Future roles of knowledge-based systems in the design process

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ABSTRACT
This paper examines the future roles of knowledge-based systems in the design process. It commences with a brief review of computer-aided design and knowledge-based systems prior to examining the present and future roles of knowledge-based systems in design under the headings of: design analysis/formulation; design synthesis; and design evaluation. The paper concludes with a discussion on design integration, novel design, and detail design.

1. INTRODUCTION

Currently the computer aids for architectural design centre around drawing programs and detailed evaluation programs. The aids available to facilitate the visualisation of the design are geometric modelling programs and CADrafting programs. Although visualisation is an important aspect of the design process, these computer aids for visualisation require that the design process be nearly completed, i.e. the designer specifies a design to the program and the program passively displays the results. The computer aids that support detailed evaluation, e.g. spatial analysis programs, provide information about a completely specified design. There has been some limited work in developing computer programs to aid the designer during the early stages of design, e.g. BDS (Hoskins, 1977), although these have been mainly concerned with spatial layout (Liggett, 1985).

Future computer aids for designers will include programs that actively participate in or support the design process. Some areas that are currently not well supported include:

design analysis/formulation,
design synthesis, and
design evaluation at the early stages of design.

The development of knowledge-based systems, founded on artificial intelligence research, provides the potential for producing computer aids that support the design process in addition to design visualisation and analysis. Knowledge-based systems in computing distinguish themselves from other kinds of systems by their use of reasoning processes based on inferencing and their use of symbolic computation rather than numeric calculation based on algebra and arithmetic. In such knowledge-based systems it is customary to make the design knowledge explicit and to separate it from the rest of the system. This is in contradistinction to most of computing where the knowledge is implicit and intertwined with the ways in which it is controlled within the system.

This paper reviews some current research at Sydney and Carnegie Mellon Universities on knowledge-based systems in building design. This is then utilised to provide a guide to future roles of knowledge-based systems in the design process.

Section 2 commences with a description and decomposition of the design process and considers each subprocess separately. Knowledge-based systems research related to each subprocess is presented, followed by some discussion on future trends and potential applications. This paper concludes with a discussion on two immediate potential roles for knowledge-based systems, design integration and detail design, and a long term goal of knowledge-based novel design.

2. DESIGN

Design is a process by which design intentions are transformed into design descriptions and has identifiable phases or subprocesses. Although the phases may not be addressed hierarchically for the entire design cycle and are often carried out recursively, there is an inherent order in the way in which designers approach a design problem. The following represents one decomposition.

(i) *Design analysis or formulation* involves identifying the goals, requirements and possibly the vocabulary relevant to the needs or intentions of the designer. It is the development of the detailed specification of the design brief.

(ii) *Design synthesis* involves the exploration of a design space indentified above and the production of one or more design solutions. Producing a solution includes the formation or selection of a prototype followed by elaboration or refinement.

(iii) *Design evaluation* involves interpreting a partially or completely specified design description for conformance with goals and/or expected performances.

The following sections address the phases listed above and their characteristics and the role that knowledge-based systems can play in supporting them.

2.1 Design Analysis/Design Formulation

Design analysis or formulation involves identifying the goals, requirements and the vocabulary relevant to the needs of the client and the intentions of the designer. The result is a detailed specification of the design brief. Design formulation has a direct effect on the success of the problem and converts the results back into a form which matches the original description.

Future systems could be constructed to address different phases in design analysis and formulation. At one extreme, design analysis involves the identification of the nature of the design issues. Such systems would act as catalysts to aid the designer in exploring and explicating the origins and goals which precede a specific formulation. At the other extreme, design formulation involves the identification and specification of design requirements and decisions. Future systems here are likely to utilise problem-specific knowledge which generates the transformation between goals and requirements and decisions.

2.2 Design Synthesis

Design synthesis involves exploring alternative conceptual solutions to the design problem. This exploration requires that the designer specify some search space, or the part of the world that is relevant for the current circumstances, and generate alternatives that are feasible in the context of the formulation. Experienced designers resort to trial and error less than novice designers when they synthesize designs, suggesting that the use of knowledge based systems to represent "experience' may improve design synthesis.

Our current understanding of synthesis is based on the notion that the design space is characterized as a state space where each design or partial design is a state within an n-dimensional bounded space. Design formulation defines both explicitly and implicitly the boundaries of the space. Design synthesis, as used here, is the process of producing designs within that space.

Design synthesis can be considered as prototype refinement where a prototype is selected as part of the formulation process or constructed during the synthesis process from other prototypes. This effectively locates the designer at a specific state in the state space and constrains movements away from that state into a narrow set defined by values for decision variables. The knowledge needed to select an appropriate prototype is not fully understood. Most current systems have implicit prototypes and utilise other knowledge to refine or specialise that prototype for the particular circumstances. RETWALL (Hutchinson, 1985) is an expert systems approach to the selection and design of earth retaining structures based on prototype refinement. Ill-RISE (Maher, 1984) constructs and refines alternative prototypes of the structural system for a high rise building.

There are several processes used in design synthesis, or prototype refinement. The processes discussed in this section are:
(i) design grammars; and
(ii) heuristic search.

Design Grammars

Design grammars commence with an initial state in the state-space and use knowledge in the form of context dependent rewrite rules to generate next states (Gero and Coyne, 1985; Flemming et al., 1986; Hanson and Radford, 1986). Thus, a design grammar contains within itself the knowledge to define completely a state-space (which might be finitely or infinitely bounded). As a compact means of representing that knowledge grammars are very efficient but require additional evaluation, generally against the achievement of specific goals, in order not simply to generate an unranked set of designs.

Design grammars have the potential to enumerate a state-space. In order to generate designs which meet specified goals the generation can be treated as search which is guided by some form of control. This control normally takes the form of *planning* the generation utilising additional knowledge. This has been explored by Coyne (1986). The function of this abstraction of design generation is to control the combinatorial explosion which occurs with the unfettered execution of a design grammar. This issue of control remains a difficult one.

Heuristic Search

Search is the process for moving from one state to another in the state space. Since the number of states in a design state space is large, blind or exhaustive search is rarely used. The alternative is guided search in which strategies for controlling the search utilise the knowledge in the knowledge base. Some common strategies are forward and backward chaining and some common representations are rules and frames.

RETWALL (Hutchinson, 1985) makes use of the BUILD expert system shell (Rosenman, 1985). This shell encodes knowledge as rules and has both forward and backward chaining search strategies. RETWALL is composed of three subsystems. The first deals with the decisions as to whether a retaining wall is needed. The second deals with the means of selecting a particular prototypical retaining wall, whilst the third refines the prototype into a unique design appropriate for the specific situation. In refining the selected prototype, the inference mechanism uses constraint directed depth first backward chaining to select appropriate values for design variables. These values are used as the basis of a graphic representation of the resulting design.

EDESYN (Maher, 1986) provides a framework for developing synthesis expert systems. The knowledge base is entered by the expert as a set of decisions and alternatives for each decision as well as constraints on synthesis decisions. The inference mechanism uses a constraint directed depth first search for valid combinations of design decisions. The result of the synthesis process is a set of alternative designs, where each alternative is described by the final product since it controls all that follows by explicitly and implicitly limiting what can follow. However, it is also a part of the design process that is highly subjective and appears to rely heavily on personal knowledge and experience.

To date, there has been little work done to provide support for this phase. There are two extremes at which design formulation can be treated: purely symbolic and purely numeric descriptions. At the symbolic level knowledge-based systems can potentially provide support in the form of a problem formulation consultant. Such a consultant could interact with the designer by asking questions that would result in a brief that is neither too specific to preclude novel solutions nor too general to result in an extremely large design space. At the numeric level, knowledge-based systems can provide support by constructing the numeric description from a declarative symbolic description. Such a system could be constructed with a knowledge base induced from existing designs to produce compiled knowledge or a knowledge base founded on episodic memory.

GUIDANCE is an example of an expert system for symbolic formulation (Sudarbo, 1987). This system interacts with the user to help identify the characteristics and requirements of an engineering design problem. The expert system uses the concept of synectics (Gordon, 1961) to help the designer generalise the problem definition, and then to formulate the brief and identify potential solution spaces. The purpose in developing this expert system is to explore the concepts and themes that are associated with creative design, such as brainstorming and lateral thinking.

STRUPLE is an example of an expert system for identifying a subset of the design vocabulary that is most promising for the current design problem (Maher and Zhao, 1987). This system accepts a description of the requirements for the structural design of a building and provides a set of vocabulary elements to be explored during the synthesis of the design description. STRUPLE makes use of a database of design solutions and a methodology for transformational analogy (Carbonell, 1982) to identify the relevant vocabulary. The expert system infers the criteria by which a design solution is similar to the new problem and recognizes the elements of the design solution to be considered during synthesis.

For numerically describable problems the knowledge required to formulate specific classes of design decision making has been externalised. For example, the knowledge required to formulate a design decision making problem into an optimization problem has been incorporated into a knowledge-based system called OPTIMA (Balachandran and Gero, 1987). OPTIMA allows the designer to describe the design requirements declaratively in a very restricted subset of English, then formulates that description via frame-based representation into a canonical algebraic description of an optimization problem. OPTIMA recognises the formulation and selects and executes an appropriate algorithm to solve the optimization combination of one alternative from all decisions. Current work on this project includes incorporation of complex decisions, where decisions may be decomposed into lower level decisions, and numerical reasoning, where a decision may require calculations based on previous decisions.

There are many different ways to view the future of knowledge based design synthesis. One is to consider the processes used for prototype refinement. Design grammars and search have already been discussed, what is missing is pattern matching as a synthesis process. Pattern matching is the selection of a state in a given state space. As the use of knowledge-based systems increases, implying that designers are able to externalise more of their design knowledge, we can reduce the amount of search by replacing search paths with patterns. Thus, states now encapsulate the search path. Future systems are likely to make increasing use of pattern matching.

Another consideration is the use and generation of prototypes. Prototype refinement has already been discussed. Prototype generation and adaptation precede prototype refinement. Prototype generation is a process by which prototypes are designed ab initio. Prototype adaptation takes an existing prototype and modifies some of its characteristics. Both of these processes require prototype refinement to produce specific designs. Future systems may include prototype generation and adaptation by incorporating systematic learning and creativity.

2.3 Design Evaluation

Design evaluation involves interpreting a partially or completely specified design description for conformance with goals and/or expected performances. Design evaluation is a process that designers apply implicitly throughout the design process. It is also a process that is largely unsupported by current computer tools when applied to early design synthesis. The use of knowledge-based systems to begin to articulate the implicit evaluation criteria used by designers will lead to a better understanding of early design evaluation.

Knowledge-based systems readily lend themselves to the role of evaluation. The input to an evaluation program is a partially or completely specified design and the output is either satisfaction or recommendation. The two difficulties in developing such programs lie in the formalisation of evaluation criteria for partially specified designs and in the interface between what is usually a syntactic representation of a specific computer-aided design system and the semantic representation of a knowledge-based system. This is apparent when considering the knowledge required to evaluate an architectural design for structural feasibility, constructability, and maintainability. The development of partial design evaluators is still at an experimental stage. Much of the evaluation programs being developed are capable of evaluating a design from the perspective of the designers own field, e.g. structural evaluation of a structural system (Maher, 1984).

Rosenman and Gero (1985) have demonstrated a system for evaluating buildings against the building code where the designer performs the syntax to semantic mappings which convert the design description into input for an expert system. Manago and Gero (1987) demonstrate how knowledge can be used to construct the syntax to semantic conversion which allows an expert system (which expects semantic replies) to communicate with the geometric model of a computer-aided design system (which is represented syntactically). This shows one way of automating explicit design evaluation against criteria which were only implicit in the design goals.

Future knowledge-based design evaluation systems are likely to concentrate on evaluating partial designs rather than only completed designs. As knowledge for design synthesis becomes externalised it will be available for use in evaluation systems. Thus, the knowledge used in construction planning might be used to evaluate a preliminary design for constructability. As conventional CAD systems increase their penetration into design offices so the need for knowledge-based evaluations of design descriptions in the form of the CAD database will increase. Future knowledge-based systems will be developed to translate database descriptions into an appropriate form of knowledge based description using the syntax to semantics transformation described earlier,

3. DISCUSSION

This discussion identifies the roles that knowledge-based systems will have in the near future and in design research. It can be expected that knowledge-based systems will support, or even partially automate, the detail design process. It is also likely that knowledge-based systems will provide a means for integrating currently available and future computer aided design tools. In the area of design research, knowledge-based systems promise to improve our understanding of novel design by providing a means to systematise this creative process.

DetailDesign

Detail design involves the refinement of a design description such that all requirements are satisfied. Many aspects of detail design are routine, yet there is relatively little support for this phase of design. Knowledge-based systems provide an opportunity to automate the portions of detail design that do not require human interaction and to support those that do.

Detail design is generally less complex and much more highly constrained than design synthesis. It commences with an implicit prototype which is refined or specialised for the case at hand by including context in the goal-driven decision making. Radford and Mitchell (1986) have written a system called EAVES which carries out the detail design of the eaves of a domestic scale roof to produce designs in a specific architectural style. They use a design grammar as the means to encode the knowledge and execute the grammar to generate context-dependent detail designs. Examples such as this demonstrate the untapped potential of a knowledge-based approach to automating detail design.

Design Integration

As the design progresses from formulation to detail design, a considerable amount of information is generated. This information is currently communicated through drawings, and nowadays computer-based geometric models in which inconsistencies and justifications are hard to find. A knowledge-based systems approach to design integration provides an opportunity to intelligently manage and present the design information to facilitate communication and integrity as the design proceeds.

One conceptual model for integration makes use of a blackboard architecture in which the blackboard serves as the global representation of the design solution. The subprocesses of design, performed automatically or manually, all communicate through the blackboard. An additional program or knowledge base need only know about the organisation of the blackboard and may ignore the purpose or existence of other programs. In order to maintain consistency and integrity, only the information on the blackboard need be considered. This approach is the basis for a project at Carnegie Mellon University for integrated building design.

Novel Design

So far we have been discussing how knowledge-based systems can and might be able to assist the designer in those situations where a design prototype exists either explicitly or implicitly. This is the case in all the state space schema described above. Novel designing occurs when designs in the state space which have not been produced before are generated or found; this is called *innovative design*. Since the state-space is bounded, extending the boundaries allows for the production of *creative designs,* i.e. those that did not exist conceptually before in the system (Coyne et al., 1987).

How to do this is still the subject of considerable research but interesting directions are emerging. Two approaches are being explored at Sydney University. The first is based on *inductive learning* where a (relational) design grammar is semi-automatically induced from a pre-existing set of designs (Mackenzie, 1987). This design grammar not only generates the existing set of designs but extends the boundary of the state space and is capable of producing other, similar designs. Since more than one grammar can be induced, there are many ways in which the state space can be expanded.

The second approach utilises the concepts of *memory-based reasoning* (Stanfill and Waltz, 1986; Oxman and Gero, 1987) where learning occurs at the specific instance level in episodic memory rather than by generalisation. This allows directed expansion of the state space including an expansion of goals. These two approaches contrast compiled and episodic knowledge used by designers.

Conclusion

There have recently been two changes in emphasis in computer-aided design. The first has been reflected in a move away from a primary concern with graphics to modelling as a means of supporting design. The second, and more recent, has been the move from numeric to symbolic computation with its ability to automate reasoning through automating inference processes. This second change is the basis of knowledge-based systems and appears to auger a more fundamental change in the role of computers in the design process.

Although there is still a paucity of well developed knowledge-based design and design support systems in use today, we have limned the state of the art and projected it into the immediate future to identify future roles of knowledge-based systems in the design process. We have suggested an increasingly active role for such systems which is likely to have the potential to change the design process itself.

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