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Expert systems in construction engineering and management: state of the art

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1 Introduction

Construction Engineering and Management is a broad area of civil engineering practice which includes: (1) planning and engineering of the temporary facilities for construction sites; (2) management of the construction process; and (3) rehabilitation, repair and maintenance of engineered facilities, where the traditionally distinct design and construction roles of participants have become merged. The broad scope of this field, combined with the empirical nature of many facets of construction engineering and management practice, have led to a significant amount of expert system activity in this domain.

This paper seeks to present a snapshot of the state of the art of expert systems in Construction Engineering and Management at the end of the 1980s. The applications described in this paper were identified through:

- Library and on-line searches of engineering, computer and business publications.
- Surveys of the civil engineering departments of all United States (US) universities and those foreign universities known to be working in this area.
- Contacts with private firms and government agencies that we suspected might be engaged in development of expert systems applications in the area of Construction Engineering and Management.

We have not attempted to identify all existing expert system applications, especially those in the early stages of development or those outside the USA. In particular, we are aware that a significant level of expert system activity is underway within several of the major Japanese construction firms, but results of this work have not generally been published in English language journals, so we are unable to report on it at this time. The paper should, therefore, be considered as a representative, but not exhaustive, catalogue and discussion of ongoing expert system work in construction at this time. The paper updates and expands upon an earlier review of expert systems in construction by the first author (Levitt, 1987).

We start by defining the field of Construction Engineering and Management in more detail to illustrate the types of decisions that might be candidates for expert system applications in this domain. Next we consider why expert systems might profitably be applied to problem solving in Construction Engineering and Management, and find strong motivations for the use of expert systems in this area of civil engineering practice. The bulk of the paper is devoted to thumbnail descriptions of a series of applications, ranging from operational systems (in routine use by persons other than their developers) to research projects still in the conceptual stages, in order to give the reader a sense both of where the state of the art currently is, and of where it might be headed over the next few years. Then, we present ongoing expert systems development in the area of construction project planning which has been an active area of research in many institutions including Stanford University, Carnegie-Mellon University, University of Illinois and MIT. In the conclusion, we summarize the work described in the paper and speculate about the directions of future research and development efforts.

1.1 *What is construction engineering and management?*

We will divide this field up into three major areas: engineering of temporary facilities for construction; management of the construction process; and rehabilitation, repair and maintenance of facilities.

1.1.1 *Construction engineering*

The first subfield of Construction Engineering and Management involves all of the planning and design decisions related to the equipment and physical facilities (e.g., coffer dams, access roads) involved in the construction process. In US practice, these decisions are typically made by different individuals than those who design the permanent facility. This represents the Construction Engineering portion of Construction Engineering and Management. Decision-making tasks associated with this area which might be candidates for formalization via expert systems techniques are listed here.

- **Design of construction methods.** Construction methods to be followed are almost always left to the discretion of the contractor in US practice. There are few formal techniques available for selecting construction methods; experience plays a large role in performing this task. Experience-based decisions to be made in this area include: configuration of crews; selection of equipment types, sizes and combinations; design of transportation facilities such as roads, railways, conveyors, cableways, cranes and hoists for moving personnel, materials and equipment around the jobsite; and approaches to prefabrication or modularization of components for the permanent facility, including locating construction joints in slabs or walls.
- **Concrete as a manufactured material.** The details of manufacturing and placing concrete in a permanent facility are almost always left to the contractor. Decisions to be made here include: mix design, both to meet final performance specifications and to accommodate the method of placement selected; design of crushers, batch plant, and transportation systems; and structural and functional design of formwork and falsework.
- **Geotechnical engineering for construction.** Although deep excavations are usually designed by a project's geotechnical engineer, the design of smaller excavations, pads for temporary facilities, access roads, tunnel support or coffer dams may involve geotechnical engineering decisions on the part of the contractor.
- **Constructability evaluation.** The evaluation and critique of engineering designs in terms of ease and cost of construction has been termed constructability evaluation. This covers a range of different problems ranging from strategic issues such as defining the boundaries of bid packages to operational issues such as optimizing connection details.
- **Site layout.** The location of temporary facilities such as material laydown areas, fabrication shops and office trailers on a construction site can have significant impacts on travel time, worker productivity and safety. This function is usually carried out by a contractor's most experienced site managers.
- **Surveying.** Surveying is associated with the precise location of permanent facilities, and is often considered a separate discipline from civil engineering; however, we have chosen to include it within the scope of this paper. Although surveying calculations are relatively straightforward, aspects of setup and performance of surveying in the field involve judgemental decisions by experienced surveyors.

1.1.2 *Construction management*

In contrast to Construction Engineering, which involves the planning and design of physical elements of the construction process, Construction Management consists of managing the administrative, legal, financial and behavioural elements of the construction process.

- **Project planning, scheduling and control.** This function is now widely supported by the use of network-based project scheduling techniques for analysis, and by database management systems for reporting. Decision-making tasks in this area that could be candidates for expert systems include: generating construction project networks; developing time and cost estimates of construction tasks, particularly in the early stages of project planning; allocating constrained resources to activities; monitoring time and resource consumption; diagnosing reasons for cost, time or resource overruns, forecasting durations and costs of remaining activities on projects; and developing remedial actions for project control. Cost and time estimating are, of course, closely related to the construction engineering decisions on a given project.
- **Contract management.** The processes of developing contracting approaches and of administering contracts throughout the life of projects involve several kinds of expert decision making. Representative decisions in this area involve: selecting an overall contracting approach or strategy; selecting contract clauses to incorporate; identifying and refining project financing or insurance options; prequalifying or selecting prospective contractors or designers; evaluating progress payments; evaluating potential claims or litigation situations; quality assurance; and project organization design.
- **Construction company management.** Several areas of construction company management are being included under our definition of Construction Management. These include: marketing strategy decisions such as whether to submit a bid for a project or how much to mark it up; personnel management decisions; company organization design; financial planning; construction equipment policy decisions; and safety management.

1.1.3 Rehabilitation, repair and maintenance

In this area, the separation between designers and contractors that exists for most new construction has become blurred in practice. The individuals who diagnose deficiencies and recommend remedies for rehabilitation, repair and maintenance of capital facilities are often also involved with overseeing or conducting the construction work. Many of the firms who carry out this type of work for industrial or commercial clients, also perform new construction. Moreover, we learned that several operational expert systems have been developed by engineering-construction firms in this area and others are under development. Consequently, we have included them in this paper.

1.2 Reasons for using expert systems in construction

Our survey found substantial research and development activity in the application of expert systems to decision-making in construction. We can see several reasons why this area of civil engineering might be a good candidate for expert systems.

1.2.1 Construction is an experience-based industry

Construction engineering is far less formalized than the engineering of permanent facilities. Codes or regulations impose far fewer guidelines or restrictions for the design of coffer dams, cableways or conveyor belts than they do for high rise buildings or highway pavements. Moreover, the materials employed for temporary facilities—e.g., soil, plywood, or recycled sheet metal—tend to be much less homogeneous than those used in the construction of permanent facilities. Consequently, expertise about how to engineer such facilities tends to be based upon individual experience, and passed down to younger engineers by "apprenticeship" with experienced counterparts.

Perhaps even more importantly, the construction process is impacted by a great deal of variance resulting from both its one-of production technology, and from external influences such as weather, regulatory agencies and the like. For this reason, structured approaches to decision making are difficult to develop. Decision rules in construction management manuals, where these exist, tend to look very much like the "IF (condition) THEN (action)" rules that are employed to represent knowledge in rule-based expert systems. Furthermore, diagnostic problems, which have been proven the most popular expert system application area and are well suited to the backward reasoning mechanism provided by most low cost microcomputer expert system shells, are common in the construction industry.

There are formal techniques available from operations research or other disciplines which could potentially help in analyzing many of the types of problems that we have outlined above. For example, linear optimization has been proposed as a technique to optimize construction site layout. However, since the processes involved in construction involve far less repitition than is true for manufacturing processes, and since the construction processes are so much influenced by site- and time-specific events, the acquisition of meaningful data to use in such formal optimization models is extremely difficult and costly to obtain. Researchers are attempting to address this shortcoming through development of techniques for automated data capture on construction sites (Paulson, 1985). However, the present shortage of reliable data on, e.g., cycle time distributions of earth-moving equipment, greatly limits the applicability of formal optimization methods in construction at the present time.

All of these factors tend to promote the value of knowledge based on experience over knowledge of formal decision-making methods in the construction industry, as many a young engineering graduate has discovered.

1.2.2 Construction decisions must be made fast

Decisions taken in a design office can sometimes involve significant pressures for speedy resolution. However, decisions to be made on a construction site, when large numbers of workers and machines are temporarily idled pending their resolution, involve far more immediate and visible pressure for speedy resolution. The construction adages, "Any decision is better than no decision", or "Ask forgiveness, not permission," spring from this environment. The ability to make decisions on the spot, based upon wholistic comparisons with analogies from past experience, rather than upon a detailed analysis of all the elements of a given situation, is the hallmark of a successful construction executive.

Expert systems present a new and promising technology for capturing an experienced manager's knowledge about the key attributes of a given situation that should be used to select valid analogies from prior experience and to recommend suitable action plans.

1.2.3 Construction decisions involve managerial issues

Managerial issues, by their nature, involve variables that are more qualitative and subjective than the variables involved in technical issues. The engineers who design permanent facilities must also consider economic aspects of their technical decisions, but the immediacy and intertwining of economic and managerial aspects of decision-making in construction is much greater.

This intertwining of managerial issues with most decisions calls for more flexible solution methods, such as decision making by analogy or the use of rules of thumb—styles of decision making that expert systems were developed to model.

1.2.4 Construction automation needs smart robots

Researchers who have studied construction automation have concluded that fixed, programmable robots such as those used in factory automation will have limited application in construction settings (Rehak, 1985; Paulson, 1985). These researchers have concluded that construction robots require adaptive planning capabilities to respond to changes in the dimensions and site conditions of a construction project over time. We have identified several expert system research efforts in progress to begin to understand the issues involved in developing more autonomous construction equipment than the laser-controlled or tele-operated "robots" currently in use. We believe that expert systems

Table 1 Expert systems in construction engineering.

System name	*Application area*	*Software*	*Hardware*	*Stage of development*
SOILCON	Evaluating subsurface conditions at an early stage of a project	M1	IBM-PC	Developmental
Real-time optimization of earthmoving equipment	Determining the optimum loading time for a scale-model scraper	EXSYS	IBM-PC	Operational prototype
CRANES	Selecting crane locations, crane type, and load/radii on a construction site	PROLOG2	IBM-PC	Operational prototype
SIGHTPLAN	Two-dimensional spatial layout of temporary construction facilities	BB1	TI Explorer	Operational prototype
RODEOS	Designing and setting out road curves	BASIC	IBM-PC	Operational prototype
BERT	Evaluating proposed designs for the brickwork cladding of a building	LUCIFER	IBM-PC	Operational prototype

may turn out to be valuable as programming languages in developing knowledge-based planning capabilities for construction robots.

For all of these reasons, we see expert systems as offering valuable new capabilities to provide decision support for Construction Engineering and Management tasks which have hitherto not been formalized. The many, wide-ranging applications described in the following sections provide strong evidence for this claim.

2 Expert system applications in construction

Our survey found expert system applications ranging from systems which are in routine use by persons other than their developers to ideas for expert system development which are currently little more than a gleam in a scientist's or manager's eye. We have chosen to classify these applications by their area of application: Construction Engineering, Construction Management or Maintenance.

In reporting on the status of each system's development we have used three levels of maturity. The first we term "Operational Expert Systems". We define these to be systems which have proceeded through a prototype stage, have undergone significant validation and refinement, and are currently in use by persons other than their developers on a routine basis. The largest number of systems in our survey are one step away from being operational. We call them "Operational Prototypes". These systems have been prototyped and run, but are still in the validation and refinement stage. If a system has resulted in a first working prototype, we have described it as a "Developmental Expert System". Finally, we will present a review of some ongoing expert system research in the area of construction project planning.

2.1 Expert systems in construction engineering

Construction Engineering involves the engineering of physical aspects of the construction process. We list six applications in this category ranging from site exploration through location of construction joints in masonry, as shown in Table 1.[1]

[1] Although Tables 1, 2, 3, and 4 list a single machine for each expert system, recent advances in computer software and hardware allow running most of the expert systems described in this paper on different computers.

2.1.1 SOILCON: Soil exploration consultant

One of the biggest uncertainties construction projects face is the condition of the soil below the surface of the ground. Owners generally complete only a minimal subsurface investigation, gathering enough data to produce cost estimates and a preliminary design. However, the correct evaluation of subsurface risk at an early stage of the project can have a tremendous impact on the overall success of the construction effort. It is for this reason that SOILCON was developed. This system attempts to eliminate some of the uncertainty involved in the conduct of subsurface exploration by evaluating the known conditions of the site and recommending the proper methods required to continue exploration, if necessary. SOILCON is designed to be used by the owner, in order to incorporate subsurface considerations into contract design, thereby helping to eliminate or reduce contractor contingencies and changed conditions.

The output of SOILCON is a list of recommended site exploration techniques. If there is very little known about the site, then SOILCON may recommend preliminary testing techniques, and vice versa. Output consists of a list of recommended investigation methods ranked by certainty, displayed descriptions of those methods, and displayed cost estimates for the methods. The system is encoded in M1™ and runs on IBM-PC class computers. It uses backward chaining from the knowledge base of rules encoded in a PROLOG-like syntax.

The main drawback of the system is its inability to handle quantitative information, particularly the geometry of the site. This is a developmental expert system (Wharry & Ashley, 1986).

2.1.2 Real-time optimization of earthmoving equipment

The optimum loading time for a scraper varies with the length of the haul, as well as with changes in variables such as the current soil grain size, moisture content, cohesion and density. All of these parameters change constantly. Experienced operators or fleet foremen can adapt quickly to these conditions; however, less experienced operators may overload or underload their scrapers under rapidly varying conditions. This project employs expert systems to select a fleet of equipment for a given project, help novice operators more nearly approach optimum loading times for each machine, and optimize fleet production by communicating between machines in real time.

This project involves using the EXSYS™ shell on IBM-PC class computers to develop several related expert systems which exchange data through a common data file (not a blackboard in the current AI sense, although the EXSYS documentation calls it this). The first is a traditional selection type of expert system which uses forward chaining to select a fleet of equipment, taking into account the site conditions and the contractor's available equipment. The second system reads data saved by the first system and forward chains to set preliminary values for its loading time, then switches to using real-time data from on-board sensors with a local expert system on each machine for optimizing future loading cycles. The third expert system receives radio communications from each machine and attempts to optimize the fleet's production, again using forward chaining through rules in EXSYS.

A scale model scraper, which represents a broad class of equipment that require optimization for their operations, was successfully instrumented and tested. Results illustrate that combining electronic instrumentation and computer data acquisition with expert systems as programming languages for real-time decision making could provide a promising environment for such equipment automation applications.

This is a operational prototype expert system (Sotoodeh-Khoo & Paulson, 1989).

2.1.3 CRANES: Crane resource and evaluation system

CRANES was developed within the Department of Construction Management at Reading University to aid in the selection of crane type and crane locations for specific load/radii problems on a construction site (Gray & Little, 1985). It is targeted for the novice user who will be able to see the range of crane options available, and for the expert user to evaluate alternative solutions to the crane selection problem. The system also evaluates the costs of the alternative solutions to the load lifting problem once the crane specifications are evaluated.

CRANES is an integrated program which first uses a graphics program to help the user locate loads, sizes, and possible crane locations on a site plan. After possible crane locations are identified, along with the corresponding crane size and load/radii, the lifting problem is evaluated through an expert system developed in conjunction with the crane hire and manufacturing industry to determine the full specification of the tower or mobile crane.

Once the full specifications of the crane have been established, CRANES refers to an integral database of available cranes to pattern-match the specifications from the expert system. In addition, a financial analysis of the alternative is made at this point.

CRANES was implemented using PROLOG2 on IBM-PC microcomputers, and integrated with another expert system called "TIME" to aid in predicting construction time and construction activities. CRANES is an operational prototype expert system.

2.1.4 SIGHTPLAN: Layout of temporary construction facilities

Layout of temporary construction facilities has the potential for substantial impact on the efficiency of future construction operations. Improper site layout can lead to extensive lost time in the form of excessive travel time of workers and equipment and inefficiencies due to safety concerns. Despite this, site planning receives little advanced planning and almost no planning during construction. Too often, layout is determined by what space is available at the time the siting requirement arises. Countless material storage yards have sprung up because "there was nowhere else to put it" when the truck delivered the material.

To solve the siting problem, SIGHTPLAN was developed to solve several difficult expert system issues:

- It must manage knowledge from multiple sources. For example, different levels of site management have different expertise concerning their operations and therefore, contribute different input to the system.
- Facility siting is a two or three dimensional, spatial arrangement problem. Spatial arrangement problems are not adequately addressed by existing rule-based expert system shells.
- Finally, temporal reasoning is a prime concern. Siting requirements change as the project progresses. Once again, rules alone have not adequately addressed this problem.

SIGHTPLAN was built using the BB1 domain-independent blackboard architecture, and ACCORD, a specialization of BB1 for constructive assembly, both implemented in CommonLisp and run on TI Explorer™ machine. BB1 was originally developed by Hayes-Roth (1985) to employ and mediate between multiple knowledge sources in expert systems. ACCORD is a general framework under BB1 specialized for solving problems involving assembling arrangements of objects under constraints.

A working prototype of SIGHTPLAN which handles a two-dimensional spatial layout was completed by Tommelein et al. (1989). SIGHTPLAN communicates with SightView, a remote interactive graphical system that displays the current state of the layout and runs on a Macintosh II. This setup provides an environment for systematic exploration of alternative layouts. SIGHTPLAN is an operational prototype expert system.

2.1.5 RODEOS: Road curve design and setting-out

Road curve design is one of the essential tasks of the civil engineer involved with highway engineering. Once the road curve is designed, whether horizontal or vertical, the surveyor must set out the curve on the ground. The difficulty of this task varies with the degree of complexity of the design and of the surrounding construction site. In congested areas, for example, where clear lines of sight are not available for setting out by deflection angles, recourse has normally been to return to linear methods, either by offsets from the tangent or long chord. Problems of access to chainage points on the center line as used in the above methods can be overcome by using the expert system RODEOS (ROad Design Expert On Setting-out). This expert system combines design and setting-out tasks.

RODEOS is a five module program written in BASIC incorporating both curve design and setting out. It is intended primarily to be used as a field engineering tool. The five modules are: curve design, transition design, circular curve design, vertical curve design, and setting-out requirements.

The program is written in BASIC to allow a greater number of users access to the knowledge through most currently available microcomputers. Knowledge is encoded in a rule-based production system. The program not only collects data necessary for the design of a road curve, but also selects the best method and gives a printout of the setting-out requirements.

RODEOS has been used successfully since 1982 at the University of Strathclyde as a teaching aid to students. It is also available for solving highway engineering problems with the user as client. It was developed by P. H. Milne of the University of Strathclyde's Civil Engineering Department. RODEOS is an operational prototype expert system (Milne, 1986).

2.1.6 BERT: Brickwork expert

BERT is an interactive design aid for evaluating proposed designs for the brickwork cladding of a building. BERT examines a submitted design from an AUTOCAD system, comments on the quality of the design, and suggests improvements. The user may then edit the drawing, and cycle through the process again.

The user inputs the design of the brickwork cladding through an IBM-PC CAD program called AUTOCAD™. This input is then restructured by a procedure written in AUTOCAD's attribute file generator to a text file which symbolically describes the face of the building in question. The text file is examined by a graphical representation processor which calculates the spatial relationships between the features of the building. Rules about the proper location of the movement joints are located in the knowledge base of the system, which is then mapped into LUCIFER programming language rules. LUCIFER is a multi-formalism programming language whose main architecture is based on forward chaining, although there are also provisions for backward chaining and a blackboard type architecture, enabling the knowledge from LUCIFER to be shared by other expert systems. BERT also accesses a brick database which contains relevant details about the characteristics of each of the types of bricks the manufacturer makes.

Once the design has been analyzed, BERT will recommend changes in the design, which the user may incorporate into the original design, and resubmit the design to BERT for another cycle or exit the program.

BERT was designed in conjunction with a major brick manufacturer in order to standardize design advice to architects in the many branch offices of the manufacturer. BERT implements two of the five fields in which the manufacturer currently offers advice to builders. It is an operational prototype expert system (Bowen et al., 1986).

2.2 Expert systems in construction management

Construction Management, as we have defined it, addresses planning, scheduling and control of construction activities as well as the design of legal, behavioral and other non-physical elements of the construction process. Applications in this area are described next and summarized in Table 2.

2.2.1 PLATFORM III: Analyzing contingencies in project plans

PLATFORM III is an expert system developed to illustrate the use of the Artificial Intelligence technique of "multiple worlds" in making project feasibility decisions under uncertainty. This technique assists the project manager in making a decision involving multiple uncertainties by generating

Table 2 Expert systems in construction management

System name	*Application area*	*Software*	*Hardware*	*Stage of development*
Platform III	Analyzing contingencies in construction project plans	KEE	Xerox 1186	Operational prototype
MASON	Estimating masonry construction duration	OPS5	VAX	Operational prototype
TIME	Predicting time and cost of construction during initial design	Prolog2	IBM-PC	Operational prototype
Platform	Automating schedule updating	KEE	Xerox 1186	Operational
Know-how transfer method	Supporting project managers with risk management at the project execution stage	Lisp	HITAC M-200	Operational
PROPICK	Selecting contract type and management method	Deciding Factor	IBM-PC	Operational
SAFEQUAL	Evaluating a contractor's expected safety performance	Deciding Factor	IBM-PC	Operational
DISCON	Determining entitlement under the Differing Site Conditions Clause	M1	IBM-PC	Operational
Construction schedule analysis	Analyzing and verifying project networks from the owner side	Personal Consultant+	IBM-PC	Operational prototype
HOWSAFE	Evaluating the safety of a construction firm	Deciding Factor	IBM-PC	Operational
TSA	Assessing the effects of operational changes in view of the technical specifications of nuclear power plants	EXSYS	IBM-PC	Operational
PREDICTE	Estimate the construction time of multi-story buildings before any design development	DEC proprietary shell	DEC mainframes	Operational
Expert-MCA	Providing a user-friendly interface for the CAPCES database	GCLisp	IBM-PC	Operational prototype
CRIS	Identifying, analyzing, and responding to risks in construction projects	C	IBM-PC	Operational prototype
ELSIE	Assessing and guiding the strategic planning of construction projects	Savior	IBM-PC	Operational

"worlds" which describe all of the possible combinations of choices available to the project manager, along with the implications of those choices, and their outcome probabilities and values, based on user-specified evaluation criteria.

PLATFORM III was developed by Kunz et al. (1986) using the IntelliCorp Knowledge Engineering Environment (KEE™), and employs the frames, rules and graphics that are tightly integrated in KEE. An important feature of PLATFORM III is its ability to use the automated truth maintenance system (ATMS) of KEE, Version 3.0. The user is allowed to make assumptions regarding a decision (e.g., whether to build the land-based activities of an oil platform in Norway or Scotland), and these assumptions are used in the program to propagate the effects of the choices made. Once a line of reasoning becomes inconsistent with earlier assumptions or their implications, PLATFORM III backtracks until it can find an appropriate place to modify the search tree, without losing the previous assumptions that the user has made and their implications. These are retained in order to examine other possibilities or "worlds". In addition, the user may modify assumptions at any time, and let the program generate new worlds with new implications and outcomes. The multiple worlds concept allows automation in the generation and evaluation of different possibilities. It also allows users to create new worlds with slightly different facts (e.g., different cost of capital) and to examine their impact on the decision, or to indicate that certain worlds are uninteresting or inconsistent with specified criteria.

PLATFORM III analyzes cost and time outcomes for each of the worlds generated, using a realistically complex time model (a PERT model with 50–100 activities) and a realistic cost function (direct costs and indirect costs, including time-related bonus/penalty amounts). The ATMS leads to rapid computation of outcome values of each of the worlds, and allows the user to browse through the facts in any world by selecting it with a mouse in a time–cost scatter diagram showing all of the worlds. PLATFORM III is an operational prototype expert system.

2.2.2 MASON: An expert system for masonry construction duration estimation

Estimating of activity durations for a construction project is typically done by using average productivities for similar activities and adjusting according to the amount of work to be done, as well as other specific job and site characteristics. These modifications are generally based on engineering judgement and experience. MASON is an expert system which illustrates a hierarchical, rule-based approach designed to make the estimating process more systematic.

MASON is a prototype system which provides facilities for estimating masonry construction durations, explaining the calculations involved in the conclusions, and making recommendations for crew compositions and technologies. MASON is written in the OPS5 expert system programming language. The program uses a backward chaining technique to evaluate a possible conclusion, and then tries to satisfy the supporting rules for the conclusion. One of the main system goals is to provide an estimate of an activity duration.

MASON not only has the capability to estimate activity durations, but will also instruct the user on possible changes that can be made to crew size or composition, or changes in technology (e.g. using high strength mortar instead of standard mortar) that might increase productivity and shorten durations. The user may either accept or reject the recommendations. MASON does not provide facilities for giving optimistic and pessimistic duration times, nor will the program handle uncertain ("fuzzy") data.

The estimation hierarchy of MASON begins with the basic duration estimate, given crew sizes and quantities of materials. Productivity adjustments and down-time adjustments are made to the basic calculations. Once the basic duration estimate is complete, other adjustment factors are figured in, to include such things as whether the work is done inside or outside, particular labor problems, elevation of the work, and temperature. All of these adjustments are combined with the basic estimate to produce a final maximum productivity estimate for the activity.

MASON estimates for productivity have been found to be very close to field-observed actual productivity. The system was developed by Hendrickson et al. (1986). It is an operational prototype expert system.

2.2.2 TIME: Predicting time and cost of construction during initial design

The construction industry is somewhat unique in that the processes of design and manufacturing are separated. Generally speaking, the use of manufacture and assembly of a building are not considered in the design process, because the designer may not have the knowledge needed for their consideration. In addition, evaluation of different methods of design requires prompt feedback regarding their time and cost implications. The expert system TIME was developed to help designers evaluate different construction methods, designs, and processes to determine their effects on time and cost of construction.

This expert system was implemented using PROLOG2 on IBM-PC microcomputers. The program takes rules from construction experts, operates on a data base of common construction activities, and proceeds to model the construction site activity. To determine the time and cost consequences of alternative design strategies and solutions, a system must acquire a great deal of interdisciplinary knowledge of the construction industry. Computing the true total cost of a design solution requires reasonable estimates of activity durations. In this system, activity duration estimates are inferred sequentially from knowledge about the technology of each construction operation, and are then adjusted by knowledge about preceding work operations, the size of the building, and the availability of labor and equipment resources. The system is in the process of being validated and tested (Gray & Little, 1986).

An interesting feature of TIME is its incorporation of nested expert systems. These nested systems are stand-alone applications as well. For instance, one of the key considerations on a construction site may be the selection of the appropriate crane for the job. The main expert system has a nested system which helps the user choose the proper crane. TIME is an operational prototype expert system.

2.2.4 PLATFORM: Hybrid decision support tool for project management

Traditional manual and computerized project management tools have been found to be deficient as real time project control tools in part because of their inability to represent and use construction task knowledge. Because project managers are unable to devote large blocks of time to maintaining schedules for real time planning, schedule updating has become essentially an archival record-keeping process on many projects. PLATFORM is an expert system which shows that an Artificial Intelligence (AI) environment can represent and use construction task knowledge and hence leverage the capabilities of network-based project management systems as realtime control tools.

PLATFORM was developed in the IntelliCorp KEE™ programming environment. This environment is a hybrid software development environment, integrating such AI tools as frame-based representation, rule-based reasoning, active images, and active values, with LISP as an underlying programming language accessible for procedural attachment to rules within knowledge bases. This integration is accomplished with object-oriented computing as the unifying methodology.

PLATFORM uses inheritance to store and propagate data about activities such as activity name, duration, and successors, as well as knowledge about potential risks that could impact each activity's duration in frames, termed units in KEE. Rules which access data stored in these frames are used to interpret past performance data and to predict future performance. PLATFORM currently operates on XEROX 1100 series, Symbolics 3600, and TI Explorer computers.

PLATFORM II, an enhanced version of the original PLATFORM, surpasses traditional project scheduling in its use of two-way interactive graphics for representing and modifying project schedules. In particular, its live Gantt chart capability for resource leveling (termed GanttAlive™) provides a level of user interaction not before available in project control tools. AI techniques of active values (termed demons in other AI systems), and two-way interactive graphics (termed active images) are features of the KEE system that permitted the rapid development of this interface, and which provide the capability for multiple rule systems (e.g., rules about cost estimating or rules about progress payments) to interface with the project data created using the graphical interface and stored in PLATFORM's activity and resource frames.

From a pure expert system point of view, PLATFORM's most significant enhancement to traditional project scheduling packages is automated schedule updating. During normal schedule updates, PLATFORM not only performs new forward and backward pass network computations with actual project data for completed activities, but also looks for significant risks, termed KNIGHTS and VILLAINS, which appear to have impacted the durations of completed activities. A KNIGHT is a risk with a favorable impact on the schedule which is shared by more than one activity; a VILLAIN is a risk with an unfavorable schedule impact on more than one activity. The system will seek confirmation of its identification of KNIGHTS and VILLAINS, and will then change future activities' durations to reflect the effects of these identified KNIGHTS and VILLAINS, asking for user confirmation as it does so.

Existing project scheduling tools can handle networks of thousands of activities for large projects in batch mode. It is anticipated that computational power issues can be addressed through links to existing scheduling packages. As a test of this, a link from PLATFORM to the Sperry Mapper™ database has been successfully built and tested. The design of suitable graphical interfaces and knowledge representation schemes to address the cognitive difficulties of dealing with large networks is continuing.

PLATFORM I was developed by Levitt & Kunz (1985). Subsequent enhancements to the interface leading to PLATFORM II have been added by other IntelliCorp staff members, notably Catherine Perman. PLATFORM was built as a prototype to show the ability of hybrid AI-Procedural systems to enhance the power of traditional procedural tools for construction project scheduling. It currently handles networks of 30 to 50 activities at each level of detail. Subnetworking permits creation of projects with several hundred activities. PLATFORM is being extended for use in several other project management domains, including software project management and factory automation. PLATFORM is an operational expert system.

2.2.5 Know-how transfer method

Changes in the world economy in the 1970s spawned many large construction projects in foreign countries, especially in the Middle East. These large construction projects faced the multitude of problems associated with working within a different culture, with different social, cultural, and religious values. There was a corresponding increase in the risks associated with building in these countries, as well as an increase in research to mitigate these risks. The Know-How Transfer Method was designed to help project managers with risk management at the project execution stage, and its main focus is on identifying risks in advance.

The primary new feature of this expert system has been the development of the "know-how" transfer method of acquiring knowledge for the system to use. Know-how is described as the multidisciplinary knowledge needed by the project manager in the areas of managerial, technical, economic, financial, social/science, and legal/political skills. The system stores the risk know-how onto a standard work package matrix. Know-how then becomes a function of the construction activity, and of the object involved in the construction. The standard work package matrix consists of columns indicating activities, and rows indicating objects. Each job in the project is an intersection of an activity and an object. Know-how acquired on a project is also related to an activity and an object, and is placed onto the grid. This "know-how grid" is then mapped onto the standard work package matrix so that the knowledge may be related to the work packages as a suitable index of knowledge.

The computer system can provide information in several different ways. For instance, the input data may be a work package, and the output data could be risk-reducing strategies that should be followed for that activity. Another example would be to input a risk, and receive as output the risk factors involved, as well as other possible risks resulting from the original risk factors.

This knowledge-based risk management system for large project execution was developed at the Advanced Research Laboratory, Hitachi, Ltd, Japan, on a Hitachi Computer (HITAC M-200) (Niwa & Okuma, 1982). In a recent paper, the author discusses planned extensions of the know-how system to a new type of associative expert system framework (Niwa, 1986). The know-how transfer system has been in use by construction managers at Hitachi, Ltd, for over five years. It is probably the most mature operational expert system in the construction industry.

2.2.6 PROPICK: Selection of contract type

Nearly all construction is done by contracts, and in today's market, owners are faced with a myriad of choices concerning which type of contract to use for their different projects. Many factors affect this decision. Time and dollar constraints, flexibility to accommodate changes, quality concerns, and the current economic market are but a few of the changing inputs in the decision analysis. Moreover, clients often have internal disagreements on the relative priority of cost, schedule, facility scope and other performance objectives for a planned project. PROPICK was developed to model the decision making process used by an owner in deciding which contract type and management method to select. The selection of an appropriate contract type and management method consistent with owner objectives and reasonable economic risk assignment is one of the most important factors influencing project success or failure.

PROPICK was developed using The Deciding Factor expert system shell running on IBM-PC and compatible computers. By analyzing responses to questions requesting from several client representatives their relative emphases on various possible project objectives, the system performs two functions: (1) it surfaces any significant disagreements in relative project objectives among the client's marketing, manufacturing, financial and facilities engineering groups, and (2) it assists in choosing the most appropriate contract type and project management method for the client, once these internal differences have been resolved.

The system attempts to determine whether firm-fixed price, reimbursable cost, or guaranteed maximum price is the correct basic contract vehicle for the project in question. The program also links a recommended project management method—single general contractor, design/construct, or construction management—to the contract type. The system ranks the most appropriate selections from the nine possible combinations of contract type and management method in preferred order for further analysis and final choice by user. It will point out to a client who wants lowest cost, shortest schedule and freedom to make changes that no form of contract will satisfy all of these objectives well; the client is forced to decide which objective is most important for the given project.

The system was developed by Donald S. Barrie, president of CM Consultants in Danville, California, and Consulting Professor in Stanford University's Civil Engineering department, as an aid to his consulting practice (Barrie, 1989). It is an operational expert system.

2.2.7 SAFEQUAL: Evaluating a contractor's expected safety performance

The Business Roundtable's study of the user's role in construction safety determined that construction buyers should prequalify contractors based, in part, on their expected safety performance. This can be evaluated by examining both past accident experience and present safety management practices of construction firms. A study commissioned by The Business Roundtable produced a preliminary questionnaire for this purpose (Levitt et al., 1981). The questionnaire was subsequently reproduced in the "A-3" summary report of the project produced by The Business Roundtable and distributed to over 100,000 readers (BRT, 1982).

As users began to try to evaluate contractors using the questionnaire, they found that some areas of the evaluation (e.g., interpreting experience modification ratings of joint venture firms) seemed to require levels of expertise or judgement beyond what their purchasing or facility engineering staff possessed. This provided the impetus to produce SAFEQUAL, an expert system to assist users in carrying out dependable and consistent contractor safety evaluations.

SAFEQUAL was developed as a decision model in The Deciding Factor™ expert system shell which runs on IBM-PC and compatible personal computers. Construction buyers send out a four page questionnaire with their other prequalification materials to prospective contractors. SAFEQUAL uses Boolean logic to combine and weight the contractor's responses to the questionnaire into degrees of belief in subgoals, e.g., "This contractor has an acceptable insurance record", and finally into a top level hypothesis, "This contractor's expected safety performance is acceptable". Out-of-range responses on specified questions, e.g., those dealing with past insurance losses, will trigger elimination of a contractor from eligibility to bid or propose on the project, by means of The Deciding Factor's conditional logic. These "kill" ranges can be easily reset by a client using The Deciding Factor editor.

SAFEQUAL is a simple expert system, akin to a comprehensive checklist, combined with a spreadsheet, with the capability to instruct a novice user as needed in interpreting contractor responses to the questionnaire, or to justify its evaluation of a contractor's expected safety performance. Moreover, the ease of use of The Deciding Factor as an expert system delivery vehicle means that users with no prior computer experience have been able to use SAFEQUAL with just a one page instruction sheet.

SAFEQUAL underwent field testing in the spring and summer of 1986, which resulted in some minor refinements. It is being distributed as an off-the-shelf product, or customized for individual construction buyers' preferences, by Building Knowledge Systems, Inc. of Stanford California. SAFEQUAL is an operational expert system.

2.2.8 DISCON: Determining entitlement under the differing site conditions clause

Most construction is performed under some type of contract. These contracts have become increasingly complex in recent years as parties attempt to limit their liability for future claims. Resolution of these claims often requires expert legal advice. However, for many reasons, parties often fail to seek this expert assistance. The goal of DISCON is to provide limited but effective legal advice to design and construction engineers, as well as to contractors and owners, concerning different site conditions claims on a US federal government construction project.

The authors of DISCON chose to limit their program development to investigation of differing site conditions claims under the standard federal contract. This was done primarily because case law concerning differing site conditions under the federal form of contract is fairly well defined and self-contained. The program does not apply to local, state or private work.

DISCON is a rule-based system implemented in M1 expert system shell and run on the IBM-PC class of computers where the knowledge of federal contract management is encoded and linked through a series of IF–THEN rules. DISCON's knowledge was acquired from construction lawyers and claim consultants using Verbal Protocols Analysis, where experts are asked to think aloud while performing a claim analysis, and structured interviews.

The program steps through a check of 22 separate modules, each defining a finite area of the differing site condition clause. Examples of these modules include: whether final payment has been made, express or implied conditions within the contract, reliance upon the information, exculpatory language, etc. Users respond to prompted questions with certainty factors, which will lead the program to conclude either "Entitlement" or "No Entitlement", along with the corresponding certainty factor. The program is also capable of determining multiple justifications for entitlement via its explanation facilities. Because the M1 shell has limited built-in explanation facilities, DISCON includes a C language program which provides explanations by invoking external text files to the knowledge base (Kraiem et al., 1989).

The program was validated with the initial domain experts as well as other outside experts and novice users through comparison with case law, and it tested well. The major limitation identified during early validation was that the program at times asks question at too high a level of legal knowledge. For instance, the program asks if different soil conditions are material. Answering this question requires legal judgement. This limitation was overcome by expanding the knowledge in the system; thus the user no longer requires a legal background.

Since publication of initial findings, researchers at the US Army Corps of Engineers Construction Engineering Research Laboratory decided to revise the program logic to fit the Corps office environment and to minimize the legal knowledge required. Their effort resulted in CGS (Claims Guidance System) which is written using the software tool Personal Consultant Plus™, and run on IBM-PC microcomputers. At the end of a consultation, CGS displays a summary of an actual case, if such a case can be found from the Board of Contract Appeals or the Court of Claims, which has similar characteristics to the situation at hand. This is performed by searching a collection of claim cases which is organized using dBASE-III software. The system was field tested and proven to be a valuable training tool for inexperienced project engineers in the analysis of potential differing site condition claims (Kim et al., 1989).

Both DISCON and CGS are operational expert systems.

2.2.9 Construction schedule analysis

Owners of construction projects must maintain control of the contract schedule in order to make project payments and ensure timely completion of the job. Thus, they continuously receive and review updated project schedules. Traditionally, however, less sophisticated owners limit their analyses to the obvious questions: estimated start date, estimated completion date, and estimated completion cost. In doing this, these owners presuppose that contractors have thoroughly verified their submissions. The expert system "Construction Schedule Analysis" was developed to capture the expertise that knowledgeable project managers use in managing their projects.

The knowledge base for this program combines construction scheduling rules, construction knowledge, and general construction experience such as effects of weather, placement rates, etc. Four major groups of scheduling decision rules were implemented in the knowledge base:

1 General requirements, such as I-J numbers and activity descriptions.
2 Time, such as evaluation of reasonable activity durations.
3 Logic, such as checking to see that submittals precede approval and construction.
4 Cost, which includes tests for total project cost and excessive front end loading.

Additionally, knowledge to revise remaining estimated duration is incorporated. The program links like activities by class; compares efficiency on completed and in-progress activities; and adjusts estimated completion on all like, remaining activities. This capability is similar in its intent to PLATFORM (Levitt & Kunz, 1985).

The program is implemented in a hybrid microcomputer artificial intelligence environment consisting principally of a project management system (PRIMAVERA™), a database management system (dBASE III™), and an expert system shell (PERSONAL CONSULTANT PLUS™). PRIMAVERA manages network data in the same way that it does in any scheduling environment, with dBASE III housing not only specific project data but also non-project information such as hourly wages and productivity rates. PERSONAL CONSULTANT PLUS is an expert system shell developed by Texas Instruments for use with TI and IBM personal computers. The shell uses both frames and rules to represent the encoded knowledge.

This program is an operational prototype expert system (De La Garza & Ibbs, 1989).

2.2.10 HOWSAFE: Evaluation of the safety of a construction firm

Stanford's Construction Engineering and Management Program has been conducting research into construction safety since 1969. When one considers that most construction firms do not have a complete library at the home office, much less in the field, combined with the inadequacy of traditional methods of knowledge dissemination—journal articles and technical reports—other means for communicating knowledge to jobsite managers must be found. This need for a more convenient means of knowledge transfer to field construction managers motivated the development of HOWSAFE.

HOWSAFE is intended as a diagnostic tool to assist the chief executive of a construction firm in determining the "health" of the firm's safety programs. HOWSAFE is implemented as a knowledge base using The Deciding Factor™ expert system shell, running on the IBM-PC class of computers. The Deciding Factor employs backward chaining and two kinds of conditional logic, termed Kill Values and C-logic, to represent knowledge as an "inference net". An inference net represents knowledge in the form of an inverted tree diagram with lower "leaf" nodes supporting higher level hypotheses. This form of knowledge representation was derived from the PROSPECTOR expert system developed at SRI International in the mid 1970s. The user's responses to leaf node questions are combined and weighted to reach a final degree of belief in the top level hypothesis, "This construction firm has the required organization and procedures to promote safe construction".

HOWSAFE was developed by Levitt (1986). It is distributed along with a companion package, SAFEQUAL, by Building Knowledge Systems, Inc., of Stanford California. It is an operational expert system.

2.2.11 TSA: Technical specifications advisor

Nuclear power plants operate under the limitations of the plant's technical specifications. The technical specifications define the conditions under which a plant can legally operate and impose restrictions on plant operation based on the status of the plant's safety systems. These technical specifications are complex enough to bewilder even experienced operators, e.g., subtle interactions between pieces of equipment that have no obvious relationship may result in a violation of technical specifications. It is imperative to avoid such violations, not only for safety reasons but also to avoid potential regulatory impacts. For this reason, Stone and Webster Engineering Corporation (SWEC) developed the Technical Specifications Advisor (TSA), an expert system that assesses the effects of operational changes or removal of equipment in view of the technical specifications of nuclear power plants.

TSA provides information regarding the safety and regulatory related consequences of proposed equipment maintenance and operator actions in nuclear power plants. Requests for maintenance can thus be approved or denied based on a knowledge of their regulatory consequences. TSA was developed using the expert system shell EXSYS and runs on the IBM-PC class of computers. It is expected that the system will be extended to reason about other aspects of the plant which are not now addressed by TSA, such as prediction of reactor trips, analysis of process parameters, and detection of paths to drain the reactor vessel. TSA is an operational expert system (Finn, 1987).

2.2.12 PREDICTE: Time estimating system

Construction firms are frequently asked to provide time and cost estimates for projects whose scopes are only very loosely defined. The expertise to do this in a manner that results in a competitive, yet profitable, time and cost estimate is very scarce. Consequently, the PREDICTE expert system was developed by Civil and Civic, a major construction firm in Australia, to permit the firm to respond quickly and competitively to such inquiries from clients with a realistic schedule. PREDICTE determines what contractors call the indicative construction time for a multi-story building before any design development takes place beyond the initial concept stage. To generate this time estimate, the system asks the customer questions about the various materials and characteristics of the building.

PREDICTE analyzes and compares indicative times for alternative concepts, searches for opportunities to reduce time, and permits the user to do what-if scenarios using interactive graphics facilities. Although the current version of the system does not address cost estimate, human cost estimators can use PREDICTE's time estimates to make much more accurate estimates of the construction cost at an early stage. PREDICTE was developed by Civil and Civic in collaboration with Digital Equipment Corporation's AI applications group. The system was built using a proprietary new AI development language, which has been designed by DEC and runs on DEC mainframes. PREDICTE is an operational expert system (Stretton, 1989).

2.2.13 Expert-MCA: Military construction army-cycle analysis

The US Army Corps of Engineers maintains data on US Army facilities in their various stages of planning, programming, budgeting, design and construction. While all of the appropriate data is maintained within a large data base named CAPCES (Construction Appropriations Programming, Control, and Execution System) which uses the FOCUS™ database management system, the database is not organized to extract complex, high-level questions such as, "Why is project X so far behind schedule?" Answering questions like this one requires some expert knowledge as well as stored data. This expert system, Expert-MCA, uses both facts stored in the CAPCES database and stored expert knowledge about problem solving procedures to answer these types of questions.

Expert-MCA was developed as a multi-module system for the US Army Construction Engineering Research Laboratory (CERL) under the direction of Ms Sandra Kappes and Dr Simon Kim. Specifically, it incorporates natural language processing, machine learning, database management systems, and expert systems techniques to develop a very user-friendly system. The system is able to understand English-like queries, direct queries, or procedural queries; and it has the ability to learn by example.

Expert-MCA is written in GCLisp and runs with mostly compiled code on IBM-PC microcomputers with at least 3 MB of random access memory (RAM). Expert-MCA consists of five major modules: a user interface, a language analyzer, a reasoner, a knowledge base, and a query generator. In manipulating any query, the system not only considers the data in the database, but also considers information about the user—including rules and responsibilities—and the MCA domain. Expert-MCA is an operational prototype expert system (Logcher et al., 1989).

2.2.14 CRIS: Construction risk identification system

The construction industry is characterized by a high potential for risk and uncertainty due to the complex and dynamic nature of construction projects. It is thriving firms that are best able to identify and manage perceived risks. However, the ability to determine these risks is usually only resident in the most senior of company personnel. Yet much of this knowledge can be formalized and analyzed. It is the goal of the Construction Risk Identification System (CRIS) to provide the mechanism to assist management in the identification, analysis, and response to risks and uncertainties in construction projects.

Risk analysis in the construction domain requires certain characteristics which are not adequately and efficiently supported in either existing expert system shells or database management systems (DBMS) alone. The use of DBMS and set theoretic inquiry has helped to guide and enhance the decision making ability of managers. However, the results of the inquiries to the databases still require subjective interpretation of the results; hence expert system technology is needed. On the other hand, existing expert system shells provide only limited support for representing and reasoning with uncertainty and for performing sophisticated numerical computations. Therefore, to meet the characteristics of this problem domain, the author has designed a hybrid system based on: (1) expert systems principles such as knowledge acquisition, representing and manipulating heuristic knowledge, and explanation; (2) DBMS functionalities; and (3) the influence diagramming technique of decision analysis for systematically representing qualitative as well as probabilistic models of construction projects.

Three man-years of effort were devoted to acquiring from 212 construction experts, as well as from existing publications, knowledge of possible construction problems, their cause–effect links, assessment of uncertainties, and the project characteristics where they occurred. The knowledge acquisition in CRIS was extensive and expensive, and hence it motivated the development of an interactive knowledge acquisition subsystem to aid experts in updating as well as expanding the knowledge base while maintaining its consistency. This subsystem not only makes the knowledge acquisition process easy to perform but also provides support for integrating a project manager's judgement with the previously encoded experience from multiple experts.

CRIS is written in the C programming language and utilized the capabilities of three software packages that provide only basic programming support. These software are Multi-Halo™ for graphical display support, db-VISTA™ (a network DBMS), and Rbase V™ (a relational DBMS). The latter two software are DBMS that are used for modelling the risk identification knowledge base. The system runs on IBM-PC microcomputers and is an operational prototype expert system (Perng, 1988).

Table 3 Expert systems in maintenance

System name	*Application area*	*Software*	*Hardware*	*Stage of development*
PUMP PRO	Diagnosing pump problems at operating locations and at the start-up phase	MAIDS	IBM-PC	Operational
Rotating equipment vibration advisor	Diagnosing problems in rotating equipment	EXSYS	IBM-PC	Operational
Field diagnosis of welding defects	Determining likely causes of weld defects	EXSYS	IBM-PC	Operational
BREDAMP	Diagnosing the causes of dampness and water ingress problems in buildings	Savoir	IBM-PC	Operational

2.2.15 ELSIE: Lead consultant—the strategic planning of construction projects

In January 1986, the Quantity Surveyors Division of the Royal Institution of Chartered Surveyors (RICS), in collaboration with the University of Salford, launched one of the most ambitious expert system projects in the construction industry to date. It was sponsored by the UK Alvey Directorate and costs more than £250,000. The system was designed to provide assistance and guidance in the strategic planning of construction projects so that the Lead Consultant can translate the client's objectives into a framework within which more tactical decisions could take place. Incidentally, the name of this system is ELSIE, which comes from the initials of "Lead Consultant" (L-C). It considers four issues (cost, time, type of contract, and expected profit) which are critical from the owner point of view at the early stages of the project. Accordingly, the system consists of four modules that provide support for decisions on these important issues. These four modules are linked through a database to allow sharing of information among these modules, to avoid repeating questions, and to maintain consistency. To earn the system's credibility, knowledge was acquired from a team of recognized experts in commercial project management, and agreement among these experts was ensured for every heuristic encoded in the system.

The system is implemented using the expert system shell Savoir and runs on IBM-PC microcomputers. It has been validated using both the expert contributors and live projects, and it provided answers better than could be expected from a single human consultant. After further refinement, the system became available for commercial sale and over 100 systems have been sold to date. The system stores only part of the knowledge and expertise of human experts, and thus there is ample room for expanding the amount of knowledge as well as for increasing the range of projects that the system can deal with.

ELSIE is a mature, operational expert system (Brandon et al., 1988).

2.3 Expert systems in maintenance

The third class of expert system applications that we will present in this paper address problems in facility maintenance. In this area, personal computer based tools already appear to be providing valuable decision support. Applications in this area are summarized in Table 3.

2.3.1 PUMP PRO™: Centrifugal pump failure diagnosis

Most industrial facilities have numerous pumps in place which must be started and tested as part of project completion. Correction of failures often necessitates the use of expensive and time consuming consultants. Although this program is principally designed to diagnose pump failure at operating locations such as power and process plants, PUMP PRO can be used to diagnose pump problems by on-site personnel during the start-up phase. The intent of the program is to allow mechanics, technicians and millwrights to avail themselves of expert knowledge in this domain.

The program is written in MAIDS, Microcomputer Artificial Intelligence Diagnostic Service, a proprietary expert system shell developed at Stone and Webster Engineering Corporation (SWEC). The MAIDS inference mechanism is a forward-chaining, rule-based program that uses a subset of the English language for representing rules. The program has two modules, a rule compiler and an execution module.

Diagnosis by PUMP PRO is accomplished in four phases: (1) identification of the symptoms; (2) identification of the causes; (3) provision of tutorials; and (4) suggestion of remedies. PUMP PRO diagnoses problems by means of 22 possible symptom classes and a summarized pump history. It allows input of multiple symptoms and provides seven extensive tutorials and many minor tutorials in the problem identification rules.

PUMP PRO is an operating system containing several hundred rules (Finn & Reinschmidt, 1986). It is one of a family of similar systems offered by SWEC, accessible by modem using an IBM-PC class of computer. About 400 of SWEC's clients have copies of the software and passwords needed to access this and several other expert systems. Users are assessed a charge (currently $15 per hour) based on connect time to the SWEC IBM-PC microcomputer in Boston, MA.

The present configuration for on-line access by users has the user's PC act as a terminal to SWEC's IBM-PC microcomputer, hosting both the expert system shell and the knowledge bases. Communication through the modem makes the program run rather slowly, especially with the large quantity of text which this system must send to the user's screen. An alternative mode of operation would be for SWEC to have the expert system shell resident on licensed users' computers, and to assess users a charge for downloading the latest version of the knowledge base each time it was run.

The notion of a large consulting firm acting as a dial-up "knowledge utility" for many kinds of routine consulting services is a unique and challenging one. It will undoubtedly be emulated by others.

PUMP PRO is a mature, operational expert system.

2.3.2 Rotating equipment vibration advisor

The process of diagnosing problems in rotating machinery, as with any diagnosis, is dependent, to a large extent, on the data used to make a diagnosis, and the expertise of the diagnostician. Vibration monitoring and measuring is a well practiced art in routine maintenance and it has been found that there are experts in this field who can identify causes of vibration after examination of very few data. This program was developed in order to improve the performance of engineers who are assigned the task of vibration diagnosis.

This program, developed by Stone and Webster Engineering Corporation (SWEC) using the expert system shell EXSYS, is designed to run on standard, IBM-PC class microcomputers. Heuristic knowledge to develop this system was captured from mechanical equipment specialists with many years of vibration measurement and analysis experience in dealing with problems in centrifugal pumps and compressors, industrial fans, electric motors, and steam turbines. The program operates in an interactive question/answer format, obtaining most of its required information from the user, or from the output of its own frequency analysis software. The system is rule-based, containing over one hundred rules. It is able to diagnose eighteen separate causes of vibration. The program presents in ranked order, the possible cause of the vibration and gives fairly detailed explanations of each (Finn & Reinschmidt, 1986). This program is also available for use by clients of SWEC through the dial-up service described above. It is an operational expert system.

2.3.3 Field diagnosis of welding defects

This system allows field personnel, welders, supervisors or quality control personnel to determine likely causes of weld defects. The program takes into account different welding procedures, code requirements, site conditions, and observations. The program enables more rapid repair of welding defects, thus reducing rework costs.

Users of this program are asked to select the type of weld in question and describe the conditions of the failed weld by answering simple English language questions. The program then reasons through a possible list of causes and determines a reason for the failed weld. An example of a response given is "slag was allowed to build up on the first pass".

There are two other welding programs developed at SWEC, though they address problems in Construction Engineering. One is an expert system to select the appropriate welding procedure, based on types of materials being welded, type of weld required, etc. Another welding program is the Welder Qualification Test Selection System which helps managers pick the appropriate qualification tests for welders hired on major construction projects. All three welding programs are written using the expert system shell EXSYS for use on an IBM-PC class of microcomputer. Users can access these expert system, like the two described above, by dial-up connections to SWEC (Finn & Reinschmidt, 1986). By distributing expertise through these welding systems, the entire welded construction process is optimized. Procedures are selected accurately and efficiently, welders are tested appropriately, and defects are minimized. These welding programs are operational expert systems.

2.3.4 BREDAMP: Building research establishment diagnosis of dampness in buildings

In 1984 Building Research Establishment Advisory Service (BRAS) in UK established a research team to identify problem areas within the construction industry that are suited for an expert system solution. The team identified building defect diagnosis as an area where expert systems can be readily applied with considerable benefit. The team's first project was BREDAMP, an expert system to diagnose the causes of dampness and water ingress problems in buildings (Allwood et al., 1987).

Dampness in buildings is a common problem in Northern climates which is complicated not only due to the ability of water to creep along unexpected pathways but also due to the behaviour of building components invisible from direct view. There are only a few experts in BRAS who deal with numerous routine questions in this field. As a result, they have limited time to deal with the more complex problems that may arise. BREDAMP was built for non-specialist in the field to enable them to handle routine enquiries, and thus freeing the highly qualified experts to tackle the interesting and demanding problems.

The system starts by asking the user a short set of preliminary questions. Then, it expands an exhaustive investigation of the likely causes of fourteen possible classifications of dampness. Finally, the system identifies the most likely cause and justifies its line of reasoning; thus it could serve as a training tool and an advisory assistant to diagnose dampness problems. The system developers ensure credibility of their product by involving one of the leading experts in dampness from BRAS in the knowledge acqusition task. The system has gone through a series of prototyping and validation since 1984. The final version was implemented in Savoir, an expert system shell from ISI Ltd which supports reprsentation and reasoning about uncertain knowledge and allows linkage with external Pascal procedures, and runs on IBM-PC computers. BREDAMP is an operational expert system.

The examples that we have presented in the three areas of Construction Engineering and Management, illustrate the broad range of expert system applications that practitioners and researchers have found for this technology. The motivations for many of these applications appear to be the use of expert systems as a powerful new communications medium for knowledge—to delegate decision making under control, to insure that relevant attributes of a problem are not overlooked, to preserve an organization's experience for use across barriers of space and time, and as a way for researchers to formalize and communicate their knowledge to peers.

2.4 Ongoing expert system development in construction planning

Enhancements to the theory of network-based tools invented in the late 1950s, along with improved hardware and software environments, have resulted in elegant and powerful tools for planning

Table 4 Expert systems in construction planning

System name	*Application area*	*Software*	*Hardware*	*Stage of development*
Construction Planex	Planning and scheduling the construction of modular high-rise buildings	Knowledge Craft	TI Explorer	Operational prototype
ISIDC	Designing, planning, scheduling, and controlling of construction projects in an interactive, integrated environment	AutoCad & SIPE	Mac II	Operational prototype
GHOST	Criticizing project networks	Blackboard	Sun	Operational prototype
OARPLAN	Planning the construction of multi-story buildings	BB1	TI Explorer	Developmental
Construction schedule generation	Planning mid-rise commercial construction projects	KEE	TI Explorer	Developmental
Scheduling of subsea maintenance	Scheduling, with the guidance of the user, the subsea maintenance of oil platforms	Prolog & ODDS	Sun	Operational prototype

today's construction projects. Existing computer technology has greatly facilitated the efficiency of the CPM and PERT computer program systems. They provide support both for scheduling, by performing network computation of dates, resources, and cost, and for reporting, by data base management systems. However, a fundamental limitation of these traditional planning techniques is that they are able to manipulate only the data generated by the planning process, not the knowledge used in generating the project plan (Levitt et al., 1988). Because of this, plan generation has been a challenging area of research for AI researchers since the 1960s.

In the course of our survey, we identified several researchers who were working on expert system applications in the area of construction planning. We felt that many readers of this paper would be interested to know about the type of research currently under way in this important area of the construction industry. We have therefore included thumbnail descriptions of these expert systems (see Table 4).

2.4.1 Construction-Planex

CONSTRUCTION PLANEX is a frame-based expert system for construction planning and scheduling of modular high rise buildings. In CONSTRUCTION PLANEX, decision tables (implemented via frames) are used for grouping rules into knowledge sources in a compact and readable form. CONSTRUCTION PLANEX was developed using the KnowledgeCraft environment on a TI Explorer machine. For a given type of facility (e.g., a modular concrete frame building), it assists in the selection of appropriate construction technologies; aggregates activity elements into project activities (by tracing back the MASTERFORMAT codes); produces plans (using lookup of successor data that are provided in advance rather than deduced); and estimates the activities' durations and costs. Subsequently, PLANEX was used, with some modification, to plan the manufacturing operations for automobile electrical wire harnesses (Zozaya-Gorostiza et al., 1989).

The operators in CONSTRUCTION PLANEX should not be confused with the operators in AI planners. In AI planners, operators represent the actions that may be performed in the given domain. In CONSTRUCTION PLANEX, operators are local effect algorithms using rules, heuristics and calculation functions. These operators are applied one after the other by the Knowledge Source Evaluator whenever there is a change. They look at the context and modify it as needed. The *Create Element Activity* operator takes information given by design elements and produces element activity frames. The *Group Element Activity* operator looks at the element activities created and groups them according to their MASTERFORMAT numbers.

An earlier effort of this type was the LIFT system developed by (Bremdal, 1988) for planning the installation of deck modules on offshore platforms with the use of floating cranes. Once again, the system was developed as an expert planning system for a particular task, with large amounts of domain-specific knowledge encoded in rules, in this case written in the OPS5 language.

PLANEX is an operational prototype expert system.

2.4.2 ISIDC: Interactive system for integrated design and construction

Three primary goals in developing this system are: (1) to allow representation and solving of many construction domains using the same system environment, (2) to develop an interactive human–computer system so that the user can guide the design and construction operations executed by the computer, and (3) to integrate the four critical functions of designing, planning, scheduling, and controlling of construction projects in a unified system.

To achieve the first two goals Kartam (1989) designed the *construction subsystem* using the SIPE domain-independent planning shell. The *construction subsystem* includes several knowledge bases of generic, heuristic knowledge; each knowledge base corresponds to a certain construction domain, e.g., multi-story buildings, houses, oil-drilling platforms, etc. The system is capable of acquiring project-specific knowledge such as site and weather conditions from the user. With a frame hierarchy, generic operators, and a constraint-based approach, the *construction subsystem* can generate logically correct activity networks for a given construction project from a description of the components of a facility. To model such construction projects in a concise and uniform framework, the *construction subsystem* uses some underlying principles such as "gravity support" and "enclosed by" for establishing ordering relationships among the project components involved in construction activities (Kartam & Levitt, 1990).

To achieve the third goal, the *design subsystem* was developed using AutoCad and an object-oriented building model called "PAMP" (Ito et al., 1989). The project-specific knowledge about structural members and their topological information needed by the *construction subsystem* is provided automatically from AutoCad using PAMP.

At present the system supports and integrates only design and planning of construction projects which is the first step toward reducing fragmentation in the architecture–engineering–construction (AEC) industry (Howard et al., 1989). ISIDC has been applied to different construction projects including a multi-story office building, an oil-drilling concrete platform, and a single family house. It will be extended to support: (1) scheduling through representation of and reasoning about time and resources during the planning process, rather than after a plan is generated; and (2) controlling by incorporating knowledge about causes or impacts that may affect the durations of the activity using SIPE's deductive rules. Such knowledge can be used along with actual performance data of completed activities to update meaningfully the duration of remaining activities; this is similar to the work completed by Levitt & Kunz (1985).

All the computer software required for the ISIDC system, i.e., AutoCad and SIPE, run on the same machine, a Macintosh-II with a built-in MacIvory board; thus, allowing for smooth integration of design and construction. The advantages of such an integrated system are widespread availability of valuable specialized knowledge, more efficient construction performance, early design decision making informed by construction impacts, fewer errors in design and construction planning, increased consistency of decision making, avoiding repeated input, and making information shareable among these highly interacting functions.

ISIDC is an operational prototype expert system.

2.4.3 GHOST

GHOST (Generator of Hierarchical networks for cOnSTruction) (Navinchandra et al., 1988) is a knowledge-based system for generating project networks by using a blackboard architecture approach to planning. It is part of a larger integrated knowledge-based environment for construction planning (called CONPLAN), which is currently under development at MIT. An attempt will be made to optimize the project networks by trade, resources and costs; to determine duration of activities and expectations; and to perform all traditional network calculations. GHOST itself is the module that handles the determination of the precedence relationships among activities. It is based on critics. These critics are of a finer grain than the critics of traditional AI planners; they are domain specific. For example, a critic called "supported-by" will look at various activities that might be executed in parallel and determine if some object is supported by some other object and, if that is the case, it will assert that the activity of constructing the support should come before the one for constructing the supported structure. Information about which objects support a given object needs to be provided to the system, however.

GHOST's planning proceeds as follows: First, it starts with a small number of high-level but particular activities, all placed in parallel with one another. Some critics might be able to tell at this stage whether some activities depend on the completion of others. If that is the case, these activities are ordered. These high-level activities are then expanded into more detailed activities, but without considering interaction that might exist among these detailed activities. These detailed activities can be derived with the help of schemata where they have been specified by the user. More specific critics are then applied to determine the ordering relationships among the detailed subactivities.

GHOST is a developmental expert system.

2.4.4 OARPLAN

OARPLAN is a prototype knowledge-based planning system for generating construction project plans from a description of the objects that comprise the completed facility. OARPLAN is implemented using the BB1 blackboard environment on a TI Explorer machine. It is based upon the notion that activities in a project plan can be viewed as combinations of objects, actions, and resources. This notion is adapted from the professional intelligent project planning assistant (PIPPA) (Marshall et al., 1987) as stated by the author of OARPLAN: "Marshall defined an activity as an action that applies to a product component and that needs resources. Our representation is essentially the same, we define an activity as the following tuple: ⟨action⟩ ⟨object⟩ ⟨resources⟩ " (Darwiche et al., 1988). The goal of this research is to generate project plans through providing a natural and efficient knowledge representation environment for construction activities and for the relations that might exist among them, including spatial, topological, and temporal constraints. A recent version of OARPLAN has been implemented in Allegro Lisp on the Macintosh-II and applied to an office building. The PMAP CAD interface (Ito et al., 1989) which provides "object" data to the ISIDC system is used with minor modifications to provide the input needed by OARPLAN. OARPLAN is a developmental expert system.

2.4.5 Construction schedule generation

This research is focused on planning mid-rise commercial construction projects, though its concept and techniques can be applied to other types of construction projects. Construction planning knowledge of four expert schedulers from four different construction firms are being encoded in this system. This real knowledge engineering task is an important feature of this system which would enhance its chances of success. Knowledge is classified into typical project features and non-typical project features which correspond to domain-specific knowledge and project-specific knowledge respectively in the ISIDC system.

The system is being developed using KEE™ on a TI explorer machine. For a specific mid-rise commercial project, the system identifies activities required to complete the project, their sequencing, and their durations. Analogical reasoning techniques will be investigated, in addition to an expert system solution, to generate project networks.

This program is a developmental expert system (Echeverry et al., 1989).

2.4.6 A knowledge-based assistant for the scheduling of subsea maintenance

This expert system generates schedules, with the guidance of the user, for the subsea maintenance of oil platforms. This work involves the assignment of tasks to technologically capable vessels, the co-ordination of those vessels' movement in the oil field, and the sequencing of tasks according to technological constraints as well as other constraints such as resource availability and weather.

The system includes a body of *domain knowledge* which can be used to create instances (e.g., tasks, vessels, constraints, etc) for a specific project and a body of *scheduling knowledge* which provide heuristics and steps to generate the schedule. Initially the tasks are defined at a detailed level of abstraction, and then grouped to form collections of work at a higher level of abstraction. This bottom-up aggregation approach of tasks is similar to the one adopted in the Construction Planex system (see section 2.4.1 above). Then, the system assigns scheduling priorities for the grouped tasks according to their properties. The schedule generation proceeds considering priorities of the grouped tasks as well as existing platform and vessel constraints using forward chaining which matches the reasoning way of most human planners.

The system is implemented using Prolog and an object oriented programming language called ODDS (Object Description and Database Structuring) on SUN workstation (Brysland & MacCallum, 1988). It is an operational prototype expert system.

3 Conclusions

Considering the widespread view of construction as a conservative industry, it may be surprising to some readers that so much work has been done in attempting to apply this new computer technology to construction problems. In the introduction, we provided several arguments for why this technology might be especially valuable to decision makers in construction. The extent and breadth of work already completed, under way, or in the early conceptual stages, indicates that many researchers and practitioners in the construction industry see expert systems as offering new and potentially valuable capabilities to support decision making in the industry.

In this final section, we will provide some analysis of the applications described in this survey, and some thoughts about possible directions for ongoing and future development work in this field.

3.1 Extent of work to date

The construction industries of most developed nations—with the notable exception of Japan—have been widely criticized for their failure to commit funds and effort to research and development. Against this backdrop, it is particularly interesting to tally up the amount of effort that has gone into research and development of expert systems in construction over the past few years.

If we assume that each operational expert system reported here involved five person-years of effort, each operational prototype has involved three person-years to date, and each developmental or ongoing research expert system has involved one person-year to date, we reach a total of:

Operational systems:	$13 \times 5 = 65$ person-years
Operational prototype systems:	$14 \times 3 = 42$ person-years
Developmental systems:	$4 \times 1 = 4$ person-years
Total for construction expert systems:	111 person-years

If we price a person-year of research or development at $100,000 (to include overhead costs), we can estimate a cumulative investment of $11.1 million in building expert system prototypes by the researchers and practitioners whose efforts we have reported here. Clearly this is an active area of research and experimentation.

3.2 Distribution of current applications

We can classify expert system applications in construction in two ways: by stage of development, and by application area. Table 5 shows this breakdown.

Table 5 Distribution of expert system applications

	Operational	Operational Prototype	Developmental	TOTALS:
Construction Engineering	—	5	1	6
Construction Management	9	9	3	21
Repair, Rehabilitation & Maintenance	4	—	—	4
TOTALS:	13	14	4	31

From Table 5, we can see that the volume of expert system work carried out in Construction Management has been more than three times as high as in Construction Engineering. This result may be merely an artifact of the voluntary nature of the information provided in our survey. It is quite possible that a great deal of expert system work is being conducted in the area of Construction Engineering by equipment manufacturers or others who are not yet ready to disclose it. However, we doubt that this is the case. Perhaps expert systems will prove to be more valuable for managerial kinds of decisions than for technical decisions in this industry.

Note also that projects reported show a good balance between developmental and operational systems. One would expect operational systems to be better represented in our sample, since many conceptual or developmental stage systems have not yet resulted in publications. There are probably many more projects in the developmental stage that we have not reported. We interpret this to indicate a long term commitment to expert systems research and development in construction by academics and practitioners in several countries. One can confidently predict active research efforts in this area for the foreseeable future.

3.3 Current and future trends

It is always hazardous to forecast technology futures, but with the appropriate disclaimers, we will attempt to do so. Two factors that we can assess reasonably well are likely to influence the direction of future applications in construction: the evolution of hardware and software for developing and delivering expert system applications, and the themes currently being addressed by systems in the early stages of development. We will summarize each of these and draw some implications from them.

3.3.1 Hardware and software technology for expert systems

Although it is difficult to predict the exact configuration or cost of future hardware and software for expert systems, the general trends are quite clear:

- Costs of personal computers are beginning to bottom out as keyboards and monitors become their most costly components, but the performance of such systems continues to grow. Powerful battery-operated laptop machines with several megabytes, of RAM, and capable of enduring the rigors of construction sites, are already available.

- Such computers already permit the use of expert system programming environments that exceed the capabilities (and far exceed the ease-of-use) of MYCIN and PROSPECTOR, the mainframe-based expert system languages that launched this technology. We expect to see estimators, project engineers, and others walking around jobsites with such computers, running expert system applications that communicate by radio with programs or data in a site or home office, within the next few years.
- A new generation of personal workstations which support the high-end AI environments, was recently introduced in the market and has been employed for building some of the applications that we described in this paper. Symbolics introduced the MacIvory board which allowed implementing the ISIDC system on a Macintosh-II machine. Texas Instruments introduced the Micro-explorer board which allowed implementing OARPLAN and SightView on Macintosh-II machines. Expert systems shells, such as IntelliCorp's KEE™ system and Inference Corporation's ART™ system, which used to run only on Lisp workstations are currently available for use on personal computer workstations with these specially designed chips.

  The creation of these LISP machines on a board enables the deployment of inexpensive computers which process numerical data with traditional microprocessors such as the Intel 80 × 86 or Motorola 680 × 0 and carry out symbolic processing in parallel on a LISP coprocessor board. It is difficult to predict whether construction engineers will find uses for these advanced expert system environments on portable computers, but the authors are confident that problems such as project scheduling or design and layout of temporary facilities will be conducted at construction jobsites using such workstations within a few years.
- Probably of greater significance than these hardware developments for high level AI tools, however, is the efforts that the high level AI tool vendors have made to port their software to industry standard Unix workstations on which engineers currently run their CAD, database, analysis and other applications. This allows integration of AI with traditional engineering applications and has permitted the development of a new generation of knowledge-based CAD tools such as ICAD (Written in Lisp), Concept Modeler (written in Lisp) and SCEMA (written in KEE and incorporating AutoCad for visualization) for automating the design of process plants and buildings. The first applications of intelligent CAD technology are currently being fielded by progressive firms in Europe and the US and are predicted to have a major impact on the construction industry during the 1990s (Riitahuhta, 1988).
- The software tools available for building expert system applications in construction have also improved dramatically over the last five years. Systems that can run on standard Intel 80 × 86 or Motorola 680 × 0 class computers and which were used by developers of the applications described in this paper already offer outstanding ease of use (The Deciding Factor), the capability to interface with external data and programs (Savoir and Level 5) and even support of frames (Personal Consultant Plus, GoldWorks, and Nexpert Object). We can expect continued significant gains in performance/price ratios, and also enhanced software capabilities over the next few years.
- Moreover, the developers of the most sophisticated expert system programming environments (notably IntelliCorp and Neuron Data) and certain manufacturers of the LISP workstations needed to host them (Text Instruments, Apple and IBM) have made their products available to construction researchers at deeply discounted prices in order to seed research on more sophisticated expert system applications. We now see the first such hardware/software environments being purchased by construction firms. This seed hardware and software, along with less expensive run-time platforms for advanced expert systems, will permit interaction and cross-fertilization of ideas between academia and industry through the exchange of knowledge bases built using the most powerful tools currently available. It provides cause for optimism.

3.3.2 Themes in ongoing expert systems research

Some of the expert systems that we presented in this paper are characterized by combining knowledge processing with database management systems and computational systems. We believe that much of the future research and development of expert systems in construction will continue using such hybrid environments.

- Several expert systems are concerned with decision support for management of construction projects. Considering the widespread use of sophisticated project scheduling packages, and the enormous resources that are currently devoted to generating project plans and updates, this area would seem to offer substantial commercial potential. Project management software vendors, contractors and others are, therefore, viewing this application area with considerable interest. We predict that this will be a major area of future research and development for expert systems in construction.
- A second, related area for fundamental research and development on expert systems in construction is the use of expert systems for integrating between design and construction decision making. KADBASE, a knowledge-based database interface between structural design and construction cost estimating expert system modules was developed by Craig Howard and his colleagues at Carnegie-Mellon University (Howard & Rehak, 1986). KADBASE is a forerunners of such hybrid expert systems in which AI programming approaches are used not only to develop individual expert system modules, but also to manage communication between these multiple "knowledge sources" and other expert systems, databases and application programs.
- A third application of expert systems in construction is interfacing expert systems to CAD systems which can attach non-graphical attributes to their graphical objects. The BERT system described above points the way towards this type of application. We believe that the PMAP system (Ito et al., 1989), which was successfully used for both ISIDC and OARPLAN, is the first system of this type. It offers the promise to move us towards "Real Time Engineering", in which the graphical representation of a project, with its attached non-graphical attributes, forms a pictorial database that can support design, construction and facility management decision-making needs from a central database in real time. We predict that expert systems will play a strong role in this type of hybrid computer-aided design environment, too.
- Finally the area of diagnostics for inspection, maintenance and repair is likely to be an area where many small systems, residing on desktop or laptop personal computers, will be developed. The minimal level of effort required to produce useful systems of this type, and the low cost, standard hardware and software make it easy to justify their development, even with present technology. Future advances in ease of use and power will make such projects even more attractive.

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References

Allwood, R, Shaw, M, Smith, J, Stewart, D and Trimble, E, 1987, "BREDAMP—an expert system to diagnose the causes of dampness in buildings" Working paper, Building Research Establishment, Dept. of the Environment, UK.

Barrie, DS, 1989, *PROPICK User's Manual* CM Consultants, California.

Bowen, J, Cornick, TC and Bull, SP, 1986, "BERT—an expert system for brickwork design" Working paper, University of Reading, Departments of Computer Science and Construction Management, 1986.

Brandon, P, Basden, A, Hamilton, I and Stockley, J, 1988. *Expert Systems: the Strategic Planning of Construction Projects* Quantity Surveyors Division of the Royal Institution of Chartered Surveyors (RICS), London.

Bremdal, BA, 1988, *An Investigation of Marine Installation Process—A Knowledge-Based Planning Approach* Institute for Marine Prosjektering, Trondheim.

Brysland, C and MacCallum, KJ, 1988, "A knowledge-based assistant for the scheduling of subsea maintenance" in: *Artificial Intelligence in Engineering: Robotics and Processes* Gero, JS, ed, pp 311–329, Elsevier.

BRT (The Business Roundtable), 1982, *Improving Construction Safety Performance: The User's Role* Construction Industry Cost Effectiveness Report A-3, The Business Roundtable, New York.

Darwiche, A, Levitt, R and Hayes-Roth, B, 1988, "OARPLAN: generating project plans in a blackboard system by reasoning about objects, actions and resources" *Journal of Artificial Intelligence in Engineering Design, Analysis and Manufacturing* **2** (3) 169–181.

De La Garza, J and Ibbs, C, 1989, "A knowledge elicitation study in the construction scheduling domain" To appear in the ASCE *Journal of Computing in Civil Engineering.*

Echeverry, D, Ibbs, C and Kim, S, 1989, "Generation of construction schedules a knowledge-based approach" *Proceedings of the Sixth International Symposium on Automation and Robotics* pp 220–227, San Francisco, California.

Finn, GA, 1987, "An expert system for technical specifications" Stones and Webster Engineering Corporation, Boston, Massachusetts.

Finn, GA and Reinschmidt, KF, 1986, "Expert systems in an engineering-construction firm" in: *Expert Systems in Civil Engineering* Kostom, C and Maher, M, eds., ASCE.

Gray, C and Little, J, 1985, "A systematic approach to the selection of an appropriate crane for a construction site" *Construction Management and Economics* **3** 121–144.

Gray, C and Little, J, 1986, "Expert system development for predicting time and cost of construction during initial design" First International Expert Systems Conference, London.

Hayes-Roth, B, 1985, "A blackboard architecture for control" *Artificial Intelligence* **26** (3) 251–321.

Hendrickson, C, Martinelli, D and Rehak, D, 1987, "Hierarchical rule-based activity duration estimation" *Journal of Construction Engineering and Management* **113** (2) 288–301.

Howard, HC, Levitt, RE, Paulson, BC, Pohl, JG and Tatum, CB, 1989, "Computer-integrated design and construction: Reducing fragmentation in the AEC industry" *Journal of Computing in Civil Engineering* **3** (1) 18–32.

Howard, C and Rehak, D, 1986, "Interfacing expert systems with multiple databases in an integrated CAE environment" *First International Conference on Expert Database Systems* Carnegie-Mellon University.

Ito, K et al., 1989, "Linking knowledge-based systems to CAD design data with an object-oriented building product model" TR # 17, Center for Integrated Facility Engineering, Stanford University, Stanford, CA.

Kartam, NA, 1989, "*Investigating the utility of artificial intelligence techniques for automatic generation of construction project plans*" Ph D thesis, Dept. of Civil Engineering, Stanford University, Stanford, California.

Kartam, NA and Levitt, RE, 1990, "Intelligent planning of construction projects" *Journal of Computing in Civil Engineering 4* (2).

Kartam, NA, Levitt, RE and Wilkins, DE, 1990, "A centralized approach for representing and resolving interactions among multi-agent tasks while planning hierarchically" *Proceedings of the Sixth IEEE Conference on Artificial Intelligence Applications* Santa Barbara, CA.

Kim, M, Adams, and Harkleroard, J, 1989, "A knowledge-based microcomputer training tool for contract claims" *Proceedings of the Sixth Conference on Computing in Civil Engineering* Barnwell, Thomas, Jr, ed., pp 67–75, ASCE.

Kraiem, ZM, Dagli, DP and Diekmann, JE, 1989, "DISCON: an expert system for the analysis of differing site conditions claims" *Knowledge-Based Systems Journal* **2** (3) 158–163.

Kunz, J, Bonura, T, Stelzner, M and Levitt, R, 1986, "Contingent analysis for project management using multiple worlds" *Proceedings of the First International Conference on Applications of Artificial Intelligence to Engineering Problems* Sriram, D and Adey, R, eds., pp 707–718, Southampton University.

Levitt, RE, 1986, "HOWSAFE: a microcomputer-based expert system to evaluate the safety of a construction firm" In: *Expert Systems in Civil Engineering* Kostem. C and Maher, M, eds., ASCE.

Levitt, Raymond E, 1987, "Expert systems in construction" in: *Expert Systems for Civil Engineers* Maher, ML, ed., pp 85–112, ASCE.

Levitt, RE, Kartam, NA and Kunz, JC, 1988, "Artificial intelligence techniques for generating construction project plans" *Journal opf Construction Engineering and Management* **114** (3), pp 329–343, ASCE.

Levitt, RE and Kunz, JC, 1985, "Using knowledge of construction and project management for automated schedule updating" *Project Management Journal* **16** (5).

Levitt, RE, Samelson, NM and Parker, HW, 1981, "Improving construction safety performance: the user's role" T.R. 260, Dept. of Civil Engineering, Stanford University, Stanford, California.

Logcher, RD, Wang, M and Chen, FH, 1989, "Knowledge processing for construction management data base" *Journal of Construction Engineering and Management* **115** (2), pp 196–211, ASCE.

Marshall, G, Barber, TJ and Boardman, JT, 1987, "Methodology for modelling a project management control environment" *IEE Proceedings* **134** (4) 287–300.

Milne, PH, 1986, "An expert system for road curve design and setting-out" *Applications of Artificial Intelligence in Engineering Problems* 1st International Conference, Southampton, UK, Sriram, D and Adey, R, ed, pp 733–74.

Navinchandra, D, Sriram, D and Logcher, R, 1988, "GHOST: project network generator" *Journal of Computing in Civil Engineering* **2** (3) 239–254.

Niwa, K and Okuma, M, 1982, "Know-how transfer method and its application to risk management for large construction projects" *IEEE Transactions on Engineering Management* **29** (4).

Niwa, K, 1986, "A knowledge-based human-compputer cooperative system for ill-structured management domains" *IEEE Transactions on Systems, Man and Cybernetics* **16** (3) 335–342.

Paulson, BC, Jr, 1985, "Automation and robotics for construction" *Journal of Construction Engineering and Management* **111** (3) 190–207.

Perng, Y, 1988, "*An intelligent system approach for construction risk identification*" PhD thesis, Dept. of Civil Engineering, The University of Texas at Austin, Texas.

Rehak, DR, 1985, "Robotic applications in construction: A white paper" in: *New Research Directions in Computerized Applications to Construction Engineering and Management Studies* Ibbs, WC, ed., The University of Illinois, Dept. of Civil Engineering, Construction Research Series No. 19, pp 108–112.

Riitahuhta A, 1988, "Enhancement of the boiler design process by the use of expert system technology." Dr. Tech. thesis, Acta Polytechnica Scandinavica, Mechanical Engineering Series No 92, Helsinki, Finland.

Sotoodeh-Khoo, H and Paulson, BC, Jr, 1989, "Sensors and expert systems in production optimization of earthmoving scrapers" *Proceedings of the Sixth Conference on Computing in Civil Engineering* Barnwell, Thomas, Jr, ed., pp 303–312, ASCE.

Stretton, A, 1989, Personal communication with Alan Stretton of Lend Lease, the parent corporation of Civil and Civic.

Tommelein, ID, Levitt, RE and Hayes-Roth, B, 1989, "SIGHTPLAN: an artificial intelligence tool to assist construction managers with site layout" *Proceedings of the Sixth International Symposium on Automation and Robotics in Construction* pp 340–347, San Francisco, California.

Wharry, MB and Ashley, DB, 1986, "Resolving subsurface risk in construction using an expert system" UTCEPM-86-1, Dept. of Civil Engineering, Univ. of Texas at Austin, Texas.

Zozaya-Gorostiza, C, Hendrickson, C and Rehak, D, 1989, *A Knowledge-Based Process Planning for Construction and Manufacturing* Academic Press.