after the building is built and occupied through the reaction of the interested parties, such as the owner, the occupants, and the community. As a result, formulating a successful value system, i.e., design criteria, requires knowing the values of the interested parties. These are usually different, because each party experiences the building differently. For example, nurses see a hospital differently from the way patients, doctors, or the hospital owner sees it.

A designer will, through experience, acquire more and more knowledge about design criteria—not only what they are, but what "good" performance and "appropriate" relative value is for each criterion. "Good" and "appropriate" will be different for different places and times. In other words, a designer may be an expert for a given geographical location and point in history. Of the three types of knowledge—what design criteria are, what constitutes "good" performance for each, and how to evaluate the relative importance of each criterion—only the first is fully specifiable; the second may be specifiable, and the third is not specifiable. "Good" performance is usually *recommended through standards* and, occasionally, *enforced through codes*. However, knowledge of the relative importance of design criteria is the most difficult to gain, because it is sensed, rather than inferred or specified, through design practice and general participation in a community. This is the knowledge associated with the formulation of the value system that expert designers have. Because it is sensed, it cannot be specified, but only *demonstrated* in the same way that it is gained and maintained: through practice.

Generation of Potential Design Solutions. Designers generate potential design solutions using their creativity and their knowledge about building construction materials and systems. This knowledge can be mapped on the hierarchical structure of the BDSE building description (Figure 3) and appears throughout the hierarchy from general categories and prototypes to specific products. Although it is independent from the knowledge needed for formulation of the value system, it is the basis of a designer's ability to meet the design objectives. This type of knowledge also varies, more from place to place than from time to time. Because its temporal variations are usually slow and additive, this type of knowledge is usually reapplicable for a given socioeconomic environment and is referred to as *common practice*. It is usually specified through the attributes of materials (e.g., transmittance of glazing, U-value of masonry) and the components and attributes of systems (e.g., double-hung window, masonry wall).

Experienced designers do not merely know descriptive characteristics of available building materials and systems. Their knowledge also includes approximate performance in various contexts. This performance knowledge can be classified into two categories:

1. Knowledge of the *absolute performance* of a design solution, which usually means knowing whether or not the performance of a design solution is *acceptable* or *promising*, according to the designer's value system.

2. Knowledge of the *relative performance* of design solutions, which usually means knowing whether or not a design solution is *better* or *worse* than another, with respect to a single design criterion.

Knowledge of absolute performance is usually used to initiate or drastically modify potential design solutions. In general, this type of knowledge is not reapplicable because it depends on the designer's value system, which includes the relative importance of the design criteria for a particular building design problem. However, it can be reapplied for single-criterion-based design suggestions, where the rest of the design criteria are kept within acceptable levels that satisfy building codes and standards. Knowledge of relative performance is usually used to modify design solutions for specific performance improvements and is reapplicable, because it is usually independent of the designer's value system.

Evaluation of Design Solutions. The knowledge used to evaluate design solutions is directly related to the value system and can be classified into four categories:

1. Knowledge of the value of a performance variable as determined by a specific set of values for design and context variables.

2. Knowledge of the acceptability or promise of the value of a performance variable as determined by a specific set of values for design and context variables, which requires a specific range of acceptable values for the performance variable considered.

3. Knowledge of "goodness" of the value of a performance variable as determined by a specific set of values for design and context variables, which presupposes a specific value system for the performance variable considered.

4. Knowledge of "goodness" of a design solution with respect to two or more design criteria as determined by a given set of values for design and context variables, which presupposes a specific value system for the values of the performance variables, the design criteria considered, and their relative importance.

Because knowledge of performance acceptability depends on the relative importance of the design criteria, only the first category is, in general, reapplicable, and the second category is reapplicable for specific performance variables for which acceptable value ranges are specified by building codes or standards. There are two types of knowledge related to the value of a performance variable:

1. *Direct* knowledge, i.e., a priori knowledge of the value of a performance variable or its acceptability as determined by a specific set of values for design and context variables.

2. *Indirect* knowledge, i.e., knowledge of how to figure out the value of a performance variable and, as a consequence, its acceptability as determined by one specific value or any set of values for the design and context variables that affect it.

Direct knowledge is usually immediate, even without concern for the value required, e.g., knowledge that the illumination level in a space is very low (or very high) without necessarily knowing exactly how low (or how high). Indirect knowledge is obtained by simulation of performance and is of interest for computer applications only if it is computable.

Simulation of Performance. Determining the values of performance variables is critical for decision making. As discussed, the experience of the designer is limited to prediction of acceptability or promise, which is only adequate to justify exploration of a potential design solution. Simulation is a designer's only means for making accurate and reliable predictions, especially when more than one criterion and various alternative design solutions are considered. Ideally, designers would like to continuously monitor the values of performance variables as they assign values to design variables.

Most, if not all, performance simulations are computable, thus suitable for computer implementation. During the past two decades, computer-based building performance analysis applications have been developed and used in research-oriented institutions, being continuously improved to add modeling complexity and increase accuracy. The main-frame computing power that was initially required for their development and use is currently available on workstations and microcomputers, and simplified versions are available even for personal computers. However, the user interface is usually minimal, appropriate for use by specialists for research purposes. As a result, these programs require time-consuming preparation of complicated input and provide specialized, hard-to-interpret output. Moreover, they are incompatible with each other, as well as with available computer-aided drafting (CAD) packages, because they use different building description models, specialized to meet their particular requirements.

We believe that performance simulation is the most promising way to use the power of computers to assist designers in making decisions. As the capacity and power of computers increase within the next decade, computation-time requirements, already acceptable, will be minimized to provide immediate, interactive feedback. The BDSE will include a library of simulation algorithms, one for each performance variable. Simulation algorithms will be activated at the designer's request to determine the value of the corresponding performance variable. If the value of a design or context input variable has not been specified, it will be requested from the designer, who may ask for an explanation about the need for the requested value. Additional information will also be available through links to the BDSE's multimedia environment (Figure 9). If computation time decreases as expected, performance simulations will follow every value assigned to design variables. In the meantime, we are exploring methods to reduce computation time for interactive use, such as maintaining performance-variable tables to store the values of the input design and context variables along with the output value for the performance variable. As each performance-variable table grows, statistical routines may be implemented to determine regression equations that will provide quick estimates in place of time-consuming simulations (Kim et al. 1989; Sullivan et al. 1988). However, it remains to be seen if such methods will remain efficient compared to the continuously decreasing computation time for actual simulations, as storage and access-time requirements change.

Knowledge-Based or Expert Systems

Although we expect simulation to provide the body of expert knowledge required for performance evaluation, we are investigating means to cover the body of expert knowledge required to formulate value systems and to generate potential design solutions. The reapplicable knowledge with which designers formulate value systems includes knowing what design criteria "should be" considered, as well as acceptable value ranges and possible optimum values for performance variables according to building codes and standards. Designers' reapplicable knowledge for the generation of potential design solutions includes knowing which single-criterion-based suggestions to make for initial design solutions and modifications to improve specific performance.

Designers assign values to performance and design variables based on knowledge that can be represented in the form of conditional statements (e.g., if the climate is cold consider double, triple, or/and low-e glazing). As the number of these conditional statements increases, conventional programming techniques to encode them become inefficient because structuring them is increasingly complicated. Moreover, adding new conditional statements to an existing compiled set, requires explicitly knowing the existing structure and involves time-consuming compilation procedures. Artificial intelligence (AI) research has produced specialized programming techniques called expert systems (ES) or knowledge-based systems (KBS), which are most efficient for encoding large volumes of conditional statements in a way that is less structured that the conventional methods (Harmon et al. 1988). Knowledge is encoded in the form of *facts*, which are the equivalent of variables and their assigned values, and *rules*, which are *if-then-else* statements that establish relations among facts. An *inference mechanism* is used to examine the rules and draw conclusions based on user-specified facts.

During the past few years, many generic expert system environments, called "expert system shells," have been developed. The most sophisticated allow grouping of rules for increased efficiency, alternative ways of examining the rules (forward and backward inference), integration with conventional data bases, and links to multimedia environments. One such system will be integrated in the BDSE to encode design knowledge and link it to the multimedia reference module.

The Expert System Module of the BDSE. Based on reapplicable design knowledge gained from experience, two types of rules can be developed to establish relations among the design, context, and performance variables:

1. *Checking rules*, which check for:

   a. Conflicts or constraint violations, i.e., incompatible values of design variables, based on established relations among them and the context variables as well.

   b. Potentially unacceptable performance with respect to one or more design criteria, based on building codes and standards.

2. *Suggestion rules*, which suggest:

   a. Design criteria to be considered, based on building type.

   b. Acceptable value ranges and possible optimum values for performance variables, based on building codes and standards.

   c. Initial values for design variables, based primarily on individual design criteria and the values of related context and design variables.

   d. Values for design variables to improve performance with respect to a single performance variable, based on the values of related context and design variables.

Checking rules may be active, continuously monitoring every design decision, or be activated at the designer's request so that they do not interrupt her/his line of thought. Suggestion rules will be activated only at the designer's request, as an alternative to assigning a value to a variable (Figure 6). When suggestion rules will be activated and values that have not been specified will be needed by the expert system, the designer will be asked to provide them. During such interactions, the designer may ask for explanations or suggestions. In addition to the immediately available response, the expert system module will be linked to the multimedia environment, providing access to references and allowing the designer to explore and understand the specific topic (Figure 10). The suggestions provided by the expert system will be treated as positions and will be recorded in the IBIS, along with the related supporting argumentation and the multimedia-environment references.

We expect that checking rules for unacceptable performance will eventually be replaced by user-defined acceptable value ranges for all performance variables, whose values will be monitored continuously by means of simulation. Adjusting the minimum and/or maximum boundaries for acceptable value ranges may be considered as equivalent to specifying the relative importance of the design criteria. As a result, the ideal of continuously monitoring the values of the performance variables will be tailored to the designer's specific value system.

Suggestion rules for the values of design variables can be mapped on a matrix, where the rows correspond to performance variables and the columns correspond to design variables. Each matrix element corresponds to expertise associated with a single design criterion or performance variable and a single building component or component attribute. Design-criterion-based experts usually suggest values for *more than one* design variable, which means addressing several matrix elements at the same time. For example, an energy-expert's daylighting considerations may result in suggestions for various fenestration attributes, electric lighting controls, and values for reflectance of walls. To reflect this fact, a building design knowledge base should follow design criteria, rather than building components, limiting building-component-based expertise to identifying and organizing alternatives to be considered, independent of performance and context variables. This does not prevent component-oriented development, as long as the rest of the building components that affect each design criterion are addressed. We expect to understand more about the application of knowledge-based systems to encode the identified building design expertise in the form of rules by developing a prototype knowledge base for designing fenestration systems, as described in the next section.

A FENESTRATION DESIGN KNOWLEDGE BASE

Based on our model of the design process and related knowledge, we have initiated development of a prototype knowledge base for designing fenestration systems. Our major objective is to establish a method for formulating and organizing rules, so we can slowly develop the BDSE's knowledge base(s).

The design variables considered for development of this prototype knowledge base are: width and height of fenestration; fenestration's wall position, specified by sill height and center offset; framing; glazing type; interior shading; and exterior shading. Other related attributes of building components and systems, such as electric lighting controls and reflectance of interior surfaces, are also considered, because they affect the performance of the fenestration with respect to the design criteria considered. These include luminous and thermal comfort, energy requirements, economics, and view. The relevant performance variables include work-plane illuminance, glare and thermal comfort indices, energy loads, and associated cost. Rules are formulated independently for each performance variable (e.g., work-plane illuminance) according to the following steps:

1. Define suggestion rules for acceptable value ranges and optimum values for the performance variable, based on building codes and standards (e.g., if video display terminals are used, then work-plane illuminance should not exceed 75 fc [750 lux]; if recommended illuminance for a horizontal task is greater than 75 fc [750 lux], then supplementary lighting should be used to provide the required illuminance [IES 1987]).

2. Identify the design and context variables that affect the value of the performance variable (e.g., glazing transmittance, space walls' reflectance, window orientation, daylight availability).

3. Consider the relation of each design variable identified in step 2 to the performance variable (proportional or inversely proportional, linear or exponential) in order to define suggestion rules for specific performance improvement (e.g., if glazing transmittance or space walls' reflectance are increased, then work-plane illuminance is increased).

4. Specify computable function(s) of these design and context variables to determine the value of the performance variable for simulation purposes (e.g., specify algorithm to compute daylight work-plane illuminance).

5. Define possible values in the form of lists and/or ranges for each design variable identified in step 2 (e.g., typical values for glazing transmittance range from 0.1 to 0.9; typical reflectance values for wall reflectance range from 0.2 to 0.8).
6. Consider the relationship of each design variable identified in step 2 to design and context variables in order to define checking rules for conflicts (e.g., window width should be less than or equal to "parent-wall" width).

7. Consider possible combinations of values of the design and context variables identified in step 2 in order to define checking rules for unacceptable performance, as considered in step 1 (e.g., if video display terminals are used and distance from the window is less than 10 ft [3 m] and window-to-wall area is greater than 0.5 and glazing transmittance is greater than 0.5 and no shading is provided, then work-plane illuminance may be unacceptably high).

8. Consider possible combinations of values of the design and context variables identified in step 2 in order to define suggestion rules for the values of the design variables, to meet performance as specified in step 1 (e.g., if video display terminals are used and glazing transmittance is greater than 0.5, then consider use of a shading system).

In addition to using handbooks and research publications on fenestration design, we have asked consultants and designers with experience in fenestration systems to go through specially designed scenarios of fenestration design problems in videotaped sessions. We study these sessions to try to understand the experts' reasoning and to formulate rules based on what we observe. Our initial design-problem scenarios have focused on design of office spaces.

Preliminary findings indicate designing fenestration systems for luminous and thermal performance becomes complicated when constraints, based on other design criteria such as esthetics and cost, are imposed by a client or designer. These constraints affect the range of acceptable values for fenestration system attributes, increasing the difficulty of any problem because the experts may have to consider fenestration systems with which they may have no previous experience. At this point, fenestration performance must be simulated. Experts usually make more than one suggestion to be explored, especially with respect to economic performance, before a final decision. If no constraints are imposed, then experts often suggest alternatives that are all the same basic type of fenestration system. For office spaces, experts suggest low-e glazing with interior venetian blinds and exterior overhang according to orientation and latitude, to reduce cooling loads and provide luminous and thermal comfort. They recommend single, double, or triple glazing to reduce heating loads and provide thermal comfort.

Various knowledge-representation problems have been identified, such as those related to the use of ordinal scales. Experts often use statements like "...since the climate is *good*..." or "...since the room is *deep*...," confronting us with the problem of determining what a "good" climate or a "deep" room is. We prepare a series of such questions for the experts to determine appropriate knowledge representation schemes. Also, experts generally suggest *generic* rather than specific design solutions, such as "...low-e glazing..." or "...light-colored venetian blinds...," which forces us to try to classify the available fenestration components and systems. In response, we are developing libraries of prototype fenestration components to be design solutions for suggestion rules. We are planning special sessions with experts to discuss developing these libraries and the advantages and disadvantages of each prototype for the purpose of formulating appropriate suggestion rules.

CONCLUSIONS

In this paper we have described the structure and operation of a computer-based Building-Design Support Environment (BDSE) with emphasis on modeling the building design process and the knowledge and expertise related to it. The design process is modeled around three iterative activities: formulation of a value system, generation of potential design solutions, and evaluation of the solutions. Building design knowledge is modeled using three types of variables: design, context, and performance. These variables are used to describe the building, its context, and its performance, respectively. The three resulting data structures are shared by all modules of the BDSE, and the interrelations of the modules support the iterative nature of the design process.

The knowledge of experienced designers is only partially reapplicable and specifiable, which limits the application of knowledge-based systems to suggesting design criteria and acceptable value ranges for performance variables based on building codes and standards, suggesting initial design solutions with emphasis on a single design criterion, and suggesting modifications for specific performance improvement. The most promising application of the continuously increasing power and availability of computers to assist designers directly is in assessing performance by means of simulation. Computers can contribute most to design decision making by determining the values of performance variables, because the other major design activity, translating these values into a measure of "goodness," requires knowledge that is not reapplicable and cannot be easily specified.

We have also presented a method used to develop a prototype knowledge base for fenestration design. Our procedures for formulating and structuring rules include videotaping and studying the way experienced designers and specialized consultants respond to specially formulated scenarios of fenestration design problems. Preliminary findings have raised concerns about representing ordinal scales and prototype design solutions that, we have found, are commonly used by experts.

ACKNOWLEDGMENTS

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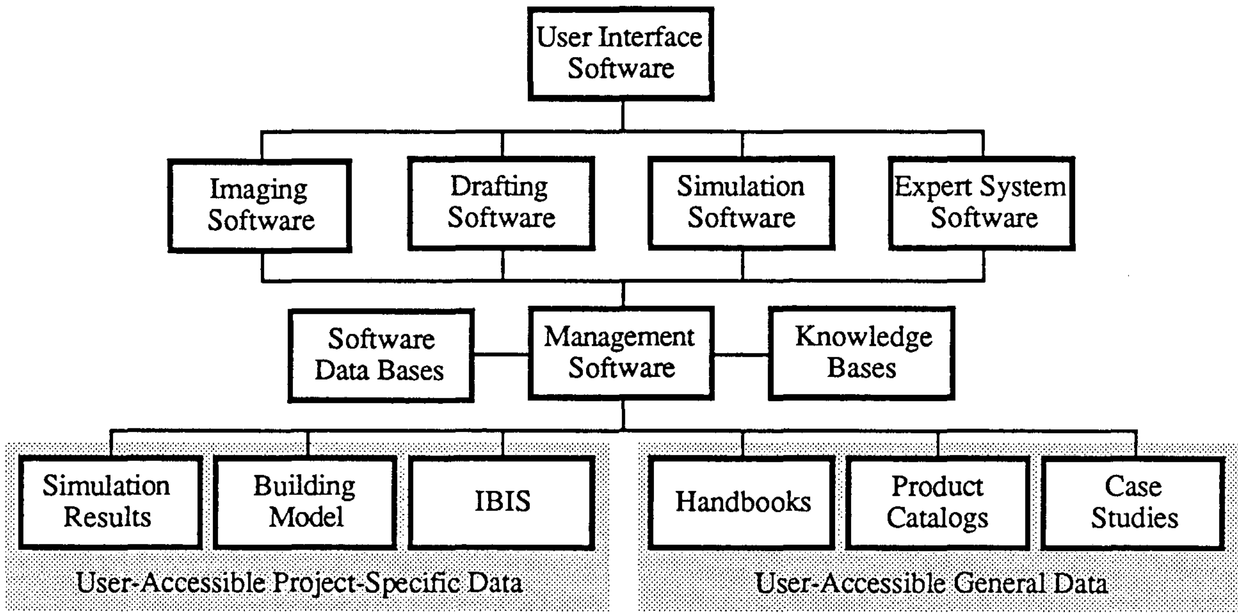

Figure 1. The components of the BDSE.

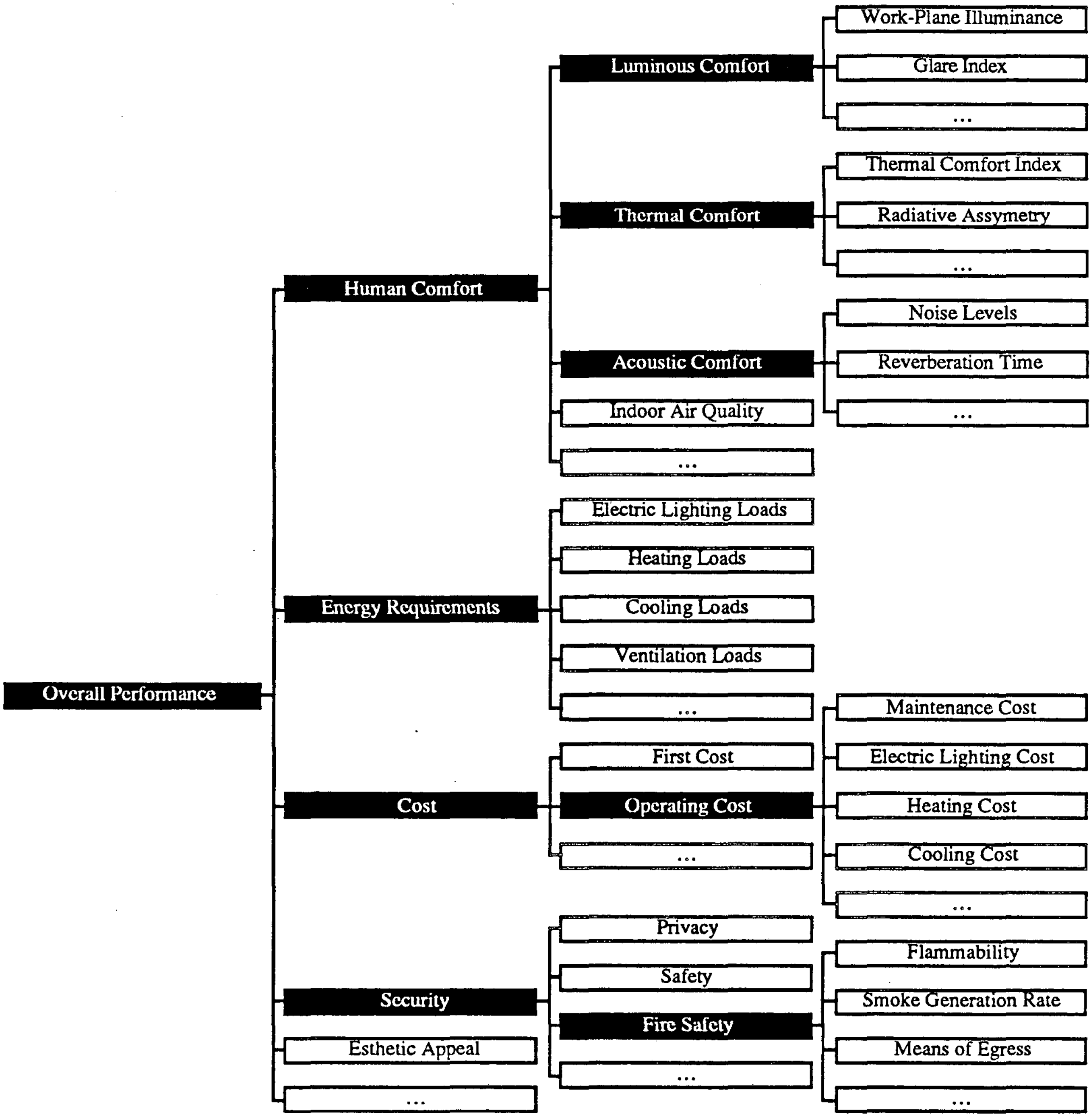

Figure 2. An example of a hierarchical representation of the value system. Black boxes indicate design criteria that are evaluated indirectly, through further specification.

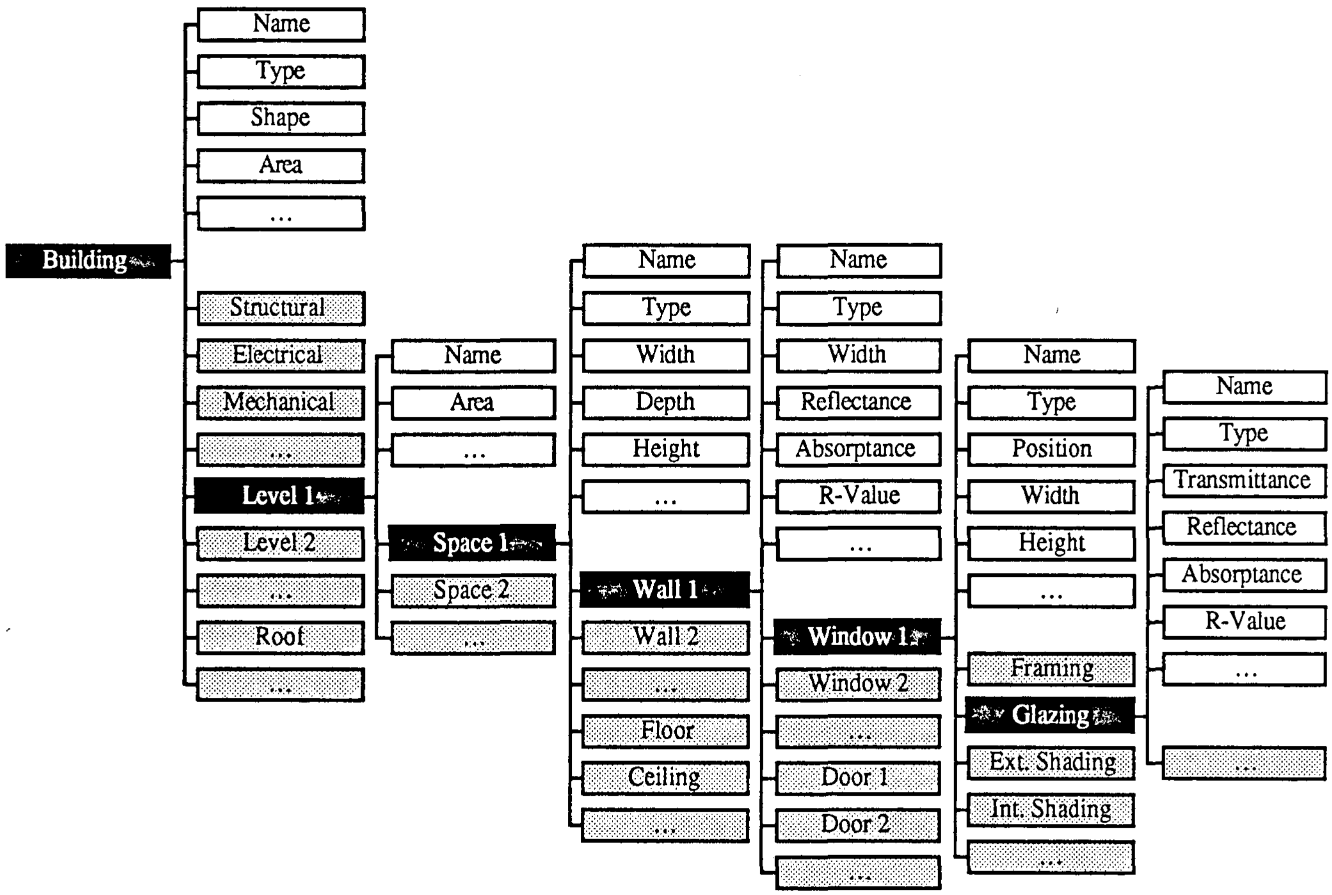

Figure 3. An example of a hierarchical representation of the building and its components. Gray boxes indicate objects whose attributes and "children" are not included in this diagram. Black boxes indicate objects whose attributes and "children" are included in this diagram.

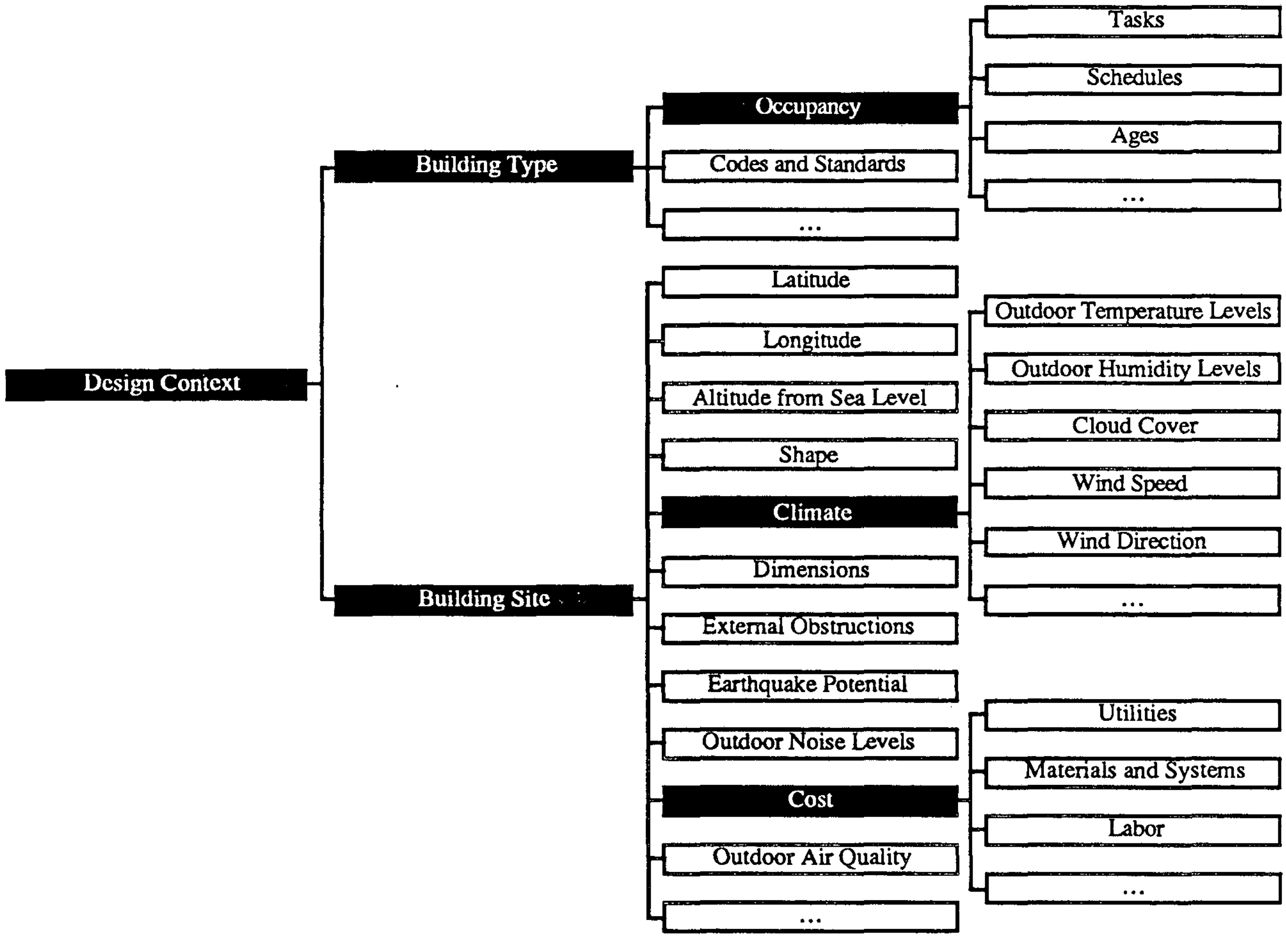

Figure 4. An example of a hierarchical representation of the building-design context. Black boxes indicate context variables that represent a set of more specific context variables.

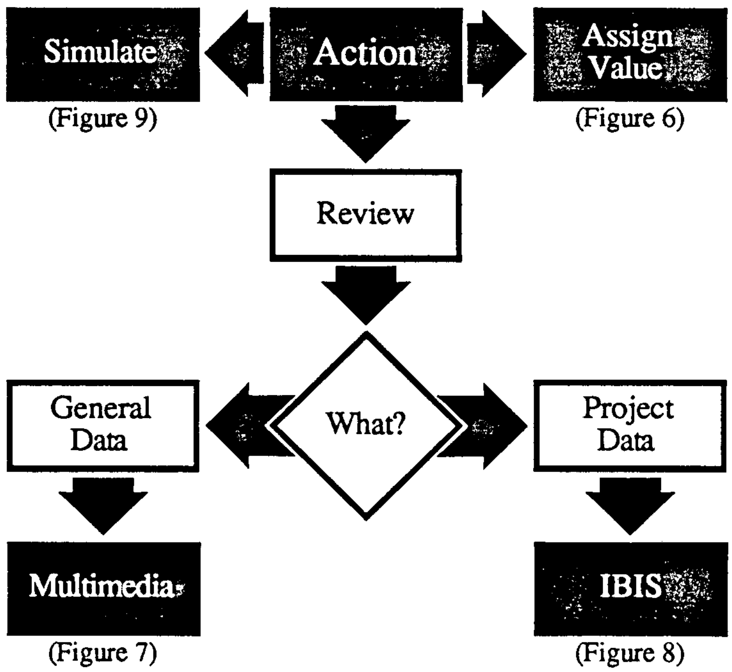

Figure 5. The main actions supported by the BDSE. The user may assign a value to a variable, request the value of a performance variable through simulation, or review either project-specific or general data. A black box indicates a BDSE module that is described in the figure specified next to it.

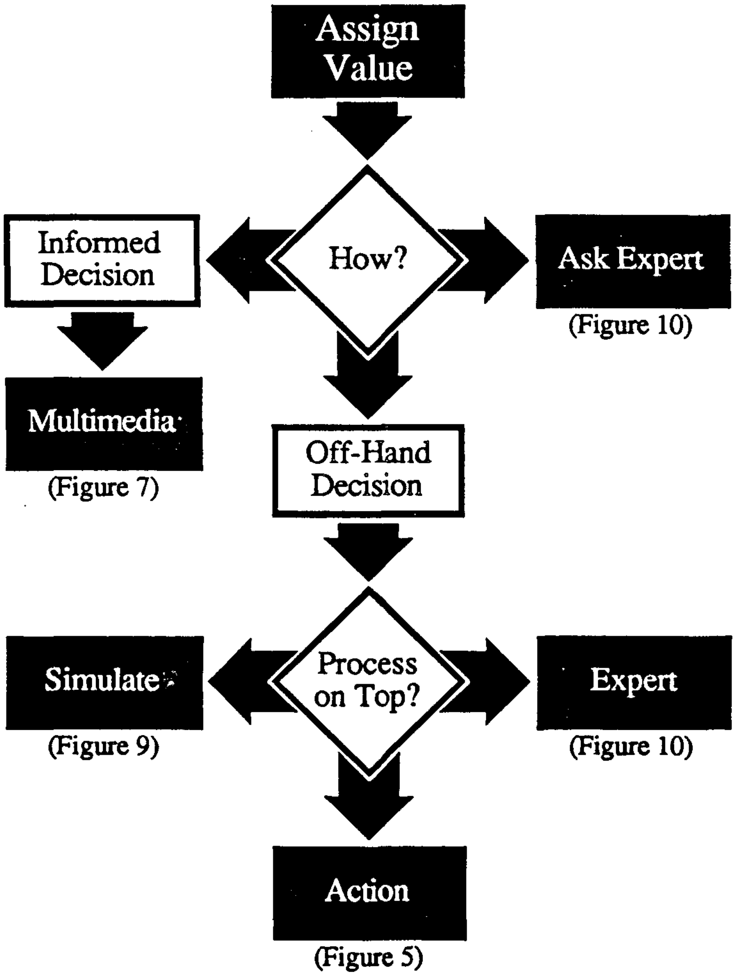

Figure 6. The options for value assignment supported by the BDSE. Once an off-hand decision has been made, control is passed either to the BDSE module that requested the value, i.e., a simulation or an expert system process, or to the Action module. A black box indicates a BDSE module that is described in the figure specified next to it.

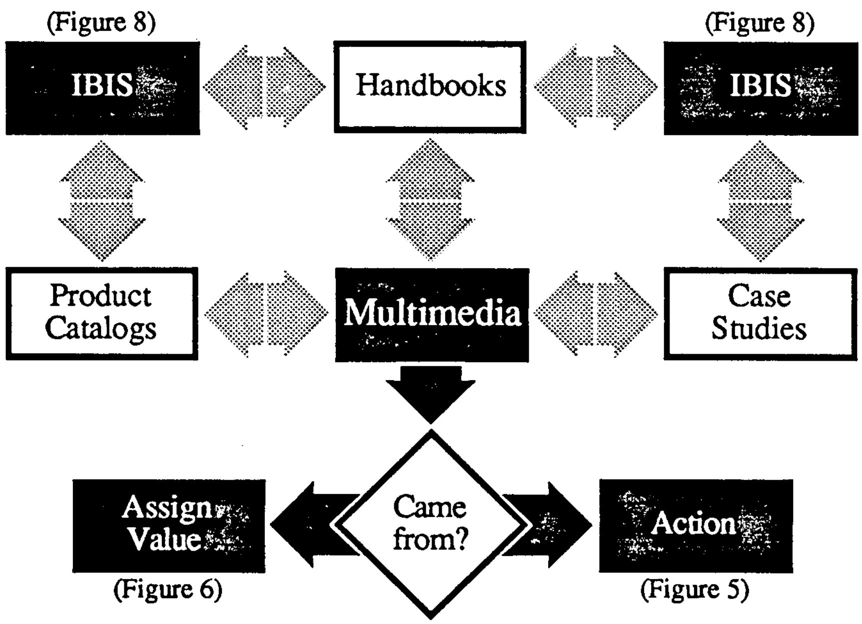

Figure 7. The multimedia module of the BDSE. A black box indicates a BDSE module that is described in the figure specified next to it.

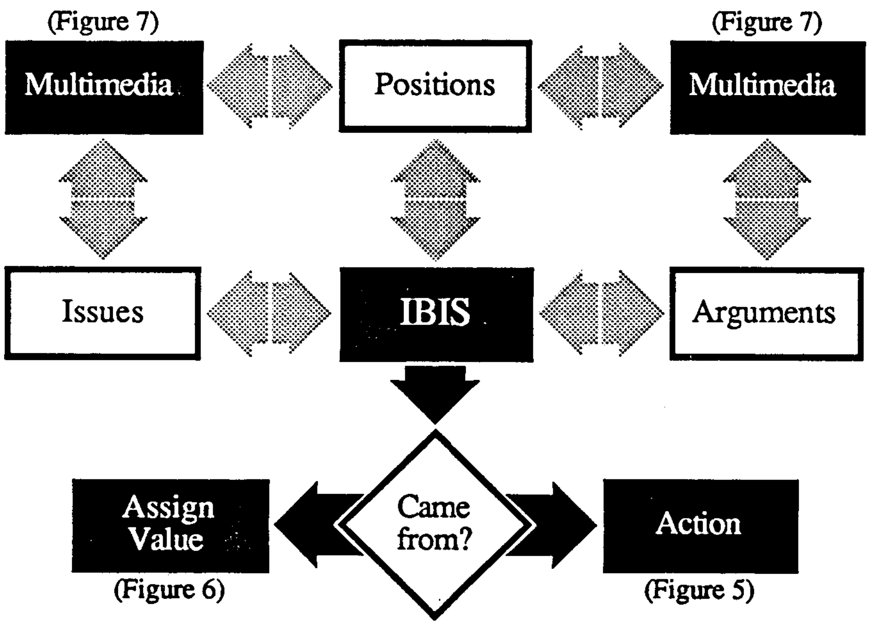

Figure 8. The IBIS module of the BDSE. A black box indicates a BDSE module that is described in the figure specified next to it..

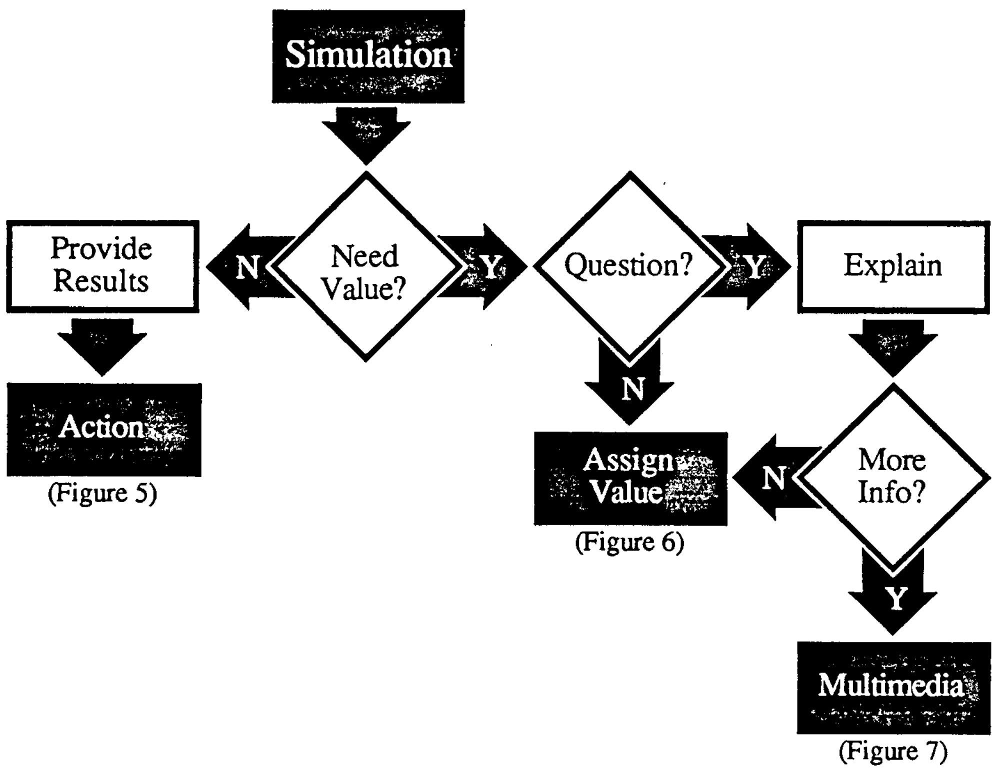

Figure 9. The simulation module of the BDSE. If a value is requested by the simulation module, the user may ask for explanation before assigning it. A black box indicates a BDSE module that is described in the figure specified next to it.

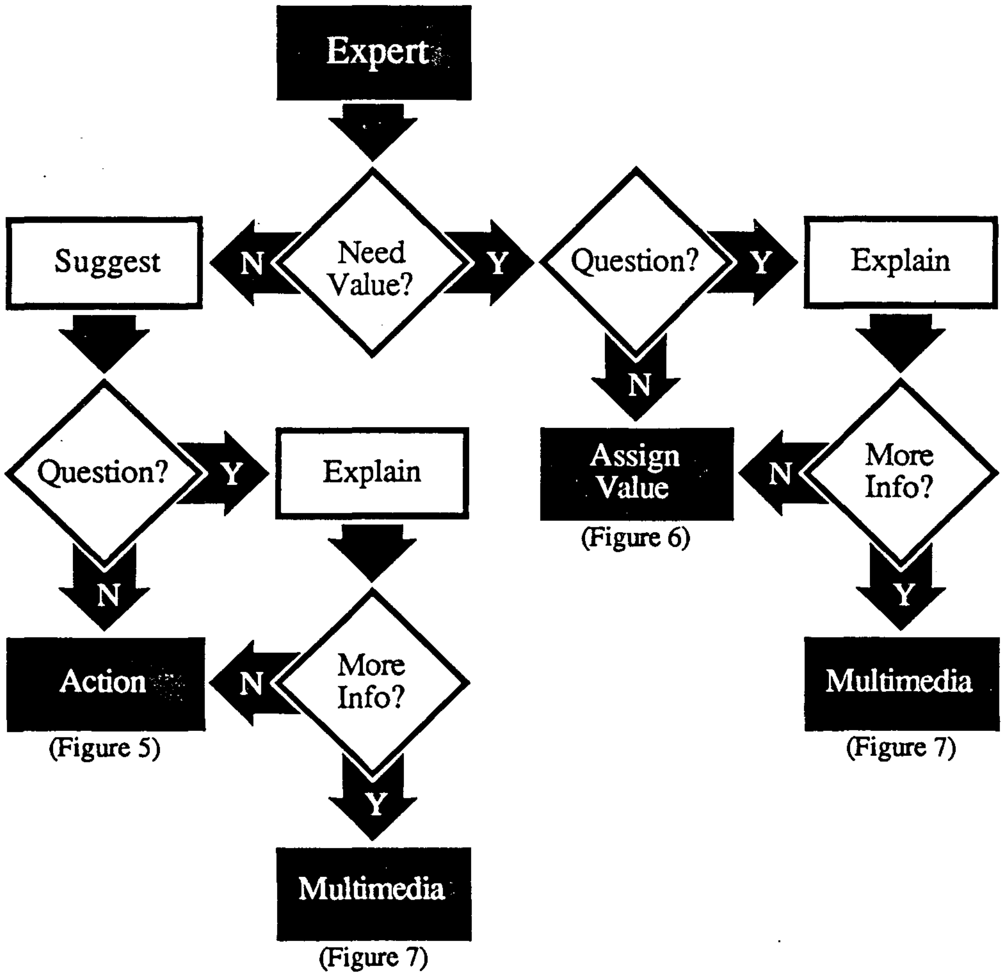

Figure 10. The expert system module of the BDSE. If a value is provided or requested by the expert system module, the user may ask for explanation before accepting or assigning it. A black box indicates a BDSE module that is described in the figure specified next to it.

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