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Publisher's version / Version de l'éditeur:

Journal of Documentation, 44, 2, pp. 91-118, 1988-06

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Conseil national de recherches Canada

Institute for Research in Construction
Institut de recherche en construction

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Appeared in
The Journal of Documentation
Vol. 44, No. 2, June 1988
p. 91-118
(IRC Paper No. 1587)

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NRCC 30237

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RÉSUMÉ

L'industrie de la construction, de par sa structure et son mandat, connaît des problèmes endémiques d'information. On s'attend donc à ce que les systèmes experts aient un impact très positif. [illegible] d'incertitude : la connais[illegible] mise à jour plus facile. [illegible] est difficile et des pr[illegible] te coopération entre i[illegible] ine. Dans la constr[illegible] èmes experts, notamm[illegible] et les résultats de rec[illegible] une étape de "filtra[illegible] de mettre au point [illegible] a recherche actue[illegible] u projet qui servi[illegible] ritères d'un systè[illegible]

THE

Journal of Documentation

VOLUME 44 NUMBER 2 JUNE 1988

EXPERT SYSTEMS AND THE USE OF INFORMATION IN BUILDING DESIGN AND CONSTRUCTION

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The building industry, through its structure and its mandate, faces endemic information problems; expert systems are expected to impact positively. Expert systems are suited to situations of uncertainty; knowledge and reasoning are separated, allowing easier updating. Knowledge acquisition from human experts is difficult and problems of information reliability arise, suggesting the scope for cooperation between knowledge engineers and documentalists familiar with the domain. In building, prevailing conditions seem to indicate the appropriateness of expert systems, particularly during the design phase; however, written documentation and general research results are rarely consulted. This highlights the need for an information 'refining' stage between production and use. It is easier to set up expert systems for specialised sub-domains; however, on-going research is attempting to develop a comprehensive approach to project-specific information that would be operational from initial design through to completed construction. Criteria for a comprehensive design information system can be listed.

Journal of Documentation, Vol. 44, No. 2, June 1988, pp. 91–118.

INTRODUCTION

FROM AN INFORMATION SCIENCE POINT OF VIEW, the building industry is a particularly interesting applications field for two reasons: (i) the nature of its organisational structure, and (ii) the nature of its mission.

Organisation. The building industry, in management jargon, is a 'multi-industry', and each building project is undertaken by a 'temporary multi-organization' [1]. The industry as a whole consists of a large number of enterprises, both professional and consultant practices, and manufacturing and construction companies. Each of them exists over a long period of time, but must form a team with others for short periods to participate in particular building projects. Long-term survival depends on a proper sequence of short-term activities. As a result, each firm has its own long-term *modus operandi* and its own ways of ensuring its presence on the market place; it develops and maintains some form of in-house information system, if only to record its acquired experience. Also, each short-term project team must develop effective coordination, by contract and by inducement, so that the firms called upon to work together (and who may never have worked together before), produce the required building within the imposed constraints; within the short time span, a project-specific information system must be designed and utilised by all participants.

Mission. The tasks of designing and constructing a building involve a complex sequence of operations as the project moves from an expression of intent to the reality of 'bricks and mortar'. Objectives and constraints are first determined explicitly by the intending building owner, and are translated into a functional and technical programme of requirements by specialist consultants; these requirements are transformed by other professionals into designs and details, accompanied by contract documents which, in turn, become instructions for the manufacturers and contractors who actually organise and execute the on- and off-site building operations. Finally, the building is handed over to the owner, who must make it work effectively to serve his purpose. All along this process, interlinking decisions are made under conditions of *interdependence* and *uncertainty* [2] – where the common thread is the project information system, built up each time from scratch. The initial inputs for this information system come from two unrelated sourses (unrelated to each other and – because each building project is different – often unrelated to the particular task at hand), namely: (a) the accumulated knowledge and know-how of each participant, and (b) the sum of general knowledge ('non-project-specific' information) vested in the various scientific and technical libraries and reference systems. As we will see, both these sources have some inherent limitations.

In this context of organisational and operational complexity, it is hardly surprising that the control of information flow is seen to hold the key to improved performance. Industry researchers, particularly in the major national and international research institutes, are starting to study ways of improving the industry's performance by looking at its information handling routines; attempts are now being made to anticipate the impact of recent innovations in computer science on the production and use of information in building – and specifically the impact of expert systems.

In the first part of this article, we present some of the pertinent characteristics of expert systems. Then we discuss the attributes of expert systems and knowledge based technology that support building design and construction. In the third part, we raise some of the information-related issues that the advent of expert systems throw into focus, particularly as they impact on the role of the documentalist.

INTRODUCTION TO EXPERT SYSTEMS

Towards a heuristic approach

No sooner had the first computers been developed and computer science and technology been fully accepted in the scientific *milieu*, than efforts were made to try and emulate the reasoning capacity of the human mind. This was a fundamental shift – from manipulating numbers to dealing with symbols, thus opening the door to the fuzzy information and concepts on which intuition, judgement and know-how are based.

In the initial enthusiasm, great expectations were vested in potential applications of the technology of artificial intelligence. Unfortunately, the majority of these expectations were not fulfilled; instead, projects led to disappointingly limited outcomes. The main difficulty stemmed from the fact that attempts were being made to develop problem-solving methods that could be applied very broadly. Also, the intellectual structures on which these systems reposed were based primarily on the fundamental theories of a particular domain of application requiring that a highly evolved set of knowledge be built up from first principles. Research continued progressively, but, with few exceptions, neither usable products nor generic technologies emerged to offer practical tools for dealing with 'real world' problems.

At the end of the '70s and during the '80s, a more pragmatic approach to the development of intelligent systems seemed more promising, and also seemed to show the way towards widespread application. In this approach, the search for very general problem-solving methods was abandoned, and, on the contrary, it was felt best to lean on the practical and specialised knowledge and skills of experts. This approach avoided the need to go back to the first principles of a domain of knowledge, because it relied on the eminently practical and operational heuristic rules used by experts in a field of application. These *expert systems*, as they began to be called, could be designed to process information without first having to develop their theoretical bases, even if, in fact, they borrow from years of experts' experience and even if they often adopt forms that are difficult to explain in terms of elementary concepts.

An expert system, therefore

> [...] handles real-world, complex problems requiring an expert's interpretation, solves problems using a computer model of expert human reasoning, reaching the same conclusions as a human expert would when solving a problem (Weiss and Kulikowski, quoted by Ó Cathain, [3]).

In a similar way, Michaelsen *et al.* [4] consider expert systems to be

> a class of computer programs that can advise, analyze, categorize, communicate, consult, design, explain, explore, forecast, form concepts, identify, interpret, justify, learn, manage and monitor.

One must be careful; the term 'expert system' can actually be applied to few systems, since most systems do not have an 'expert' level of performance, and their information base does not allow them to behave like consultants or colleagues. The term *knowledge based system* (KBS) is more applicable for describing most systems today.

Applications of expert systems technology

This new technology is promising but it must be used appropriately. The use of expert systems is pertinent when certain informational and methodological conditions prevail (Table 1). Once it has been established that the techniques

TABLE 1. *When to use an expert system*

1. When the problem-solving techniques for an application cannot be identified clearly.
2. When several alternative problem-solving paths and methods can be used, depending on the characteristics of the problem on hand.
3. When the optimal characteristics of the result can only be identified with difficulty (i.e. when one can only aim at 'satisficing' [5], that is to say, finding one of many acceptable solutions).
4. When the knowledge used in the problem solving process is bound to change very often, due to developments in the field of application.
5. When the type of query that will be made of the system is difficult to identify in advance.

of expert systems should be used for the application at hand, one would proceed by evaluating the degree of 'fuzziness' involved (i) in the problem-solving processes in question and (ii) in the elements of data and knowledge available for the application. The degree of fuzziness can vary, depending on

- the possibility that rules or structured sets of goal-oriented knowledge can be established, and on
- the attitude of the system users towards pre-defined problem-solving processes.

For example, the knowledge, and the techniques structuring that knowledge, which are used in architectural offices, are much more difficult to set down in the form of rules than for most applications in the applied sciences. Furthermore, even if a formal set of rules could be established, it would be felt inconceivable by the people performing design tasks that they ought to follow any rigidly pre-established decision-making sequence [6].

The technology of expert systems

Expert systems can be classified within the broader class of knowledge based systems, with the specific characteristic that their objective is the solution of practical problems that normally only an expert can resolve. Knowledge based systems are based on separating the reasoning or *inference* mechanisms (grouped in a 'shell') from the elements of knowledge (grouped in the knowledge base). Because knowledge and know-how are contained separately in their own databases, they can easily be modified. The reasoning mechanisms are defined by an *inference engine*, which can carry out operations on knowledge bases that are structured in a particular way. This approach is fundamentally different from 'traditional' programming, where the elements of knowledge are closely integrated with the statements which are written in a programming language and which constitute the software. Furthermore, the traditional algorithmic approach (i) presupposes that the programmer is familiar with the applicable problem-solving methods, (ii) limits the complexity of the reasoning, and (iii) demands that the knowledge be exact, complete and stable. Indeed, on this last point, it should be noted that modifying an algorithmic program can turn out to be a complex and costly operation, since it is necessary to work at the level of the programming language statements, that is to say at a level where there is a complex and closely knit combination of knowledge and procedures.

The representation of knowledge. Representing the expert's knowledge is a major challenge, since that knowledge can adopt a number of different forms. In addition, the expert will modulate the expression of his knowledge to reflect the circumstances for which he is called upon to use it.

The most commonly used types of representation of knowledge (and know-how) are: production rules (Figure 1), predicate logic (Figure 2), semantic networks (Figure 3) and frames (Figure 4). They can be used singly or in combination.

(a) *Production rules* are based on condition-consequence relations of the type 'if <condition> then <conclusion>' (see Figure 1). It is quite easy to express as a series of rules that part of the *heuristic* knowledge of the expert for which he can identify a set of circumstances leading to a set of conclusions. These conditions or circumstances can correspond to facts, or to initial, intermediate or final states of a line of reasoning. The mechanisms of inference are well known and can be applied relatively easily. As for the rule base (which is, of course, a particular form of the knowledge base), it is – *in principle* – quite easy to add or withdraw a rule. *In practice*, even though each rule is, by definition, independent from other rules, one has to be careful not to modify fundamental components of the *sequences* of rules that exist in a knowledge base.

```
If          "seismic region"
then        "high risk of earthquakes"
...
If          "high risk of earthquakes"
then        "symmetrical construction"
        or  "convex plan-shapes"
        or  "light-weight construction"
...
```

FIGURE 1. *Example of the 'production rule' representation of knowledge*

(b) *Predicate logic*, as applied in some shells (like ART) or languages (like Prolog), allows elements of knowledge to be expressed by a series of relationships attached to concepts and by a series of rules governing these relationships (see Figure 2).

(c) *Semantic networks* are a direct representation of the structural relationships that exist between concepts. A set of concepts (or nodes) are related to each other by a set of links which have predetermined meanings, and on which the reasoning mechanisms operate (see Figure 3). This type of representation of knowledge has the disadvantage of being difficult to set up and modify. Each element must be confronted with all the other elements of the network to see if there is an influence or dependency relationship. Furthermore, it is difficult to have an overview of the whole network and to obtain any justifications for results during operation. However, the links and nodes can be weighted, which enables the notion of scales of importance to be covered. Also, this way of representing knowledge closely resembles the behaviour of neuron circuits which, it seems, will probably serve as a model for the automation of intelligence and reasoning in the future.

(d) *Frames* allow classes corresponding to groups of knowledge to be expressed and related to each other hierarchically, and described by their characteristics or *variables*. The basic structure of the knowledge is built up around an arrangement of concepts going from the general to the particular (see Figure 4). Each frame contains a certain number of 'slots' (or elements of information), such as: characteristics, links to other classes or instances, procedures that carry out certain processes when the frame is consulted, etc.

knowledge/rules:

```
vertical(stone1).
vertical(stone2).
horizontal(stone3).
vertical(stone4).
point-contact(stone3, stone1, above).
point-contact(stone3, stone2, above).
point-contact(stone1, stone4, alongside).
column(Col):- vertical(Col).
lintel(Lint):- horizontal(Lint).
be-supported-by(Top, Bottom):- point-contact(Top, Bottom, above).
adjacent(El1, El2);- point-contact(El1, El2, alongside).
arch(BlockA, BlockB, BlockC):-
    column(BlockA),
    column(BlockB),
    not(eq(BlockA, BlockB)),
    lintel(BlockC),
    be-supported-by(BlockC, BlockA),
    be-supported-by(BlockC, BlockB),
    not(be-supported-by(BlockA, Block B)),
    not(adjacent(BlockA, BlockB)).
```

(note that all *variables* start with an uppercase letter).

query:

```
?arch(C1,C2,L).
    C1=stone1
    C2=stone2
    C3=stone3
```

FIGURE 2. *Example of predicate logic used to describe an arch and to distinguish between situations which are, or are not, arches*

(e) *Hybrids* enable several types of representations and their respective advantages to be exploited. For example, it is quite normal to use production rules in association with frames to arrive at inferences on structured knowledge. It is also possible (i) to integrate a capacity to process rule bases into the slots of frames, or (ii) to associate them with the nodes of semantic nets. The recent development of expert systems called 'deep knowledge systems' attempts to combine the respective advantages of heuristic statements with methods of qualitative and algorithmic analysis; this trend also supposes a more widespread use of hybrid representations of knowledge.

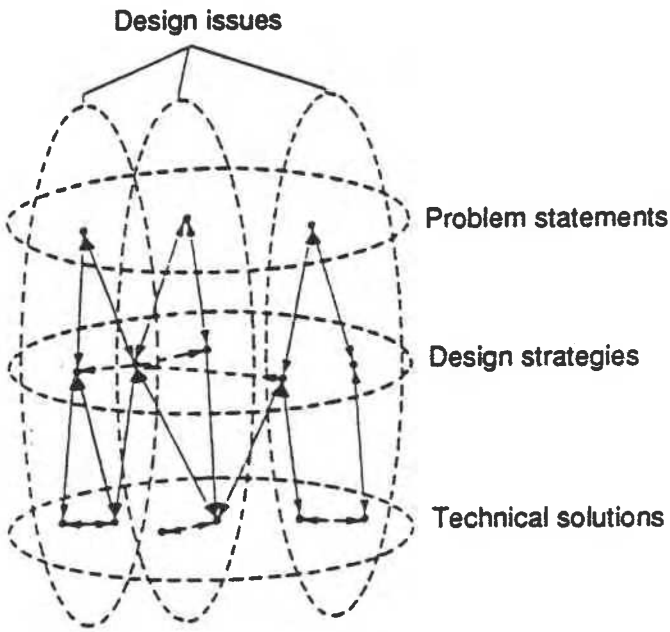

FIGURE 3. *Representation of information types and their connections. (Source: [7])*

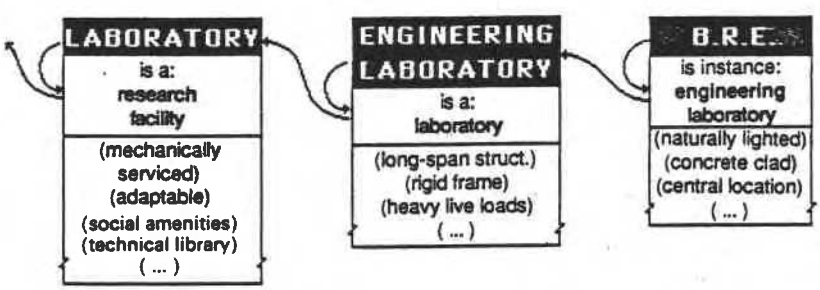

FIGURE 4. *Example of frames and slots. Note that an instance is located at the bottom of the hierarchy*

Using the same classification, Lansdown [8] also gives some other examples of knowledge representation methods.

Inference mechanisms. The workings of the reasoning or inference mechanisms are strongly dependent on the structure of the knowledge base to be processed. As far as production rules are concerned, there are two types of inference: forward chaining (Table 2) and backward chaining (Table 3).

TABLE 2. *Principles of forward chaining*

1. *A method of reasoning that starts from known facts and progresses towards all the conclusions that can be deduced at a given moment* (all the chains of rules are considered, until the rule base is exhausted).
2. *A type of inference that allows many different kinds of reasoning to be tried out and alternative solutions to be explored* (a consideration which is important when the user has no idea about the nature of the results he is looking for).
3. *A method which adapts readily to dynamic changes in the state of the system* (this method appears to be clearly indicated for some applications such as the control of evolving systems; however, broad and general searches in the knowledge base carry the penalty of requiring potentially very long processing times, and, in addition, there is the problem of filtering out from this mass of information the elements that are truly pertinent for the user at that time, since the expert system tends to produce all the inferences that are true at any given time).

TABLE 3. *Principles of backward chaining*

1. *A method that is based on a hypothesis supplied by the user, or on a plausible solution* (the inference engine will process the rules, working from the given solution – necessarily one of all the solutions it possesses in the knowledge base – by starting from the 'consequences' of the rules and going up all the chains that lead towards the stated hypothesis one by one; this process is repeated either until one chain is shown to be true, or until all the possible chains are exhausted).
2. *A method which sets up an iterative process* (when a condition is met in a chain under examination that is not recognised as having been verified, an objective is set up to prove this condition first of all).
3. *An approach when an expert system is intended to assist a user who is accomplishing a task for which he already possesses some expertise* (its function is then to complement and check the user's knowledge).
4. *A method of drawing inferences that allows the power of intuition of the user to be coupled to the capacity of the expert system to draw inferences exhaustively*.

Some shells, like ART, use both forward and backward chaining together. The forward chaining enables the information that is necessary for reaching certain goals to be determined, and then backward chaining atttempts to provide the missing information.

Applications of predicate logic in some shells (like ART) or languages (like Prolog), often follow an approach resembling backward chaining. The Prolog language is based on three characteristics: (i) 'pattern-matching', (ii) data structure and (iii) automatic 'backtracking'. Prolog is, in point of fact, a kind of inference engine that attempts to establish instances for the variables that compose the relationships defined in the Prolog program; it does so by starting from the facts given to the system at the outset.

The inference mechanisms applicable to semantic networks and frames are more varied and applications-dependent. In fact, these forms of knowledge representation are often used for their inherent capacity to represent and manage complex structures of concepts and relationships.

Knowledge acquisition for expert systems (Table 4)

The most important and delicate step in devising an expert system is the establishment of the knowledge base. It is necessary to 'extract' the knowledge and know-how from one or several 'experts' in order to formalise the information that is needed in one or other of the types of knowledge representation that have been described. This is difficult, as experts often use fuzzy or intuitive reasoning, based on their experience. A number of authors [9–13] provide details of the process, and comment on the reactions of participants in the process of knowledge acquisition; to guarantee the accuracy and adequacy of the information provided, interviews with the experts must be organised and planned with extreme care, often requiring the application of principles of group dynamics to reinforce the verbalisation of knowledge and know-how.

TABLE 4. *Acquiring the expert's knowledge and know-how*

1. Interviewing and using questionnaires;
2. Attitude scaling and using projective tests;
3. Observing experts at work (e.g. when designing) and asking them to reason aloud;
4. Studying practical examples with a view to identifying general concepts;
5. Considering typical, limit or erroneous cases;
6. Repertory grid and protocol analysis;
7. Tracing through a line of thought – starting from initial facts (resembling forward chaining) or from outcomes (resembling backward chaining);
8. Validating and improving on elementary prototypes;
9. etc.

Indeed, the complexity of knowledge acquisition effectively hampers the development of expert systems for many domains of application. In an attempt to reduce the impact of this problem, the system used by the knowledge *engineer* for setting up expert systems can incorporate several computer-based tools such as: ergonomic interfaces, methods for checking the coherence of rules, high-level explanation modules, and methods for automatically inducing rules.

ATTRIBUTES OF EXPERT SYSTEMS AND KNOWLEDGE BASED TECHNOLOGY SUPPORTING BUILDING DESIGN AND CONSTRUCTION

Information use during design

Expert systems, as we have seen, are a product of a pragmatic approach based on practical and specialised knowledge, expressed in a directly applicable form. This approach has already raised great expectations in research and industry, for its broad range of potential applications.

However, computer technology and its implicit advantages are not used for information retrieval by the building design professions. In building design generally, information retrieved from central information sources (i.e. the general, non-project-specific information mentioned in the introduction), is low compared with scientific information retrieval for industrial applications. This raises two issues:

- what is the type of information available and its retrieval during building design and delivery;
- what is the ability and topology of computer technologies and information sources to support these information types.

The first issue of knowledge use during the design process has been investigated for more than two decades without any clear resolution [14]. What has emerged is a repudiation of design as an algorithmic procedure [15], and building design is now recognised to be a heuristic process where a right or wrong solution cannot be determined, but where better or worse solutions can be debated. As a heuristic procedure, the information needed during design must accommodate the possibility of non-solutions, and must work even when there are gaps in data to arrive at a solution. Rather than being a process of information accumulation only, design requires that information be discarded as decision-making progresses.

Developments springing from artificial intelligence research are well suited to heuristic information processing. Expert systems or knowledge based systems (KBS) are programs encoding heuristic, algorithmic and factual knowledge. Microcomputer hardware now has the capacity to support the heavy memory and interface demands made by the KBS software, so that even the under-capitalised building industry users can make use of knowledge based systems today.

A range of 'information' is used during building design. Information for building design comprises a spectrum from 'soft' conceptual design ideals to 'hard' specifications of materials for the project. Required information ranges from project-specific information to general information applicable to 'all' building design and construction. Because of the breadth of information requirements during design and because each project varies in its use of information, a single access method or information format is not feasible. Indeed, a spectrum of information types of this magnitude demands responses ranging from specialised library sources to informal queries from colleagues.

Information use during design has been observed by Mackinder [16,17] in both academic settings and in architectural practice. Information is solicited first from a colleague, followed by a query to the superior, a phone call to a supplier or 'expert' in the field, browsing design journals for examples, consulting a professional handbook, browsing catalogues for manufacturers' information, reading technical information, and as a last resort, ordering technical information from a library or research establishment. In this process, time and budget are seen by the designers as their key constraints, limiting information access during decision making.

As a further complication, in design problems there exists an unavoidable circularity during the access of information. For example, while considering the wait time behaviour of people in lift lobbies, two possibilities (at least) emerge: (a) the design of a more efficient lift system will result in less waiting, but (b) the design of a nicer space will change the frustration associated with waiting. Wade [18] maintains that information is circular with question framing. 'How can the decision maker know what information is useful until he knows what information is useful?' Akin [19] adds 'information acquisition follows guidelines suggested by the anticipated usefulness of the information'.

A discussion of architectural research issues by the Architectural Research Consortium included a review of architectural firms' views of information use [20]. In this study, a large and successful USA firm reported that professionals would prefer to consult an expert, rather than to receive a written report or a book. Marvin Goody (an architect-educator) indicated that research 'is frequently incomprehensible to designers and needs translation' and Louis Sauer further stated '[research] is heavy jargon [. . .] after the first page we start falling asleep'.

According to Seidel [21], architects tended to look for information with precedent and trustworthiness established by its author's reputation as opposed to demanding information based on precise research methods or exactness of results; furthermore, they look for information specific to a building type rather than specific to a topic. For example, while designing housing for the elderly, rather than search for 'furniture layout' the designer would search for 'old age housing', in order to be able to look at furniture layouts in typical plans.

There is a consensus among architectural researchers that there is no agreement about what research is, and consequently what communication of results should be, and even more importantly, what language should be used to represent knowledge in building and construction fields! Joroff and Morse [22] propose that a spectrum of knowledge should be recognised, ranging from personal observation through to laboratory research, and that it is all equally critical.

Computer technology and information access

There is great belief and hope in the future of computer technology to support design decision making in the architectural profession, but according to McGraw Hill industry surveys, the *algorithmic* procedures found in most information-based design aids have been under utilised by architects while they have received wide use in engineering circles. Perhaps this underscores the differences between a *problem solving* architectural design process and a *puzzle solving* methodology found in engineering design [23]. Problem solving is a heuristic process, puzzle solving is an algorithmic one [18].

However, computer technologies do exist for accessing information during design, but most of them have been designed to address a particular problem that can arise, such as: investment planning, estimating, space planning, drafting, or energy performance [24]. As mentioned by Wade [18], and by Romanycia and Pelletier [25], these systems are algorithmic in nature, because 'a process yielding a solution each time it is applied is an algorithm [, while] a process that might or might not produce a solution is a heuristic'. Computer systems are also available for accessing descriptions of materials used during construction and specifying construction methods and materials [26].

Despite (or, nothwithstanding) the scant use of out-of-house information that has been widely reported (to which we referred previously), databases for the building industry are being developed on two levels. In Europe, online centralised technical information libraries have been established. These include a product database at the Bouwcentrum in the Netherlands with over 50,000 data product entries [27], the Swedish Byggdok [28], the German building technology database BODO, and ICONDA – the International Construction Database (the latter managed by Informationszentrum Raum und Bau, Stuttgart), and the French ARIANE. A new effort is also under way in New Zealand with the Building Research Establishment's BRANZ [29]. The technical information bases are often supported by national building research establishments, but their use has been limited because the information is generic and topic related – not specific building or building-type related.

In the United States, MASTERSPEC provides specification information, while product data is being provided by Sweet's and Dodge [26]. Both library and materials catalogue systems depend on database methods for information retrieval, where the data plays no role in the computational process; in this regard, they differ from KBS, where the data are *dynamic*. However, 'Electronic Sweet's' – a new family of computerised product-related services – includes an expert specification system, *Sweet's Spec*. 'It is an expert system that asks the user the kinds of questions an experienced specification writer would ask. Each question depends on previous answers; each answer edits a master specification and creates the final specification document' (Sweet's/McGraw Hill brochure).

It is now clear that no single technology or information strategy has the capacity to represent the wide range of information and format types demanded during the design process. A generally accepted framework for project-specific information *and* project-related general information is necessary before an integrated approach to a building expert system can realistically be proposed.

Forms of information and the appropriateness of artificial intelligence (AI) techniques

Architectural design, as an ill-structured problem, requires a medium with a mechanism providing information to ill-defined processes and methods [18]. During design, client programme information (demand information) must be transformed into a product description – typically a building. Another person – hopefully someone with an answer – is the source of information most often sought for; the form of that answer might either be a sketch or a verbal communication, or it might be a suggestion as to another information source. A symbolically based medium is necessary to respond to queries with varying levels of certainty and with varying degrees of authority. But while contemporary methods of symbolic and mathematical reasoning have limited capabilities for solving architectural design problems [30], knowledge based system techniques have the capacity to respond to uncertainties and to backtrack during information processing. AI techniques, when confronted with ill-structured problems, employ a heuristic approach, and can provide a spectrum of answers from generic to specific.

Knowledge based systems in building

KBS applications include geological structure analysis systems (for finding mineral and oil deposits), drill rig advisors, diagnostic systems for bacterial infection, computer system configuration systems, diagnostic systems for microelectronics and atomic power plant control systems. Though there are a number of emerging expert systems related to building (see Appendix 1), it is safe to state that there is really only one *fully operational, field tested and verified* system existing in the construction industry at the present time: MENTOR from Honeywell, used by service personnel to determine faults in their commercial building cooling system compressors. This particular KBS cost $US 2 million and took four man years to build and a subsequent year to implement in their service procedure [31].

MENTOR was developed on a LISP machine, a computer designed for symbolic computation, and then transported into a microcomputer environment – in this case, a portable PC environment used by service personnel on-site. It uses a simple keyboard and text interface, but its reasoning is sophisticated enough to find faults in ten minutes that typically took two hours or longer to find.

As mentioned previously, a knowledge base comprises the knowledge or object descriptions of the field being described. In MENTOR, one small part would contain the rules concerning the interaction between the compressor, pressure readings at certain test points in the system and the time of the last maintenance procedure [32]. In rule based systems, the knowledge is expressed as '*if* . . . *then* . . .' rules. In the MENTOR example, the change of compressor oil would be governed by:

if 'runtime meter > 2000 hrs, or last oil change > 120 days ago'

then 'change the oil'

Over 550 rules describe the possible states of, and actions required on, the compressor.

Other knowledge representations resemble databases in their form, having frames built with slots, where these slots may have values describing the object (for example, a frame may describe the object 'compressor', and a slot would be its 'oil pressure'). Additionally, slots may have active values that respond to the condition of the object – in this case, an active value might be the oil level, which has a rule associated with it; the rule would 'fire' when a certain oil pressure level is reached and infer that some ACTION must be taken.

In rule based systems, two basic types of inference mechanisms are possible: backward chaining and forward chaining, as explained in the first part of this article (see also Tables 2 and 3). Using an example from MENTOR to illustrate backward chaining,

if 'oil is changed'

then 'ACTION to be performed is to remove the oil plug and drain the oil'.

If the goal of the system were to determine the value of ACTION, the system would then look for the rule which has ACTION as a result of its application. It then attempts to determine if 'the oil is to be changed' is true. To determine this, it must find the rule considering the number of days since the last change; here the user must supply the information concerning the last change. If this number of days is greater than 120, the ACTION to be taken is to remove the oil plug and drain the oil.

Forward chaining systems search through the knowledge bases and 'fire' or execute a rule if the antecedent is known. If the number of days were known, the ACTION would be inferred.

Another example [33] of an autonomous, stand-alone system is WINDEKS – WINdow Diagnostic Expert Knowledge System (Figures 5–7). The envisioned user was a central government agency that answers public queries about building problems. In this kind of situation, it is necessary to describe and analyse the user's information requirements and envisioned information use clearly. The system, however, would rarely be used in an architectural office.

The system was built using published knowledge and informal interview techniques as the sources of knowledge and know-how during knowledge acquisition. About fifty articles dealing with glass and window failure were scanned for the implied rules; these proved to be a good source for organising the overall knowledge base. During the development process, three experts were consulted, and rules were added in the knowledge base as new situations arose. The system comprises forward and backward chaining techniques and about 220 rules. In addition to a rule based procedure, the system accesses a procedure (algorithm) to determine the potential risk of condensation.

Some conflicting rules were discovered in the knowledge base as it had been developed initially; they still remain to be resolved, and an automated verification procedure is being developed using classification tree methods [34].

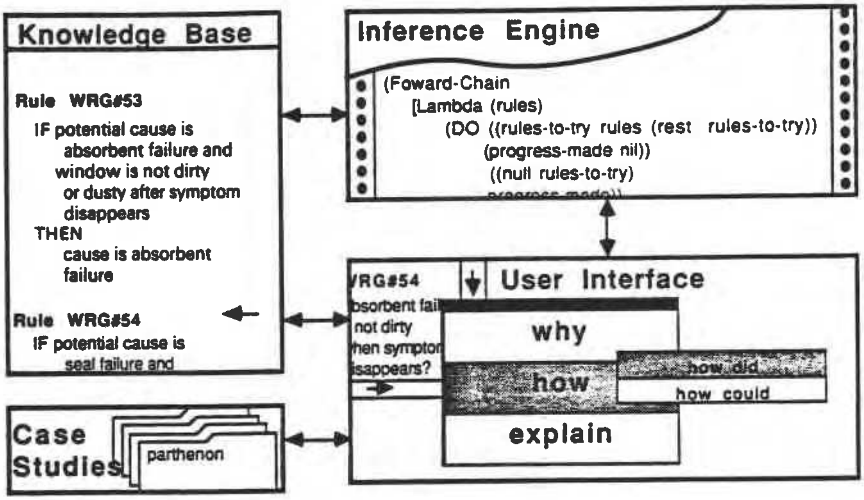

FIGURE 5. *Organisation of WINDEKS. It comprises three parts: the knowledge base, the shell and the user interface. Case studies were used to build the knowledge base through the user interface. Explanations are possible from the user interface*

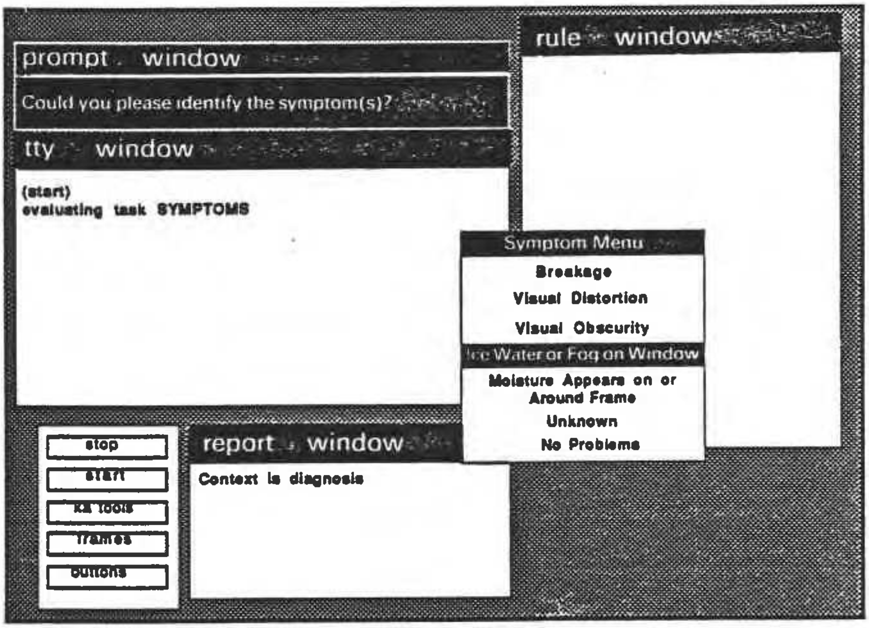

FIGURE 6. *Initial screen with WINDEKS. Prompts are answered from a 'pop-up' menu. Answers are highlighted by moving a 'mouse' pointing device*

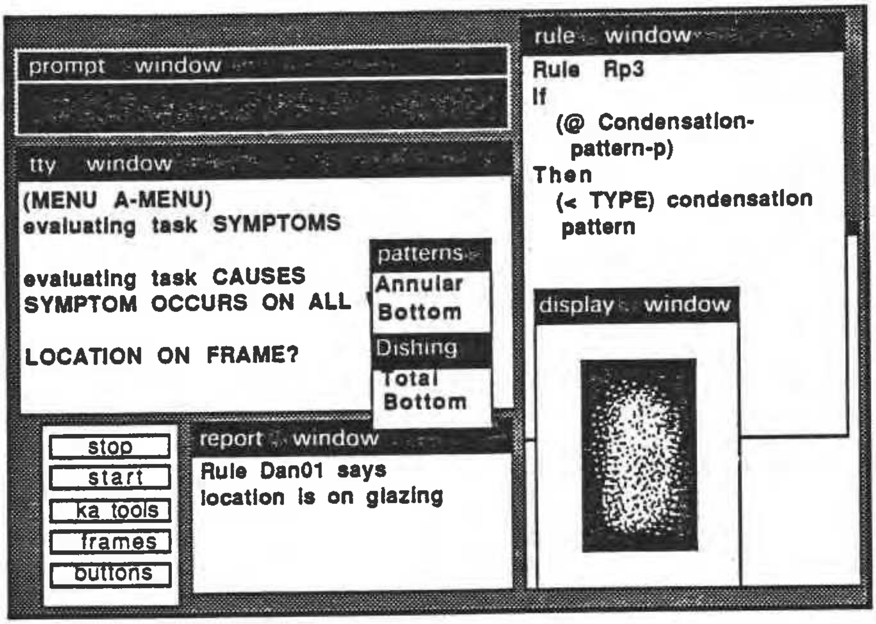

FIGURE 7. *Indicating symptoms to the machine. A display shows the user the type of symptom associated with an item list on the menu. This type of interface filled with windows has not proved effective. A simpler system consisting of one query window and a 'pop-up' explanation window has proved less confusing*

EXPERT SYSTEMS, INFORMATION AND THE DOCUMENTALIST

> The fairy tale is false. There is no special method that guarantees success or makes it probable. Scientists do not solve problems because they possess a magic wand – methodology, or a theory of rationality – but because they have studied a problem a long time, because they know the situation fairly well, and because they are not too dumb [35].

The difference between project-specific and general information

As a building project develops through briefing and design to production, it is accompanied by the growing project file of project-specific information; this file exists in an environment of general information and knowledge, to which it is tenuously attached. The project file serves to *accumulate* graphic and non-graphic data and descriptions, starting from the accumulated experience of the involved parties, the project brief and site-particular considerations (Figure 8). The accumulation process is part of the design and development process itself, for, as Kalay [37] points out,

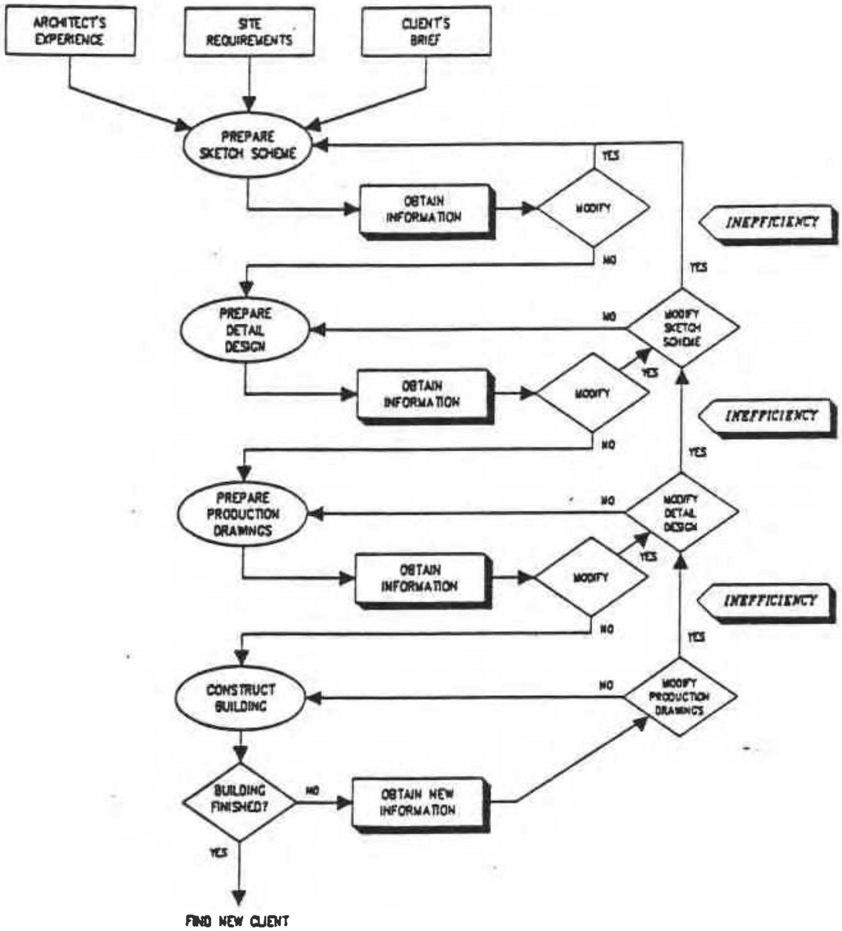

FIGURE 8. *The use of information during the design process. The 'obtain information' actions are critical in the context of a study of information and knowledge in building. Note the inefficiencies that occur when activities have to be corrected because new information or knowledge shows that they had been inadequately performed. (Source: [36])*

> The solution [. . .] of a design problem consists of a set of states, each representing a specific solution for the problem in some degree of detail. [. . .] The process can thus be viewed as a sequence of actions that advance the current state from one state to the next. Typically, the transition process is guided by local or heuristic knowledge, so as to guarantee its convergence on a recognizable solution state in reasonable time (if such a state exists), and thereby bring it to a successful conclusion. [. . .] Architectural design is distinguished from many other problem-solving processes by two major characteristics: the states representing candidate solutions must be generated before they can be evaluated [and] the heuristics that guide the search rely not only on information internal to the particular problem, but also on information which is external to it, for example, cultural norms and styles.

This 'external' information may be found within the offices of the project participants, or within the regulatory documents they must respect. Or it may be found in the world of general, non-project-specific information. However, as shown by Mackinder [16, 17] and others, it seems to be with extreme reluctance that busy professionals turn to the sources of general information (libraries and referral systems), spending as little time and effort as possible, particularly if research-generated information is involved. The reasons for this regrettable state of affairs are well-known: 'theoretical knowledge resides in books, skill resides in people' [38]; it is just too difficult to 'translate' the general knowledge supplied by the information services into indications that are specific enough to enable project design or development to progress rapidly.

Jean Michel [39] proposes an analogy with energy to describe this aspect of the information problem.

> [. . .] information, like energy, is available in a primary or 'crude' form which cannot be used as such to satisfy man's requirements. A series of different transformations are necessary: they end up with the creation of a new resource or a new good which can be distributed to a user environment in response to needs.
>
> Three main functions can be identified in the processing and use of energy:
>
> - *an up-stream function* of extraction and supply which gets the crude resources out of a supply environment and makes them available;
> - *a down-stream function* of distribution which offers the good or resource thus 'created' in a user environment in response to demand;
> - finally, *a central function* of transformation, which is essential, and aims at creating a new good from the crude resource.
>
> [. . . using such a general energy model] it is possible to learn some lessons from a comparison with the 'information' channel: (a) [. . .] in the case of 'information processing', emphasis has almost exclusively been laid on increasing the supplies: this leads inevitably to the 'information

> overload'; (b) the central function (transformation of the crude resource and creation of a new good) is almost totally ignored or taken for granted. Yet in the 'information' channel, this [transformation] is a key step in creating cognitive forms, concepts, models and explanatory schemata, and is at the center of decision making [. . .].

It is reasonable to suggest that the problem of the gap between 'crude' general information (using the term in the sense given to it by Michel) and the form of information that is most appropriate for practical, project-specific decision making, is less inhibiting at the project development and production end of the building cycle, where systems resembling Management Expert Systems (MES) are presently available – provided the right knowledge can be introduced into them. On the other hand, the gap is worse at the beginning of the design process, since it is typical of design that both the process *and* its products are not subject to explicit and completely overt criteria, particularly during the earlier phases [40]. And, of course, early design decisions have the greatest impact on the cost and the quality of the building being designed.

Integrated expert systems?

In the building industry, expert system development has progressed in an *ad hoc* manner, with initiatives concentrated around particular problems. Consequently, no system is complete enough to use in a design office as a practical source of information [41], and each of the knowledge based systems emerging for the building industry is an 'expert' in a specific field (see Appendix 1). Even the systems that assist with structural design employ specific rules requiring updating before application to other structural systems. There is no overall framework or method to tie these systems together. Presently, the US National Research Council's Building Research Board is devoting much effort to developing a framework for knowledge and interchange of specific building information [42].

Since (i) the smaller expert systems development projects, with fairly modest aims, are the ones that are most likely to succeed in the near future [10], and (ii) the process of knowledge elicitation demands many hours of consultation with experts and development is difficult if the knowledge domain is not easily defined or bounded [43], it follows that expert systems are likely to be developed that address themselves to small parts of the broad design related information field, at least in the immediate future. Fawcett [44] pointed out that, in architectural design for example, there is a hierarchy of problems from simple mechanical aspects up to more sophisticated and value-sensitive areas of decision making; expert system design, he suggested, should start with the former. Rosenman *et al.* [45] write that

> there are several levels of design. The first, and the most difficult, is the design of an artefact to satisfy a set of goals when even the general form of the artefact is not known. [. . .] A second level of design is when the general form of the artefact is known and the design problem is one of selecting the various parts and deciding on their parameters. [. . .] At the

> bottom level of design, the problem is one of selecting a solution from a set of fully- or partially-described solutions. [. . .] At this bottom level of design the problem is one of classification and hierarchical refinement of the objectives and constraints. [. . .] The use of expert systems at the elementary level of design [can be seen] as a start to the use of such systems for more advanced levels.

However, despite the practical arguments in favour of a piecemeal approach to the development of expert systems, one would like to think that all these project-specific expert information systems could evolve in such a way that some form of continuity could be obtained; the project file would grow as the project develops, receiving compatible inputs from the various participants in the building design and production process. A computer model of an emerging building, it is postulated, could be built up and enriched with graphic and non-graphic information, checked against regulatory and other requirements, and constantly evaluated against functional and performance requirements. For Bijl [40],

> [such] an integrated design system is one which employs a single model that can accommodate all information describing a design object, corresponding to different knowledge supplied by different people. The model has to be capable of supporting a range of operations on the same description, to advance people's interests during the course of designing the object. [. . .] The model of design used in the integrated systems approach may be described as [a procedure where]:
>
> (a) a design is a single coherent description (of a building) that can supply information for many varied design tasks;
> (b) any part of a description may be defined by any other parts;
> (c) any part may serve more that one task.

Against this background, Rehak and Howard [46] developed a database management system called KADBASE (Knowledge Aided Database Management System), with special emphasis laid on interface management. Their system comprises (i) a network data access manager (which integrates the local schemata to form the global schema in terms of the global data model), (ii) a knowledge based system and interface (which formulates queries sent to, and processes replies received from the network data access manager, and includes the local context schema knowledge) and (iii) a knowledge based database and interface (which acts as an intelligent front-end for the local databases).

Whether an information system is designed to act immediately in an integrated way, or whether it is to form part of some network of expert databases, certain criteria for its design must be respected. These include (i) a specification for the information used during architectural design, (ii) a description of the kinds of information required in design, and the type of computer techniques that can be used to address the requirements, and (iii) an indication as to the format for the information (Table 5).

TABLE 5. *Criteria for a design-related information system*

1. *Specification for the information used during architectural design.*

1.1 *Providing concise and authoritative advice justified by the source.*

1.2 *Offering advice only at the appropriate point in the process.* (This point is well illustrated by the problems that arose with the code checking algorithms in the CAEDS programme developed by the U.S. Army Corps of Engineers; this automated code-checking facility had to be turned off while design was progressing through early stages, as it constantly warned the designer of code violations.)

1.3 *Offering imaging (graphic) capabilities at the appropriate stages during design.* (Freehand sketch recognition and understanding graphic uncertainty, particularly during early stages of decision making, must be supported.)

1.4 *Embodying handbook information and code information.*

1.5 *'Critiquing' rather that diagnosing.* (Critique occurs at almost all levels, from sketch to final details and acts on uncertain conditions.)

1.6 *Supporting volumes of text, such as specifications.*

2. *Description of the kinds of information required in design, and the type of computer techniques that can be used to address the requirements.*

2.1 *A progression from soft to hard information.* (Graphic and photographic descriptions of building types, including cost data, and case descriptions of building type designs and construction. These cases may be presented on demand by databases similar to the architectural data retrieval system built by the Architecture Machine Group at MIT, where images are stored on laser disk and retrieved upon voice command.)

2.2 *A spectrum of information, ranging from general building design and construction techniques to project specific information.* (Information, for example, about microclimate or energy performance, showing how that information pertains to a specific project. When a KBS cannot determine a specific answer to a problem, it will deduce as much as is possible from what it knows; for example, if all that is known about a design at a given moment in time is its square footage, and the designer is concerned about passive solar design and window placement, a reasonable rule of thumb for Canada would be about 10 per cent south facing double or triple glazing; a series of 'if . . . then' rules would lead to greater specificity.)

2.3 *Both supply and demand information.* (Conditions of the site, resources for a particular job and available building products comprise the supply side; demand information includes information about (a) the client-supplied building-specific requirements – i.e. the programme, and (b) institutional demands – i.e. codes and standards.)

2.4 *Fact and authority information.* (Information from observation comprising facts in the industry and authoritative examples provided by designers and consultants with experience. In this case, 'if . . . then' rules are used to capture experience, while 'facts' would be stored in the data base.)

2.5 *Vague to concrete information.* (The 'best possible' available knowledge is required, and its degree of uncertainty must be indicated formally – but even low certainty information or experience is better than none at all.

Table 5 *(cont'd)*

Uncertainty would be determined using one of many techniques found in KBS methods, including fuzzy set theory and Bayesian probabilistic methods.)

2.6 *Algorithmic and heuristic methods to find information.* (Processes and methods are available to determine precisely conditions that have been left fuzzy, once the design has progressed to a point that merits their application, as, for example, with energy analysis algorithms. In general, information systems must incorporate rules of thumb, because 20 per cent of decisions are made during sketch design when algorithms cannot be applied [36]. Knowledge based systems were conceived to capture heuristic methods; they may be augmented by modelling methods where required.)

3. *Indications as to the format for the information.*
3.1 *Computer generated spoken response or concise text.*
3.2 *Varying degree of graphic presentation depending on the stage at which information is required.* (For sketch design, wire-frame representations are sufficient; for details, current drafting standards must be adhered to [47]. Imagery is an essential component during design, and the system must be able to distinguish between hard and soft decisions and the harder or softer representations that are suited to each – '4H or 4B pencils'; the form of graphic representation may range from input of perspective and output of plan and section to input of section and its consequences in plan and perspective.)
3.3 *Tabular data for cost and materials.*
3.4 *Iconic control of information demand.*

Knowledge engineering and information science: problems and solutions.
In architecture, as in most disciplines, much of the knowledge and know-how is vested in experts, and written sources are often irrelevant for building design and production in practice. As far as knowledge *acquisition* is concerned, this means that the bulk of expertise will have to come from human experts – known to be an expensive task [48]. But, in a domain like building, where professionals and contractors assume considerable contractual liabilities, another question comes up: since by definition, the expert system contains the knowledge of experts, what guarantees exist to ensure that the experts' know-ledge is up-to-date, that it reflects the best available theoretical knowledge as well as the best contemporary skills, and that it is properly reflected in the expert system?

In many areas for which expert systems are being designed, *knowledge engineers* participate in the process of knowledge elicitation and acquisition; in this, their role is somewhat analogous to the systems engineer in the field of systems analysis. However, since the expert system is only as good as its knowledge base is reliable, the knowledge engineer has to understand fully the domain and all its subtleties if he is to assess the expertise he is eliciting – and in building, this is far from being automatic [13]. The difference between general and project-specific information (which we have mentioned several times in this article) takes on a new and critical dimension, and one wonders where the knowledge engineer places himself; is he an expert in general knowledge or in project-specific skills?

The time seems to be ripe for a coalition to be formed between (i) the information specialists who have acquired in-depth knowledge about available general information and how to access it, and about the intricacies of information use in the building design and production process, and (ii) the knowledge engineers and expert systems designers called upon to work with the building industry. Luckily the proponents of the step-by-step approach to the development of expert systems suggest that there may still be some lead time for the providers of information to develop new strategies and new solutions to the problems of using information in building.

Meanwhile, researchers such as Ibbs [49] see the crucial research needs as: (i) developing appropriate representations for different data types; (ii) defining and classifying generic objects; and (iii) mapping the information which is actually used and which contributes to quality building design and construction.

ACKNOWLEDGEMENTS

The subject matter of this article was discussed with members of Commissions W57 and W74 of the International Council for Building Research, Studies and Documentation – C.I.B.; we thank them for their comments and support. Background research was supported in part by a grant from the Vice Chancellor for Research, Université de Montréal.

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APPENDIX

Annotated list of building design and construction-related expert system developments (references to a recent publication are given). Entries marked with an asterisk are also described in this article:

- a dry-rot detection and diagnostic system (LANSDOWN, JOHN. *Expert systems: their impact on the construction industry, report to the RIBA Conference Fund.* London: Royal Institute of British Architects, 1982);
- a compressor preventative maintenance and diagnostic system – 'MENTOR'* (COCHRAN, E.L. *and* HUTCHINS, B.L. *Testing, verifying and releasing an expert system: the case history of MENTOR. Paper submitted to AAAI '86.* Golden Valley, Minn: Honeywell Corporate Systems Development Division, 1986);
- a structural high-rise steel preliminary design aid (includes interfacing with a structural component relational database) – 'HI-RISE' (MAHER, MARY L. *HI-RISE: a knowledge based expert system for the preliminary structural design of high rise buildings.* Pittsburgh: Carnegie-Mellon Institute of Technology, Department of Civil Engineering, 1985. Research Report R–85–146.);
- a computer room layout assistant (WATANABE, TOSHINORI *and* SASAKI, KOJI. Design of an expert system for computer room layout. *Hitachi Review, 35* (1), 1986);
- an architectural design generator based on Christopher Alexander's 'Pattern Language' approach to architectural design (GULLICHSEN, E. *and* CHANG, E. An expert system for generative architectural design. *Design Methods and Theories, 4* (2), 1985);
- a timber design expert (THOMSON, J., MARKSJO, B. *and* SHARPE, R. *A knowledge representation language for engineering design codes.* Victoria, Aus.: CSIRO, Division of Building Research, 1987. Report No JVT 007 (221286) RMZ 136.);
- a fire design KBS (NBSIR. *ASKBUDJR.* Washington DC.: U.S. Department of Commerce, National Bureau of Standards, 1986);
- an architectural design assistant for housing design – 'Budapest (Architecture)' (MARKUSZ, Z. Design in logic. *Computer-Aided Design, 14* (6), 1982, 335–343);
- an integrated structural design system (particularly suited for coping with ill-structured problems) – 'DESTINY' (FENVES, S.J. *and* SRIRAM, D. 'DESTINY': a knowledge based approach to integrated structural design. *SIGART Newsletter,* (92), 1985, 66–67);
- a facility design system, including structural design (addresses problems that are both interpretive and generative in nature) – 'FADES' (RASDORF, W.J. *and* FISHER, E.L. Engineering knowledge management research at North Carolina State University. *SIGART Newsletter,* (92), 1985, 97–99);
- an integrated approach to structural engineering applications – 'KADBASE'* (REHAK, D.R. An integrated knowledge-based systems architecture for CAE. *SIGART Newsletter,* (92), 1985, 53–54);
- a design refinement aid (based on decomposing a complex body of knowledge into small knowledge sources) – 'Ohio (CAD)' (BROWN, D.C. *and* CHANDRASEKARA, B. An approach to expert systems for mechanical design. *In: Proceedings: Trends and applications, automating intelligent behavior.* Gaithersburg, Md.: IEEE, 1983, 173–180);
- a civil engineering design system (allowing the cooperation of multiple viewpoints) – 'SMECI' (HAREN, P., NEVEU, B., GIACOMETTI, J.P., MONTALBAN, M. *and* CORBY, O. SMECI: cooperating expert systems for civil engineering design. *SIGART Newsletter,* (92), 1985, 67–69);

— a system for computer-aided design (stressing man-machine interaction) – 'TROPIC' (LATOMBE, J.-C. Artificial intelligence in computer-aided design: the 'TROPIC' system. *In:* ALLAN, J., *ed. CAD systems.* Amsterdam: North Holland, 1977, 61–120);
— a CAD system implemented for kitchen design and evaluation (operates in an area which has been extensively researched and for which design information is available) – 'WRIGHT' (FOX, M.S. *and* BAYKAN, C.A. WRIGHT: an intelligent CAD system'. *SIGART Newsletter*, (92), 1985, 61–62);
— a system for damage assessment of existing structures after an earthquake (based on the principle of inexact inference, fuzzy set theory and a production system with certainty factors) – 'SPERIL' (OGAWA, H., FU, K.S. *and* YAO, J.T.P. An inexact inference for damage assessment of existing structures. *International Journal of Man-Machine Studies, 22* (3), 1985, 295–306);
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(*Received 13 January 1988*)