Computer environments for design and designers

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The mode of use of expert systems in design applications is significantly different from other application areas. First experience in the design domain suggests that expert systems will be employed on a design problem in a variety of functions. For example, they will be employed as consultants in generating architectural programs. They will also find an important critiquing role in the appraisal of proposals by the designer. There is evidence also that design automation, especially in design detailing, will be an important application.

This paper reports on the work undertaken as part of the research programme 'Designing and Design Knowledge in Architecture and Engineering' (NSF Grant 98348). It investigated the application of knowledge engineering methods in a general computational environment for designers. A representative selection of four knolwedge-based system tools or 'shells' were used in the study. The primary interest was to determine the performance of these software packages as the core element in a new genre of integrated KBDS (Knowledge-Based Design Systems). The final sections of the paper describe the further work that remains to be done, including a methodology for acquisition of design knowledge.

Keywords: expert systems, computer aided design, design knowledge

This paper represents a discrete element in the research programme 'Designing and Design Knowledge in Architecture and Engineering' (NSF Grant 98348). The programme is composed of four associated research topics. The first three topics focus on different aspects of research in the design process. One addresses the development of a design constraint manager and a design knowledge base. The second topic is concerned with the observation and simulation and exploration of the design constraint manager in a collective design situation. Topic three uses design exercises to explore the development of leading design ideas.

The fourth topic, here being reported, worked to assess the impact of current computational techniques on the practice of design, to assess the potential of new technology to enhance the study of the design process and to augment the techniques of design research.

In the investigation of the current computational environment, a diverse set of techniques was studied, including data and information processing, digital modelling and knowledge engineering. These techniques were used in different phases of the design process. Design-related visualization techniques included graphics, videographics and computational video. Analytic, synthetic and consultative applications of the technology in design were appraised. Languages including Lisp and 'C', as well as special-purpose computer-aided design and AI languages were used.

Knowledge engineering, as in many other professional domains, is being very actively researched for its application potential in architecture and other design disciplines. Design has many features that distinguish it fundamentally from the more conventional applications of knowledge-based systems such as medical diagnosis and actuarial prediction. Not least are those abstract and qualitative issues that form the core of design knowledge

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at the conceptual stages of the process. The initial approach taken in this study was to appraise the individual technologies that relate to the design process, for example digital modelling, knowledge engineering, and optical laser technology. There was also an interest to explore, in a design environment, current developments in operating systems.

COMPUTATIONAL ENVIRONMENTS

The computer environment for design is one that started as a limited group of programs in a few basic areas of data processing operations. Currently it has grown to become an extensive software library of over fifty discrete applications. For the purposes of this study, several broad areas of application were appraised as the current computational environment for design. These were the applications that lay at the intersection of design with the following topics, namely knowledge engineering, digital modelling, information processing (with special emphasis on the technology of prescribing visual information) and lastly calculation procedures.

In keeping with the current development towards operating environments that can deal with concurrent processes and a disparate range of hardware devices, the appraisal of the computation included an interest in developing an integrated system that was capable of operating concurrently the several facilities included in knowledge engineering and the other topics listed above. So the associated idea of an integrated design support system was a parallel concern during the course of the study. The primary elements in the integration process were an inferencing facility, a visual information system, a modelling package and a suite of external calculation programs (including structural, space and energy calculations).

Design knowledge and knowledge engineering

The main thrust of the enquiry was to look at the application of knowledge engineering in the unusual application domain of design and to look at the potential of the knowledge-based design systems to augment the performance of the designer. The tools that we used were those generically referred to as 'shells', typically composed of knowledge base, inference engine, inheritance traits, probability facilities and associated interface features (Figure 1).

Shells also had a special interest as tools for the development of formalisms for the representation of design knowledge. These formalisms will include the conventions of knowledge-based systems such as frames, O–A–V triplets (object–attribute–value) and rule-based procedures.

The strategy adopted was to select a representative set of the most powerful and versatile of these tools and to make informal comparison between the ways in which each software package performed in the chosen design

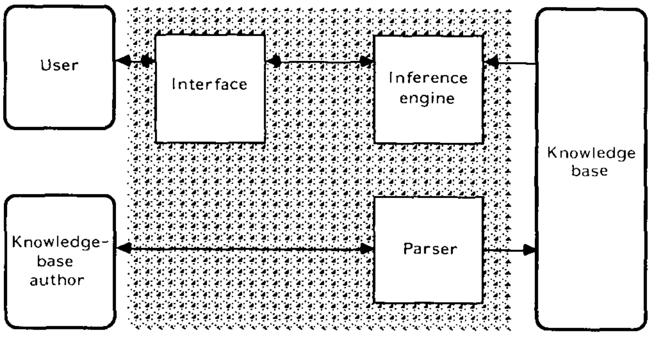

Figure 1. Typical configuration for a knowledge-based system 'shell'

domain. We were also interested to investigate the mode in which the inference engine used general problem-solving strategies to operate on design knowledge bases to generate results, review proposals or reach new conclusions. In our representative selection of shells, some of the tools were rule based, some frame based and some hybrid in composition (including both rules and frames). Hybrid systems have the advantage of integrating frames and production rules into a single unified knowledge representation facility. One of the important advantages of the hybrid tool is that it makes the organizational and expressive power of object oriented programming available to domain experts who are not programmers.

Design information

In terms of computational advance, one of the areas of the greatest technical interest in design applications is that which deals with the storage, retrieval and transmission of high-volume information systems. However, that which distinguishes a designer's data base from those in other professional applications is the scope and versatility of the graphic analogues which the designer employs or references to represent the artifacts, the buildings or the complex of buildings that he/she produces. These graphic data forms constitute the material, from which were formed the visual information systems in the case studies. Both magnetic and optical laser devices have been used as information storage media in the case studies. Earlier projects had confirmed the technical feasibility of using such media. The special interest in this study was to develop a means of interfacing the integrated inferencing system with the visual information system, so that the knowledge-based system could automatically retrieve visual references from the image libraries, as a special feature of the support system.

Initially, we developed a custom-built relational data base. Latterly, however, the approach taken has been consistent with the development of the other aspects of the integrated design support system, in that we adopted several state-of-the-art proprietary data base managers (namely Informix and Ingres).

As part of the case studies, several information systems (including two for libraries and cafeteria) were developed, relevant to the applications of the knowledge-based tools. In another case study[8] a VIS (Visual Information System) facility was developed. The image files on libraries were held as analogue video images on a video disk under computer control and were accessed by the data base manager. Also being appraised here was the capacity of the expert system to reference information or to present different types of data, effectively and coherently in the course of a consultation with the designer at different stages of the design process.

Modelling

Modelling is the central form-creating activity that differentiates design applications from the more usual applications for knowledge-based systems. In the integrated design-support system the modelling facility has to facilitate the input of the designer as well as providing links for the inferencing system to generate graphics in the modelling environment. Additionally, the modelling system has to provide access to a suite of calculation procedures.

Similar to the appraisal of the knowledge-based system tools, a selection of computer-aided design systems was used in the several case studies. They were mainly PC based and included Autocad by Autodesk Inc., Solidvision by Calcomp and Microcadds by Computervision. Additionally, in one of the projects (CAPES) a special-purpose graphics package was written as the modelling facility.

A main task was to build an interface in each of the knowledge-based systems between the CAD system and the knowledge-based tool, so that an expert system could generate graphic information to the designer, or, conversely, that the human designer could present proposed graphic layouts for review by the expert system.

The ability of the design support systems to trigger and run external routines and effect calculations was felt to be a significant part of their performance. Programs were developed, for example, to calculate area, structural behaviour and fenestration patterns. These were accessed effectively by each of the knowledge-based shells used in the study.

A SELECTION OF SHELLS

During the period of this study we worked with the following representative examples of knowledge engineering tools.

KES (Knowledge Engineering System)

KES[1] is a knowledge-based system, mainly for rule-based applications. Its principal characteristics include a backward-chaining, goal-directed control scheme, certainty handling mechanisms and a statistical pattern-classification subsystem. Facts in KES are represented as A–V (Attribute–Value) pairs with associated confidence factors or probabilities. Attributes or values can be arranged in hierarchies. Relations among facts are represented as production rules, using statistical pattern classification techniques or with hypothesize-and-test cycles.

Control is maintained by the inference engine, which uses explicit statements in the knowledge base called statements of action. The commands that a user issues can be stored in the knowledge base and executed during a consultation. For example, one action is declaring a goal attribute. When this occurs, the inference engine back-chains through rules in order to obtain a value for the goal. Action statements extend the flexibility of backward chaining inference engines.

The support environment contains interface facilities to explain the system's reasoning and to acquire new knowledge. The system is being used as a vehicle for the development of two architecture knowledge bases (namely a fenestration layout system and a system for designing library stacks).

ESE (Expert System Environment)

ESE with its origin in PRISM[2] is a knowledge engineering system, being used primarily for rule-based representation. Its principal characteristics include forward and backward chaining control schemes, certainty handling mechanisms and the ability to organize the knowledge base into hierarchical structures, each with its own inference engine and control strategy (called Focus Control Blocks).

The support facility consists of an integrated editor to create and maintain the knowledge base in the form of English-like rules. ESE was used as the vehicle for an expert system for cafeteria planning.

KEE (Knowledge Engineering Environment)

KEE[3] is one of the more versatile of the knowledge-based system tools that are currently being assessed. Primarily seen as a system for frame-based representation, it also supports rule-based, procedure-oriented and object-oriented representation methods. Its notable characteristics include multiple knowledge bases to facilitate modular system design with forward and backward chaining for its rule interpreter. Its support environment includes a graphics-oriented debugging package and an explanation facility that includes graphics facilities to indicate inference chains.

HPRL (Heuristic Programming and Representation Language)

HPRL[4], as its name suggests, combines a knowledge representation scheme and a method for conducting the heuristics that are part of the design process. Its origins lie in FRL (a frame representation language that was created at MIT). HPRL's frame languages provide a knowledge-base builder with an effective special-purpose method of describing the types of domain objects that a design system must model. A frame provides a structured representation of an object or class of objects. In one case study a frame represented an architectural element such as a window or class of windows. Frames also assist a knowledge system's reasoning activities by organizing and directing these activities.

Written in Lisp, HPRL provides access to the underlying Lisp system and it can be integrated into Lisp programs. Its associated facilities are extremely comprehensive. They include a browser-based user-programming environment that presents results in a visual-spatial way (rather than a sequential-syntactic way). This environment allows the user to readily create, explore, modify and manipulate HPRL constructs.

In the course of developing several knowledge-based systems a special study[5] compared notes on their general characteristics as software tools to act as knowledge-based system 'shells'. The manner of assessment was informal. The packages described above, KES, KEE and HPRL were included in the comparative appraisal. ART (Automated Reasoning Tool)[6] was the fourth additional package. In addition to the features described above it was found that HPRL's forward-chaining and backward-chaining capabilities were remarkable. Also, HPRL allows exceptional degree of control over inheritance and has special provision for rule-based representation. Its pattern-matching facilities were also on a par with ART and with KEE. HPRL also has the versatile architecture to allow the incorporation of new features as well as an ability to communicate with other application programs extremely easily.

APPLICATIONS OF KNOWLEDGE-BASED SYSTEMS IN DESIGN: SOME CASE STUDIES

In the course of working with four selected knowledge-based shells a number of specific projects were developed on specific design topics. These included a knowledge base on the design of corporate cafeteria, the layout of book stacks in a library design context, the design of fenestration in a library context and lastly, the design of a business graphic system.

The experience of building these several knowledge-based design projects has been extremely useful, particularly in terms of the feedback they created on the shells as development aids in a variety of application domains. It showed us that as far as knowledge engineering is concerned, the role of expert systems in design spans the whole spectrum of design, from pre-design through the final stages of design realization.

The first knowledge-based system to be developed was STACKS. STACKS ran in KES. LWINDOW[9], a knowledge base that knows about fenestration design in a library context also runs in KES. It can also review a design layout and engage in a consultation with the designer until a mutually acceptable layout is achieved. Expertize in fenestration design and its use in special climatic conditions come together in the 'Arid Lands Advisor'[10]. It also uses KES as operating environment.

CAPES[11] (Cafeteria Architectural and Planning Expert System) is an expert system that offers consultation and criticism in cafeteria planning projects in corporate settings. It mainly helps the corporate client in the preparation of an architectural program, in particular the impact of functionality on space constraints and their resolution. As critic, CAPES reviews the preliminary design created by the architect comparing a design with the criteria contained in a program. In its consultative role, its expertize is geared to compliance with client policies and to establishing the principal features of the proposed building, including service characteristics and gross space allocation. CAPES uses the IBM package ESE (Expert System Environment), both as its development and end-user environment.

BARGRAF is a knowledge base with a very different application. Its expertise is in the development of a graphics layout facility for business barcharts. It uses HPRL (Heuristic Programming and Representation Language) as the knowledge engineering tool for structuring a knowledge base, which is capable of composing and recomposing charts in response to a succession of user revisions. In its implementation the system is hybrid with graphics facilities written in C.

The range of applications of the knowledge-based design system in the design process is quite a wide one. It spans the design process from the earliest design phase and pre-design through the individual stages of conceptual and schematics through to the working drawings and post-contract design activity. In the CAPES project the primary role of the system was to act as a consultant in the preparation of the design program and in the generation of the conceptual layout. Critiquing the designer's first layout was also a function of CAPES. Critiquing[12] is a recent and topical issue in the application of knowledge engineering tools, particularly in the field of physical medicine, where critiquing is often used in the form of providing a second opinion on the management of patient care. In design, its main application lies in the review of design proposals in terms of the original building program.

THE OUTCOME: INTEGRATED KNOWLEDGE-BASED DESIGN SUPPORT SYSTEMS

Recapitulating on the experience gained in the conduct of the case studies has provided insights into the specification of a distinctive design support system, which brings together a number of special operational features.

The two main areas of interest in the conduct of this exercise have been the intersection of knowledge engineering with the design process and secondly the form and operational characteristics of a new generation of design support systems, which have as their core a knowledge-based inferencing facility. In terms of the first objective, it is fair to say that useful experience was gained in the application of a representative group of knowledge-based system tools in several design domains. Design is a distinctive application domain from those normally associated with knowledge-based systems. Applications in design typically require digital modelling facilities, information processing and calculation at successive stages of the design process.

In the conduct of the several design case studies, knowledge-based systems have been employed in a variety of modes, synthesizing solutions, reviewing design proposals, or consulting with the end user. Design with its strong visual component has an increasing capacity for high quality graphics, videographics and computer-driven analogue video. As a result, the computational environment in design is very diverse. This is why when we look at each of the selected knowledge engineering shells (ESE, HPRL, KEE and KES) for application in a design domain, considerable emphasis was placed on their ability to act as the coordinating core of an integrated design support system. The individual components of the integrated design support system are shown in Figure 2. The constituent elements are a modelling package, information management system (text and images), a knowledge-based inferencing system and a user interface.

The roles of the system may be characterized as follows. It may operate on a variety of local and remote databases and image libraries. It may review predictively the future performance of proposed designs in several areas such as operational building costs, structural performance and energy efficiency. It may propose outline design solutions including automatic layout proposals.

Experience with the case studies has provided an outline of a distinctive integrated knowledge-based design support system, as a basis for a computer environment for design. Its primary task is to integrate the various features that the system is designed to provide for. It is based on the experience of using a prototype form of the system in the several case studies, already discussed above. The central element in the system diagram is a knowledge-based inferencing package acting as a communicating and coordinating core in the integrated support system.

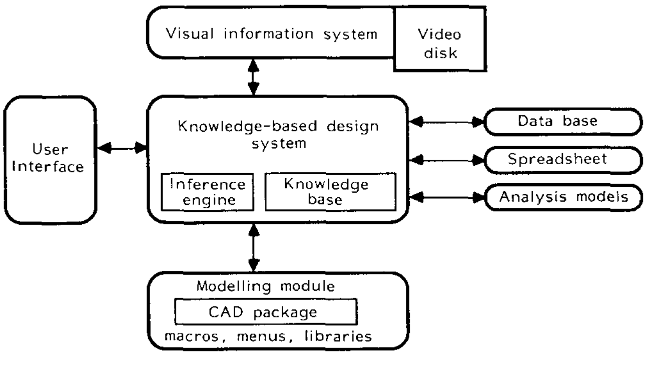

Figure 2. Outline of a prototype integrated knowledge-based design support system

The knowledge base may be a single element or multiple cluster of elements which may deal with a range of specialist areas of expertise or which may relate to different phases of the design process from the earliest conceptual stage of design right through to the final production drawings and schedules. The knowledge-based module also has the facility to interact with each and all of the other nodes in the integrated system, for example the data base managers, the visual information system, the modelling package, the user interface and the suite of external programs and calculation procedures.

The modelling package is accessed by the calculation and analysis routines. It also provides access to both the designer and the inferencing system. The primary feature is the integration of a number of facilities that together constitute an innovative knowledge-based design support system.

FURTHER DEVELOPMENTS IN INTEGRATION: THE NEXT PHASE

Building on the experience of incorporating knowledge-based design systems (KBDS) into a design environment[13] represents the main agenda of the future programme of development. The current programme and the objective of the next phase is primarily concerned with the issues generated by the integration of the knowledge-based design system, namely integrating individual knowledge bases and integration of KBDS with specific design processes. These issues occur in two areas. The first issue to be addressed is the problem of interfacing the knowledge of the designer with that of the designer's consultants. This will entail more formal methods for eliciting the skill, knowledge and experience of the designer.

Achieving a more effective interface between the expert system and the design problem to be solved will require an extended study of the sequence of design stages as the initial concept progresses to design realization.

These two areas, design process and design knowledge will be the subject of an empirical study combining a repertoire of observational methods for recording design activity with techniques for eliciting design knowledge.

In the conduct of the case studies the emphasis has been on knowledge acquisition from those experts of consultants with which the designer engages in the course of a design project. For the CAPES project it was the cafeteria expert whose knowledge was elicited and which later became the basis of the CAPES knowledge base. In the STACKS project, the expert was a library specialist. In LWINDOW the expertise was specific to the issue of fenestration layout. The method of knowledge acquisition used was a conventional method of interviewing the domain expert, translating those interviews into a knowledge base and interfacing that knowledge base with the inference engine, the data bases and the external programs that were needed to run the expert system.

Now that the goal of this aspect of the project is to establish, test and refine the designer's knowledge base, a distinct methodology of knowledge acquisition will be adopted. Experimental techniques will include verbal protocol analysis and repertory grid techniques. While the empirical study of the design stages will be comprehensive, the focus of interest will be where the design process begins, that is at the coming together of the problem description and the designer's skill and knowledge of the problem domain. Documented case study will form the basis of this phase. Individual techniques to be used within the study will include flow analysis charts, communication histograms and goal resolution diagrams.

It may be possible in the future to have the capacity to maintain an evolutionary design expertise, sustained by continuous updating and renewal by feed-back from successive generations of complete design projects. It is envisaged that these developments will lead to a more adaptive refined and responsive support system for the designer to use.

CONCLUSION

Originally, the computational environment for design and designing was data processing. Information processing succeeded data processing, offering the discipline of design a set of techniques and a theoretical framework that regarded design as an information processing task. Today, we have in knowledge engineering both a powerful application technology and a theoretical framework for design research. This initial encounter with the tools of knowledge engineering has been valuable in providing experience of the capacity of the technology to enhance the computational environment of the designer.

The experience has shown that the intersection of knowledge engineering with design occurs on a very wide bandwidth. Knowledge-based design systems can play the roles of consultant, critic and designer. Unlike expert systems in other knowledge domains, which tend to be cast in a single role and communicate in alphanumeric mode, design systems have many roles to perform and communicate in various media, including graphics, videographics and computational video.

A second thrust of the project has been geared to the performance of knowledge-based technology in terms of its ability to integrate with and to coordinate the range of activities to be found in the full sequence of design processes. In that respect design has been a challenging test bed for the tools that we selected. However, promising results were achieved in the form of an integrated design system.

Knowledge engineering tools have come from different backgrounds, including medical diagnosis, actuarial prediction and geological exploration. Design has shown itself to be a uniquely distinctive application area and indeed may yet have to develop its very own knowledge engineering tools and methodology.

To create such technology will require an extensive programme of design research, which will focus in the following related areas, namely knowledge acquisition in design, interfacing knowledge-based tools with graphic and video media, and interfacing knowledge-based design systems with individual phases of the design process.

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REFERENCES

1 **KES: Knowledge Engineering System** Software A&E Arlington, VA, USA (1987)

2 **Hirsch, P *et al*** 'IBM PRISM: Prototype Inference System' *Proc. AFIPS* Reston, VA, USA (1985)

3 **Fikes, R E and Kehler, T P** 'The role of frame based reasoning' *Commun. ACM* Special Issue on Knowledge Based Systems, Washington, USA (1985)

4 **Rosenberg, S** 'HPRL: Heuristic Programming and Representation Language' *Proc. AAAI* Menlo Park, CA, USA (1985)

5 **Ayyadurai, V** 'A comparison of four knowledge based tools – HPRL, KES, KEE and ART' *Term Paper MIT Visible Language Workshop* (1987)

6 **ART: Automated Reasoning Tool** Inference Corp. Los Angeles, CA, USA (1986)

7 **Purcell, P A** 'The data station: An integrated graphic information facility' *Proc. PARC 83 International Conference on Computers in Architecture*, London (1983)

8 **Miller, F C** 'Electronic design studio' *Proc. symp. computers in design: Emerging research directions* MIT, Cambridge, Mass., USA (1986)

9 **Fang, J Z** 'Decision support for window design: A computer-based prototype' *M. Arch Thesis* MIT, Cambridge, Mass., USA (1987)

10 **Bennett, A M** 'The structure of conservation: Experiments in representing design knowledge for arid lands design' *M. Arch Thesis* MIT, Cambridge, Mass., USA (1987)

11 **Logcher, R D and Purcell, P** 'CAPES: An expert system for cafeteria planning' MIT Laboratory for Architecture & Planning Report, Mass., USA (1986)

12 **Miller, P L** 'A critiquing approach to expert computer advice: ATTENDING Pitman, London (1984)

13 **Purcell, P A** 'Integrated design systems' *Proc. Symp Computers in Design: Emerging Research Directions* MIT, Cambridge, Mass., USA (1986)