EXPERT SYSTEMS APPLICATIONS IN CONSTRUCTION MANAGEMENT AND ENGINEERING

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ABSTRACT: Because of their characteristic attributes of combining factual knowledge with judgment, being able to handle incomplete and uncertain data, and communicating with their users in the natural language, expert systems have a special appeal for the construction profession. In spite of this appeal, there are currently very few operational expert systems in the field of construction. One reason for this may be a lack of awareness by the industry as to what expert systems currently exist, what their capabilities are, and who their developers are. Presenting this information to the potential users in an easily scannable format is one of the objectives of this paper. A second objective of this effort is to present the characteristics of the state-of-the-art expert systems to researchers and expert-system-developing institutions. This information will help them in making a choice of the most appropriate tools and trigger communication between developers working in similar domains. This paper has listed 37 expert-system applications in the field of construction management and engineering. Of these, seven are operational, 14 exist as operational prototypes, and 16 are at the developmental stage. A majority of the expert systems developed so far are available on microcomputers, have the rule-based knowledge-representation scheme and are implemented using commercial expert-system shells.

INTRODUCTION

Because of their characteristic attributes of combining factual knowledge with judgment, being able to handle incomplete and uncertain data, and communicating with their users in a natural language like English, expert systems have a special appeal to the construction profession. The following typical features of today's construction environment show the need for an expert-systems-like technology for improving construction quality and productivity (Levitt 1987, 1985).

- Unlike manufacturing, construction is nonrepetitive, each project being different in design, layout, materials used, construction methods, time, crews, weather, and management. Ready algorithmic solutions are therefore not applicable to the day-to-day construction problems.
- Construction environments are full of uncertainties in respect of labor and equipment productivity, market forces, material availability and changes, variations in regulatory agencies' influence, and variations in weather. Algorithmic computer programs cannot handle such uncertainties.
- So far, not enough knowledge in the field of construction engineering and management has been formalized and encoded in textbooks. The industry runs on conventional knowledge and experience based judgment. This is very true in respect of the construction of temporary facilities, a first and an important task, where the construction is undertaken using local ma-

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terials like wood and gravel with widely variable properties.

- In many construction situations, there is not enough time to make a detailed analysis of all the influencing factors. Such decisions are often made on the spot so that the construction process is not interrupted. Expert systems can provide quick decisions in such situations.
- Many construction decisions like safety management, labor relations, decision to bid, bid evaluation, and risk management are qualitative and subjective in nature, needing heuristic approaches.
- On a construction project, all the necessary information on a subject is almost never completely known and the decisions have to be taken on the basis of incomplete information.
- Many construction professionals and managers do not have enough knowledge of computer science to be able to use and update algorithmic computer programs.
- Expert-system building requires domain experts, and there are highly knowledgeable experts in the construction industry who have successfully completed several projects and who are widely recognized in the profession.

In spite of the need and potential benefits, there are currently very few operational expert systems in the field of construction. One reason for this may be a lack of awareness by the industry about what expert systems currently exist, what their capabilities are, and who their developers and vendors are. Presenting this information to the potential users in an easily scannable format is one of the objectives of this paper.

A second objective of this effort is to present the characteristics of the state-of-the-art expert systems to researchers and expert-system developing institutions. This information includes knowledge structure and system-building tools, which will help them in making a choice of the most appropriate tools, and trigger communication between developers working in similar domains. These links will then encourage some cooperative effort resulting in the production of richer, more universal and consequently more useful expert systems.

As a result of an extensive literature search and the writer's personal contacts with many researchers and expert-system-building organizations, this paper lists 37 expert-system applications in the field of construction management and engineering. Of these, seven are operational, i.e., in routine use by persons other than their developers, 14 exist as operational prototypes, and 16 are at the developmental stage. A majority of the expert systems developed so far are available on microcomputers, have the rule-based knowledge-representation scheme, and are implemented using commercial expert-system shells.

One other factor that will affect the use of expert systems in the construction industry is the nature of this industry, which is highly competitive and risk averse. Specialized problem-solving knowledge in a company is considered proprietary and the concept of sharing that expertise with competitors is not accepted. Building small expert systems for internal use will, however, be seen as beneficial in the industry. But company's proprietary information is limited to a few sensitive areas like bidding strategies, strategic planning, and financial management. Several other areas in construction planning, engineering, and management are potential candidates for expert-system formulation and its effective application. Thirteen major tasks have been identified in this paper including constructability evaluation; temporary-facilities layout; construction-company management; equipment selection, diagnosis, and repair; human-resources management; project planning, scheduling, and control; materials management; design of construction methods; concrete mixing and placement; operational problems in constructed facilities; construction-quality control; and legal issues.

What lies ahead in the use of expert systems in the field of construction depends on how useful the construction industry finds these first expert systems. So far, expert-systems research has been confined to academic institutions, Carnegie Mellon University, Stanford University, and Massachusetts Institute of Technology in the United States, and the University of Reading in the United Kingdom, being the leaders. The work done has shown that expert-systems technology has the potential of offering practical tools for making intelligent and fast managerial and technical decisions. The following trends can be safely predicted at this time: (1) The next few years will see several small expert systems and company-proprietary expert systems routinely used within the industry. A good number of these expert systems will be capable of interfacing with graphics, data-base-management programs, and algorithmic programs; and (2) the expert-system-building process will consolidate and document construction knowledge currently dispersed among many individuals, journals, and books. This consolidation of domain knowledge will give rise to the building of larger expert systems, which will have frame-based-knowledge representation with graphic input and output, will be integrated with several external programs, and have a blackboard architecture. Furthermore, most of them will be implemented in more efficient languages like "C," and will run on UNIX-operated workstations.

State-of-the-Art Expert Systems in Construction

The development of expert systems in the field of construction is in the very early stages and very few operational expert systems exist today. However, a significant amount of activity is starting to take place in this area. Most of the expert systems developed so far are available on microcomputers, have rule-based-knowledge representation, and are implemented using commercial expert-systems shells. Table 1 summarizes the state-of-the-art expert systems in construction, detailing the input-data requirements, system output, knowledge structure, control strategy, hardware and software used in the building of each of the expert systems, address of the system-building organization, and the name of the key contact. This summary is based on literature searches and personal contacts with developer institutions (Ashley and Levitt 1987; Hendrickson et al. 1987; Jounis 1988; Koskela et al. 1986; Levitt 1987; Navinchandra et al. 1988; Sathi et al. 1986).

Levitt (Levitt 1987) has grouped expert systems into four categories:

1. Operational expert systems: Expert systems that have been validated and refined, and are in routine use by persons other than their developers.
2. Operational prototypes: Expert systems that have been prototyped and run but are still to be validated and refined.
3. Developmental expert systems: Expert systems that have passed the conceptual stage and whose first prototypes have been built.

J. Constr. Eng. Manage., 1990, 116(1): 87-99

TABLE 1. State-of-the-Art Expert Systems in Construction

Expert system (1)	System input (2)	System output (3)	Knowledge structure, tools, developer organization, and key contact (4)
		(a) Operational Expert Systems	
WELDING ADVISOR	Type of materials involved Weld geometry	Estimate of welding supplies Any special-equipment list Appropriate welding procedure	Rule-based (150 rules); IBM PC-class microcomputer; LOTUS 1-2-3; K. Reinschmidt, Stone Webster Engineering Corporation (SWEC) Boston, Mass. 6 man-months
WELDING DEFECT ADVISOR	Weld procedure Code requirements Site conditions Condition of failed weld	Causes of weld defects Individual defects System defects Advice to prevent poor welds	Rule-based (150 rules); IBM PC-class; EXSYS shell; K. Reinschmidt, SWEC, Boston, Mass. 6 man-months
KNOW-HOW Transfer Method	Work packages Risks	Possible risks Risk reduction	HITAC M-200 (Hitachicomputer) PROLOG; K. Niwa, Advanced Research Lab, Hitachi Ltd., Japan
SAFEQUAL	Accident experience Safety-management practices	Prequalification of contractors	IBM PC; Deciding Factor; Raymond E. Levitt, Building Knowledge Systems, Inc., Stanford, Calif.
HI-COST: Cost Estimating from Preliminary Design	Preliminary design alternatives	Cost estimate based on preliminary design	PSRL, LISP and C; Carnegie Mellon Univ., Pittsburgh, Pa.
HOWSAFE: Safety Analysis System	Personnel procedures	Social safety rating of a construction firm	IBM PC; Deciding Factor; Raymond E. Levitt, Stanford Univ. Stanford, Calif.
PUMP PRO: Centrifugal Pump Failure Diagnosis	Data on the pump condition etc.	Identification of the symptoms and causes of pump failure Tutorials on microcomputers Suggestions for remedies	Rule-based; MAIDS AI language, Gavin Finn, SWEC; Boston, Mass.
		(b) Operational Prototypes	
BERT—Brickwork ExpeRT	Design of brickwork cladding Brick data base (Graphical form)	Comments on design quality Suggestions for improvements Best design solution	IBM PC, AutoCAD, MUFL; J. Bowen et al., Dept. of Constr. Management & Computer Science, Univ. of Reading, U.K.
MASON	Basic duration estimate Crew size Quality of materials	Masonry-construction duration Recommendations for crew composition Maximum-productivity estimate	Hierarchical, Rule-based; OPS5; Chris Hendrickson et al., Civil Engineering, Carnegie Mellon Univ., Pittsburgh, Pa.

J. Constr. Eng. Manage., 1990, 116(1): 87-99

TABLE 1. (*Continued*)

(1)	(2)	(3)	(4)
CRANES	Site plan	Possible crane locations Crane size and type Cost of alternative solutions	AMDAHL, and PDP-11; PROLOG, Collin Gray et al., Dept. of CM, Univ. of Reading, U.K.
PROPICK—Selection of a Contract Type	Project objectives	Conflicts in project objectives Appropriate form of contract	PC, Deciding Factor; Donald S. Barrie, CM consultants, Diablo, Calif.
DSCAS—Differing Site Conditions Analysis System	Differing site conditions	Entitlement with justification No entitlement	Rule-based; IBM PC; ROSIE; Diekmann, University of Colorado, Colo., and U.S. Army CERL, Champaign, Ill.
PLATFORM	Activity name, duration, successors, and potential risks	Automated schedule updating	Frames & rules; XEROX 1108; KEE; Raymond E. Levitt, Stanford Univ. and John Kunz, IntelliCorp, Calif.
PLATFORM-III	Project data	Project feasibility under certainty	Frames; XEROX 1108; KEE; Raymond E. Levitt, Stanford Univ. and John Kunz, IntelliCorp, Calif.
Predicting Time and Cost of Construction During Initial Design	Activity details and resources	Time and cost of activities	IBM PC; PROLOG; Collin Gray, Dept. of Construction Management, Univ. of Reading, U.K.
Military Construction Army-Cycle Analysis	Data on army facilities	Status of each project	IBM PC; GC LISP; Robert D. Logcher MIT and Sandra Kappes, U.S. Army, CERL, Champaign, Ill.
Construction Schedule Analysis	Project and activities data	Status of project schedule Revision of activity durations	IBM PC, PERSONAL CONSULTANT PLUS; William East, U.S. Army, CERL, Ill.
CALLISTO: An Intelligent Project Management System (For Large Projects)	Project knowledge Activity duration precedence resources project constraints	Constraint-directed negotiated approaches to activity management resource management configuration management	KNOWLEDGECRAFT; Arvind Sathi, Carnegie Group, Pittsburgh, Pa.
Interpreting Collective Agreements in the Building Industry	Type of absence Sick-child care Work accident Normal sickness Definition of extra holidays in the agreement	Amount of sickness pay of the employee	Rules; PC; GURU & INSIGHT2+; Jolkkonen Jonni, Tech Research Center (VTT), Itatuulentie 2, Finland
ELSIE; Expert System for Strategic planning of Construction Projects	Client's Project scope Client's needs Aesthetics and quality Design flexibility Environmental factors Client's brief	Initial budget Procurement options Optimum project durations Profitability of the project	SAVOIR shell; IBM PC/AT; Peter Brandon, Univ. of Salford, U.K.

J. Constr. Eng. Manage., 1990, 116(1): 87-99

TABLE 1. (*Continued*)

(1)	(2)	(3)	(4)
CGS-DSC: A Claims Guidance System—Differing Site Condition Claims	Final-payment status Claimed conditions Site conditions Contract provisions	Contractor's chance of entitlement with explanation	PC; PERSONAL CONSULTANT PLUS; Moonja Kim, U.S. Army CERL, Champaign, Ill.
		(*c*) Developmental Expert Systems	
SITEPLAN: Layout of Temporary Construction Facilities	Available space	Project-site layout Updating of site plan	Blackboard Architecture; XEROX 1108 and 1186; KEE; Iris Tommelin, Civil Engineering, Stanford Univ., Stanford, Calif.
IPMS85/2: Intelligent Project Management System	Job time and cost monitoring data	Evaluation of project personnel	Rule-based, IMST written in LISP, Robert D. Logcher; MIT, Mass.
CPO-ES: Construction Project Organization Design	Project details	Appropriate project organization Evaluation of existing project organization	PC; Deciding Factor; Rudolf Burger Motor Columbus Consulting Engineers, Inc., Baden, and ETH, Zurich, Switzerland
ICT: Time Estimating System	Loose definition of project scope	Project-time estimate	DEC mainframe; DEC's new AI developmental language; Alan Stretton, Civil & Civic, Australia and DEC, USA.
KB for Repeating Construction Project Success	Project details Resource constraints Project objectives Strategy under consideration	Preferred planning and execution strategy Likelihood of success	Microcomputer; M-1 shell; David B. Ashley; Univ. of Texas, Austin, Tex.
Risk Management Expert System	Project details	Project risks	Rule-based; PC; INSIGHT2+; Roozbeh Kangari; Civil Engrg., Georgia Inst. of Tech., Atlanta, Ga.
IRIS: Intelligent Construction Risk Identification System	Project data	Identification of risks on a construction project	Microcomputer; M-1 shell; D. Ashley, Civil Engineering, Univ. of Texas, Austin, Tex.
Vertical Construction Schedules	Project data	Correctness of a given schedule	Frame-based; TI Explorer & IBM PC/AT; ART, Primavera; C. W. Ibbs; Univ. of Illinois and U.S. Army CERL
Maintenance Advisor for Old Elevators	Data on malfunctioning elevators	Diagnosis and suggested repair strategy for malfunctioning elevator	IBM PC; Expert-Ease shell; Alan Stretton, Elevators Pvt., Ltd., Australia

TABLE 1. (*Continued*)

(1)	(2)	(3)	(4)
CONSTRUCTION PLANEX	Project data	Project activities duration estimates network Cost estimates Cost schedules Appropriate technology High-rise buildings: activity planning associated with site preparation, excavations, foundation construction, and structural erection	Frames; TI Explorer; Knowledgecraft on Common LISP; C. Hendrickson, Civil Engineering, Carnegie Mellon Univ., Pittsburgh, Pa.
GHOST: A Project Schedule Generator	Set of construction activities	Precedence among activities Project schedule	Blackboard architecture; IMST framework—an ES environment developed at MIT, LISP; Robert D. Logcher, MIT, Mass.
Expert System for Repainting of Wooden Facades	Category of deteriotion Type of previous paint Current paint brands	Types of paints to be used	ES/P Advisor and INSIGHT2+; PC; 70 rules; 4 man-months, Tech. Res. (VTT), Itatuulentie 2, Finland
Expert System for Choosing the Type of Ready-Mix Concrete	Environmental class Water-impermeability requirements Frost-proof requirements Corrosion-proof requirements Spacing between rebars Type of structure Compressive strength class Production equipment	Warning if compressive-strength requirement is too low Recommendations about appropriate concreting techniques Information about the use of admixtures Maximum size of aggregate	PC; INSIGHT2+; 189 rules; Tech. Res. Ctr. (VTT) Itatuulentie 2, Finland
FDES: Failure Diagnosis Expert System (Construction errors)	Component properties Component geometry Loading conditions Postfailure appearance	Causes of failure Type and extent of failure Design errors Failure-triggering events	Microcomputer; EXSYS shell; Fabian C. Hadipriano, Civil Engrg., Ohio State Univ., Columbus, Ohio
Expert System for the Construction and the Resolution of Multicriteria Dwelling Design Problems	Representation of the building project	Design parameters with the following viewpoints: Architectural Acoustical Thermal Economical	PC; PROLOG; Rule-based interfaced with CAD'X2A'; P. Le Gauffree, Institut National Des Sciences Appliques De Lyon, 69621 Villeurbanne, Cedex, France
ESEMPS: Expert System for Earth Moving Plant Selection	Task definition soil type topography Job condition	Best equipment type Best equipment make Best equipment size Cost of recommended equipment	PC; SAVOIR shell; Rule-based; Frank Harris, The Polytechnic, Wolverhampton, U.K.

4. Conceptual stage expert systems: Expert systems whose ideas have been worked out and are at the programming and knowledge-acquisition phase.

The expert systems of the first three groups have been included in Table 1. Conceptual expert systems have not been included because they are too many and too changeable.

Characteristics of Expert Systems in Construction

The various characteristics of the state-of-the-art expert systems listed in Table 1 can be summarized:

1. Developer institutions: Most of the expert-systems development work is being done in academic institutions. Of the 37 expert systems listed in Table 1, 22 are affiliated with universities, eight with research institutions, and only seven with the construction industry. Although this trend is expected for an emerging technology, it delays the field testing and marketing of potentially successful expert systems. It is very likely that several of the expert systems now being developed at universities will never be fully operational.
2. Knowledge sources: For many of the expert systems listed in Table 1, the sources of knowledge encoded are not explicitly defined in the literature or in other sources used in this effort. It is roughly estimated that about 40% of the expert systems have extracted knowledge from experts and the remaining ones from books and journals.
3. Hardware: Twenty-four of the 37 expert systems listed were developed on the IBM PC class of microcomputers, and 10 were developed on LISP machines like the TI Explorer or the Xerox 1100 series. Others have used the HITAC M-200 Hitachi computer, PDP-11, and DEC mainframe computers. A distribution of the hardware used in the building of various expert systems is given in Table 2. The current trend is away from LISP machines and toward advanced PCs and workstations.
4. Software: Various types of software have been used in expert-systems development. The distribution of software is given in Table 3. Eighteen of the 37 expert systems used commercial expert system shells; seven were developed on expert-system environments like KEE, ART, KNOWLEDGECRAFT, and OPS5; seven have been implemented in AI programming languages (4 in PROLOG and 3 in LISP); and 5 were developed in other proprietary languages/environments.

TABLE 2. Hardware Used in Expert Systems Development

Hardware (1)	Number of expert systems that used it (2)
IBM PC class of microcomputer	24
Xerox 1108/1110	3
TI Explorer	2
DEC Mainframe	1
PDP-11	1
Hitac M-200	1
Other LISP machines	5
Total	37

J. Constr. Eng. Manage., 1990, 116(1): 87-99

TABLE 3. Distribution of Software Used in Expert-Systems Development

Expert system language/shell (1)	Number of expert systems using it (2)
Expert-system shells	
DECIDING FACTOR	4
INSIGHT2+	2
M-1	2
EXSYS	2
PERSONAL CONSULTANT PLUS	2
SAVOIR	2
EXPERT-EASE	1
ROSIE	1
GURU	1
ES/P Advisor	1
Subtotal	18
Expert-system environments	
KEE	3
KNOWLEDGECRAFT	2
ART	1
OPS5	1
Subtotal	7
AI programming languages	
PROLOG	4
LISP	3
Subtotal	7
Other/proprietary languages	5
	37

In the commercial expert-system shells, the more popular shells were DECIDING FACTOR, INSIGHT2+, M-1, EXSYS, PERSONAL CONSULTANT PLUS, and SAVOIR.

5. Knowledge representation: Rule-based knowledge representation was the most popular scheme, used in 19 of the reported systems.

TABLE 4. Construction Areas Covered in State-of-the-Art Expert Systems

Broad area covered (1)	Number of expert systems (2)
Project planning, scheduling, and control	11
Project management	9
Construction methods	6
Equipment management	4
Legal issues	3
Human-resources management	2
Concrete mixing and placement	1
Temporary-facilities layout	1
Total	37

J. Constr. Eng. Manage., 1990, 116(1): 87-99

6. Construction areas covered: The distribution of the various areas addressed in the state-of-the-art expert systems is given in Table 4. A majority of the expert systems have been developed in the areas of project planning, scheduling, and control (11 out of 37) and in areas of project management (9 out of 37). No expert system has been developed in the areas of materials management, company management, constructability evaluation, and quality control.

7. Blackboard architecture: Very few of the listed expert systems use knowledge from multiple sources. Construction process is a team effort and oftentimes the team members have diverse goals. Therefore, to gain success and acceptance in the construction environment an expert system will have to integrate knowledge from multiple sources in a blackboard architecture organized into a number of levels.

Potential Expert Systems Application Areas in Construction

Several planning, engineering, management, and operational tasks are candidates for expert-system formulation (Jounis 1988; Levitt 1987, 1985; Rehak and Fenves 1985):

- Design of Construction Methods—The various candidate topics include configuration of crews; choice of construction methods; man-machine trade-offs; choice of transportation mode(s) for the movement of materials, personnel, and equipment; selection of optimum sizes, configurations, and methods of jointing of various components in modular construction; and deep-excavation problems.
- Concrete Mixing and Placement—The subsystems that need decisions include mix design to meet performance standards for a variable set of site conditions and materials; choice of a placement method; configuration of crushing, batching, and transportation equipment; and design of formwork.
- Constructability Evaluation—Some important issues include analysis of the constructibility of designs, choice of construction materials, selection of the best design-function-cost combination, bid packaging, choice between prefabricated and in-situ construction, and feedback into the design process.
- Temporary Facilities Layout—Optimal layout of temporary facilities that can have a significant effect on productivity such as access roads, parking areas, change rooms, material lay-down areas, fabrication shops, site office, and hoisting equipment.
- Project Planning, Scheduling, and Control—Some candidate tasks in this area include developing variable time-cost estimates of activities; generation of construction schedules; critical-path analysis; resource allocation; time and cost control; diagnosing reasons for time, cost, and resource overruns; prescribing remedial actions; cost estimating; and construction-process monitoring.
- Project Management—Several kinds of expert systems that could be built in this area include choice of a project-delivery strategy, selection of a contract type, design checking and management of design changes, construction-contract formulation, project-financing options, A/E and CM selection, prequalification of contractors, bidding strategies, bid evaluation, evaluating progress payments, evaluating claims, management of risks, evaluating the quality of a constructed component or facility, formulation

of general conditions, and formulation of technical specifications.

- Construction Quality Control—Several candidate tasks for expert-systems application include sample size, sample location, time of sampling, permissible tolerances, construction-quality-control methods, lab tests for quality assurance, and acceptance of subquality work.
- Construction Company Management—The various candidate topics that can help a construction company include bidding strategy, financial planning, and equipment-policy decisions.
- Equipment Selection, Diagnosis, and Repair—The various candidate problems in this area include selection of equipment types, sizes, and combinations; diagnosis and monitoring of equipment condition; repair; preventive maintenance; and operational procedures based on crew behavior.
- Human Resources Management—The various candidate topics in this area include designing project- and company-organization structures; personnel management; labor relations; safety management; and productivity-improvement techniques.
- Operational Problems in Constructed Facilities—Some important problems that are usually solved using heuristics include causes and remedial actions for functional failures such as leaking, sweating, poor ventilation, and temperature control; causes and remedial actions for structural failures such as foundation settlement and cracking; posthazard damage assessment of facilities; and reconstruction and rehabilitation methods.
- Materials Management—Some candidate topics in this area include choice of materials, scheduling order and movement of materials, materials handling and testing, and storing and use of explosives.
- Legal Issues—The various potential areas that can be useful to the construction industry include generation of contract documents, maintaining historical data bases of settled cases and matching them with the current situation, settlement of claims and disputes, generating negotiating strategies, and changing conditions management.

Conclusions

Some enthusiasts rank expert systems with steam power, some with electricity. Some say with AI technology now in usable form, the second computer revolution has begun. These may be premature assessments. But Knowledge-Based Expert Systems (KBES) technology at least parallels the FORTRAN of the 1950s, the problem-oriented languages of the '60s and the CAD of the '70s (Buchanan and Duda 1982). The contribution of expert systems to the extension of human capability and to our effectiveness as managers will indeed be profound. The more we have learnt about expert systems, the more we have become convinced that expert systems will of course change the way people think about solving their problems. Expert systems have given us a way to collect and organize data that can be used to create information that in turn can be used to help make better decisions, for today as well as for the future.

So far, most of us have learnt the hard way, by making mistakes and learning from them, since there was no mechanism to store the domain knowledge and experience of people in a friendly and usable manner. So far, the benefits of computers have been more confined to computer scientists. AI technology has now given us the art of building expert systems that do not require hard-core computer scientists. These expert systems, thus promise to harvest the fruits of computer science and make all of us more productive.

What lies ahead in the use of expert systems in the domain of construction depends on how useful the construction industry finds these first expert systems. Any innovative concepts will have to be cost-effective. One other factor that will affect the use of expert systems in the construction industry is the nature of this industry, which is highly competitive and risk averse. Specialized problem-solving knowledge in a company is considered proprietary and the concept of sharing that expertise with competitors is not acceptable. The building of small expert systems for internal use will, however, be seen as beneficial by construction companies. But, company proprietary information is limited to a few sensitive areas like bidding strategies, strategic planning, and financial management. Several other areas in construction planning, engineering, and management are potential candidates for expert-system formulation. Thirteen such major areas have been identified in this paper including constructability evaluation; temporary-facilities layout; construction-company management; equipment selection, diagnosis, and repair; human-resources management; project planning, scheduling, and control; materials management; design of construction methods; concrete mixing and placement; operational problems in constructed facilities; construction-quality control; and legal issues.

So far, expert-systems research has been confirmed to academic and research institutions. The work done in these institutions has shown that expert-systems technology has the potential of offering practical tools for making intelligent and fast managerial and technical decisions. The following trends can safely be predicted at this time: (1) The next few years will see many small expert systems and company proprietary expert systems, routinely used in the industry. A good number of these expert systems will be capable of interfacing with graphics, data-base-management programs, and algorithmic programs; and (2) the expert-system-building process will consolidate and document construction knowledge currently dispersed among many individuals, journals, and books. This consolidation of domain knowledge will give rise to the building of larger expert systems that will have frame-based knowledge representation with graphic input and output, will be integrated with several external programs and will have a blackboard architecture. CONSTRUCTION PLANEX, being developed at the Carnegie Mellon University, has some such potential but its full development and testing is at least a few years away.

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APPENDIX. REFERENCES

Adeli, H., ed. (1988). *Expert systems in construction and structural engineering*. Chapman and Hall, New York, N.Y.

Ashley, D. B., and Levitt, R. E. (1987). "Expert systems in construction: Work in progress." *J. Computing in Civ. Engrg.*, ASCE, 1(4), 303–311.
Buchnan, B. G., and Duda, R. O. (1982). "Principles of rule-based expert systems." *Heuristic programming proj. report no. HPP-82-14,* Stanford Univ., Stanford, Calif.
Harmon, P., and King, D. (1985). *Expert systems: Artificial intelligence in business.* John Wiley and Sons, Inc., New York, N.Y.
Hayes-Roth B. (1985). "A blackboard architecture for control." *Artificial Intelligence,* 26(3), 251–321.
Helander, M. (1981). *Human factors ergonomics for building and construction.* John Wiley & Sons, New York, N.Y.
Hendrickson, et al. (1987). "Expert system for construction planning." *J. Computing in Civ. Engrg.,* ASCE, 1(4), 253–269.
Jouni, J. E., and Salokivi. (1988). *Expert systems interpreting collective agreements in the building industry.* Draft Paper, Technical Research Center of Finland (VTT), Itatuulentie 2, Finland.
Koskela, L., et al. (1986). "Expert systems in construction—initial experiences," *Proc., Int. Joint Conf. on CAD and Robotics in Arch. and Constr.,* Marseilles, France, Revised Version.
Levitt, R. E. (1987). "Expert systems in construction: State of the art." *Expert systems for civil engineers: Technology and Application,* M. L. Maher, ed., ASCE, New York, N.Y.
Levitt, R. E. (1985). *Research Areas for the Application of Knowledge Based Expert Systems to Construction Engineering and Management,* white paper for NSF workshop, Champaign, Ill.
Navinchandra, D., Sriram, D., and Logcher, R. D. (1988). "GHOST: A project network generator." *J. Computing in Civ. Engrg.,* ASCE, 2(3), 239–254.
Logcher, R. D., and Sriram, D. (1986). *Knowledge-based approaches to scheduling and controlling of projects,* technical report, Massachusetts Institute of Technology, Cambridge, Mass.
Mohan, S. (1987). *Expert systems technology in the domain of construction. Proc., 4th Int. Symp. on Robotics & Artificial Intelligence in Building Constr.,* Haifa, Israel.
Rehak, D. R., and Fenves, S. J. (1985). "Expert systems in civil engineering, construction and construction robotics." *Annual Res. Review,* Robotics Institute, Carnegie-Mellon University, Pittsburgh, Pa.
Rounds, J. L. (1987). "Small tailored expert systems for private companies." *Proc. Int. Symp. on Robotics & Artificial Intelligence in Building Constr.,* Haifa, Israel.
Sathi, A., Morton, T. E., and Roth, S. F. (1986). "CALLISTO: An intelligent project management system." *AI Magazine,* 7(5), 34–52.
Waterman, D. A. (1986). *A guide to expert systems.* Addison-Wesley Publishing Company, Reading, Mass.