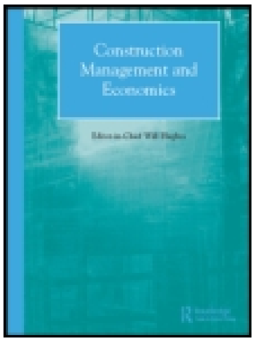

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Expert systems for crane selection

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Expert systems for crane selection

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An expert system seems to be particularly attractive as a decision tool in the unruly construction environment. Application of expert systems, to various facets of construction planning, has been described in various publications. The paper examines two expert systems applied to the crane selection and location problem, evaluates them and draws some conclusions with respect to the general applicability of expert systems to construction planning.

Keywords: Buildings, construction planning, cranes, expert systems

Introduction

An expert system is a problem solving computer program which contains a knowledge base with facts, rules, and heuristics about a particular domain, an intelligent querying mechanism for the extraction of a context information from the user and an inference procedure for an evaluation of this information in view of the knowledge base rules. The main features of expert systems and their applications have been extensively described.[11,12,33]

The advantage of an expert system, with respect to a conventional computer program, is its ability to handle non-structured and uncertain information, and offer solutions based both on causal and normative knowledge, and also on subjective and heuristic experience. For these reasons expert systems are better equipped than other conventional decision making tools to deal with complex real life situations.

An expert system seems to be particularly attractive as a decision tool in the unruly construction environment. The complexity of construction projects, the large number of solution alternatives, the multitude of controlled and non-controlled factors which affect the outcome of each decision, the high degree of uncertainty–all these factors make the construction milieu particularly difficult for establishment of clear cause-effect relationships, and identification of applicable 'textbook' solutions to each conceivable problem. The potential of expert systems, under these premises, has been emphasized.[21] As explained in the following paper, one must also consider very carefully their limitations.

Expert systems for construction use have been described for the following uses in various publications:[1–5,7–10,13,14,16–25,27–29]

–scheduling
–site layout planning
–efficient performance of various buildings works
–organization of construction project
–safety on the building site
–equipment maintenance

–interpretation of construction contracts
–procurement of construction project
–assessment of construction risks.

It is therefore surprising that expert systems have not yet established themselves in this domain as recognized, universally applied and marketable tools, in the same sense as various conventional application computer programs for scheduling, cost estimating, and other purposes.

It is particularly interesting to examine more thoroughly the applicability of expert systems to the construction planning on site. Construction project planning consists usually of the following tasks:

1. selection of activities for execution of various work items;
2. determination of dependence and timing of these activities;
3. allocation of resources for their execution;
4. organization of work force;
5. selection and location of equipment and other facilities on site.

Each of these tasks involves many decision variables, and requires analysis of many solution alternatives in view of accepted criteria of efficiency and effectiveness. Although the various construction planning tasks are interdependent, the common practice in complex projects is to look at them separately, with due consideration, when dealing with each task, to the possible effect of this task–on the others. Very often such planning process may require several iterations, with some tasks evaluated again in view of the output of the planning process of other tasks. For example, some scheduled activities may be re-evaluated in view of their possible effect on equipment or labour allocation.

The conventional managerial tools, such as CPM, flowlines, etc., are typically applied to individual tasks. They act mostly as information processing algorithms which assist the decision maker in the evaluation of the implication of his assumptions or decisions. An expert system could do more than that, provided that it can realistically emulate the real decision making process and produce satisfactory results under *all* circumstances. Otherwise its limitations must be very carefully examined and defined, so as not to mislead the potential users.

The applicability of expert systems to individual construction planning tasks will be examined in this paper, with reference to one task–the crane selection for a building site, and some general conclusions will be drawn.

Expert systems for crane selection

A crane which was introduced into construction about 40 years ago, is today the most important materials' handling device on a building site. Since materials' handling is a very important part of the construction process, the selection and location of a crane may considerably effect the cost and efficiency of construction.

A selection of an appropriate crane is a relatively well-structured process, defined by various rules which specify its required performance in view of the projects to be constructed, and the various site conditions. Some mathematical approaches to crane location have been described.[6,26,32] They could not, however, realistically model all the user's considerations under real life conditions. Since many considerations for crane selection are of qualitative nature, and most of them deal with special features of the site, or of the available equipment, an expert system seemed to be an appropriate decision tool in this case. Two expert systems suggested for this purpose will be examined here. One system–LOCRANE–which was developed as a test case for the application of expert systems methodology to construction planning tasks, has been described by Peled[25] and Warszawski and Peled.[30] The other–CRANES–was extensively described by Gray and Little[8] and Gray.[9] Both systems will be briefly described and evaluated with respect to their applicability under real life conditions.

LOCRANE

The purpose of LOCRANE, developed by N. Peled and A. Warszawski at the Technion, I.I.T., was to assist the construction planner in the selection and location of a crane on a given building site. The development of the system was intended, as noted earlier, as a test case for the application of an expert system to practical construction planning problems. Its applicability was limited to the following cases:

1. The crane was selected as the appropriate materials' handling device for the buildings under consideration.
2. A single crane was not to serve more than two buildings at the same construction stage.
3. The planning is based on a representative layout of the building floor, assuming implicitly that the shape of the work area, or the work content do not change over the employment time of the crane on site, to an extent which will justify a modification of the design.
4. The timing of the equipment employment over the working day could be scheduled in such manner that it would not be needed at the same instant in different work locations–buildings or floors.
5. Some decision rules and all default values were applicable to the particular situation in Israel at the time of the expert system construction.

The knowledge base of LOCRANE is described by Warszawski and Peled.[30] The shell, which was used by the system, was the SAVOIR, Expert System Package.[15]

The selection of the crane is performed in three stages. In the first stage, the user is asked to supply all the pertinent information about the building geometry and the nature of the crane employment. The general types of cranes applicable to his case are defined in this stage. In the second stage, the user is asked specific questions about possible applicability of each pertinent type of cranes to his particular case. As a result, the feasible alternatives of cranes are identified and defined in terms of their major features. In the last stage, the user is guided towards a rational selection of the most appropriate alternative from the set of equipment available to him, based on economic evaluation.

CRANES

The other system–CRANES–was developed by C. Gray and J. Little at the University of Reading, as a prototype of a universal operational tool. The purpose of the system, as in the former case, is to assist the user in the selection of an appropriate crane for his project, and its location on a construction site. CRANES employs a knowledge base of rules, which are extensively described by Gray and Little.[8] It is also to include a data base with the pertinent characteristics of all crane types employed in the UK.

CRANES uses self made PROLOG-based system for knowledge processing. It also has a graphical device which permits the user to indicate locations of his main loads on the building, and returns the necessary load/reach profile for the required crane. Other operational features of the system are described by Gray,[9] and will be reviewed in the following evaluation survey.

Evaluation

Both systems–CRANES and LOCRANE-will be evaluated with respect to their scope, the elimination process which determines the type and main features of possible crane alternatives, and the ultimate selection of a preferred alternative. Other limitations, as far as real life conditions are concerned, will also be examined.

The scope of application

Both systems base their decision on an assumption that a crane is a preferred handling device on the building site. LOCRANE does it explicitly, while CRANES advises preference of a crane if some conditions are met (if a load exceeds 1 ton *or* the load location is further than 2 metres from the building edge). Both systems oversimplify the real life situation, considering the fact that a large selection of materials' handling equipment–concrete pumps, hoists, elevators, conveyors, devices, truck-mounted jibs, etc., can substitute for a crane or be used in conjunction with it. LOCRANE disregards a decision which is very important in some projects. CRANES offers a criterion which may be true in many situations, but certainly not in all of them. It is easy to show that the existence of few loads which exceed 1 ton (e.g. some roof precasts), or appropriately packaged materials which have to be moved more than 2 metres from the building periphery, does not always necessitate, especially in smaller projects, continuous employment of a crane on a building site.

As far as the nature of the project is concerned–LOCRANE applies to sites which consist of one or two buildings, as is sometimes the case in residential projects. CRANES possibly restricts its solution to large buildings which require, for their completion, one or more cranes.

LOCRANE applies only to those buildings which have the same shape throughout their total height. CRANES also considers also buildings with a changing layout, but leaves to the user the decision of how to deal with them. The implication of a possible change in selection or location of a crane, due to a change in the floor layout, is not evaluated by this program.

The characterization process, in both systems, involves the identification of cranes appropriate for the particular project, and definition of their characteristics–in terms of reach and load. The preferred crane is then selected from the feasible solutions defined in this manner, based on economic consideration explained later.

Both systems identify the appropriate crane types by eliminating the infeasible alternatives, i.e. those which are inapplicable in view of the shape of buildings or the site conditions in the particular project.

Some of the rules applied for this purpose are objective and universal, e.g. sufficient access for crane installation, sufficient space, resistance to superimposed loads, etc. They form, in fact, a 'checklist' of issues which must always be addressed under an orderly selection process. Other rules reflect a 'common wisdom' of users, or are derived from common features of equipment types available on the market. Examples of such rules are limitation of maximum height for cranes on rails, minimum height for climbing cranes, or maximum radius for mobile cranes.

An abundance of rules of the second type makes the selection easier to user and less dependent on characteristics of a particular crane type considered. On the other hand, it depends very much on the timely revision of those rules in light of new types of equipment produced and offered to the market. For example, limiting the applicability of a mobile crane to a reach of 15 or 18 metres may be justified only in view of the present situation on the crane rental market in a certain country.

Both programs use analytical methods for an optimal location of a crane, and a consequent determination of its required reach. The CRANES uses, for this purpose, a graphical representation of the building contour, while LOCRANE accepts, as an input, the coordinates of its characteristic corners. LOCRANE assumes implicitly that a maximum load, accepted from the user, can be located anywhere in the building. The crane is therefore characterized by its maximum reach and payload. In CRANES the user may input into the program location and magnitude of all loads on the examined floor, and receive, as an output, a complete reach and payload profile for the required crane. This feature of the CRANES gives it an advantage over the other system in situations when the distribution of loads, to be handled over the building floor, is not regular.

The selection of a crane

The ultimate selection of an appropriate crane, from those matching the required type and load/reach profile, is guided by economical considerations.

In CRANES the criterion for selection is the hire rate for a crane, which is to be stored in the knowledge base together with its other characteristics. In LOCRANE the user is guided towards a decision, whether to use a rented crane or his own crane. He is also advised which parameters are to be used in the cost calculation of his own crane, and offered default values if unable to assess them. The use of hire rate as a sole device criterion may be justified only in countries where the rental of a crane for a building project may be an exclusive or a common practice. But even in this case, such criterion must be used with caution. Rental rates of cranes may change depending on the particular situation of the market, the length of rental period, the special relations between the rentor and the renting company, and other considerations.

The limitations of both systems

Both systems may suffer from several common limitations under real life application conditions.

One limitation has to do with other material handling equipment, which may fulfil some or all of the crane tasks. It was already noted that an option of a complete substitution of a crane by such equipment–pumps, hoists, carts, etc., is not evaluated satisfactorily by either program. Moreover, often the use of such equipment in conjunction with a crane, may affect its required reach, location, capacity, and other characteristics.

Another limitation involves so-called threshold situations, where an insignificant relaxation of a certain constraint may considerably affect the cost or other implications of a managerial decision. For example, some relaxation of a requirement that 100% of the building floor area will be covered by a crane, may sometimes 'move' the selection into a region of more readily available, or much cheaper cranes. A shortage of reach of 1–2 metres at isolated locations may be easily overcome by the use of a cart or funnel (in case of concrete pouring). An insufficient lifting capacity of a crane, when few heavy elements, e.g. facade walls or stairs must be assembled, may be helped, in some cases, by renting or transferring an extra crane for this purpose, for a short period of time in which their erection takes place (LOCRANE deals, to some extent, with such case). An unavailability of space for a crane, at a certain location, may be helped by rearranging the preplanned site layout, etc. An expert always examines such solutions within the planning process, but the expert systems reviewed here do not, and possibly could not take them into account. What they should do, at least, is to alert the user to the possibility that such solutions exist and, indeed, should be examined.

The third limitation of these systems is their inconsideration of the dependence between the crane (or other building equipment) selection, and other tasks of construction planning. A dependence may exist, for example, between crane selection and work organization. Employment of two cranes, instead of one, can result from special requirements of shape or size of a building. But, even if those requirements do not exist, it can enable more efficient coordination between teams of workers employed in different parts of a floor. Availability of an additional crane on the floor may, under appropriate work management, considerably reduce or eliminate the downtime of labour and resources associated with a crane breakdown. A dependence may also exist between crane selection and scheduling. Some changes in timing or sequencing of certain activities may result in a considerable saving in crane employment needs at any particular time, and in some cases in shorter reach, more convenient access, etc. Finally, crane selection may affect the nature of other activities. For example, a selection of crane with some characteristics may sometimes justify production of concrete or precast elements on site.

Such possible trade-offs between changes in organization, construction schedule, or allocation of other resources, and the requirement for crane performance, are often formally or informally examined by an experienced practitioner in an iterative process, which may be quite difficult to model into the knowledge base rules.

Domain knowledge base

Based on the former discussion, one may identify the basic elements of a conceptual 'domain' knowledge base for selection and location of cranes on a building site consisting of one or more buildings of different shapes. Such a knowledge base can easily be adapted to the particular needs of each use and overcome some limitations enumerated before. It will consist of three components, as explained below, arranged in an object-oriented fashion.

This first is the context information containing geometrical data about the project to be constructed. It includes the location and outline of the buildings and the location of other loading or unloading areas on site that the crane must reach. Each building is defined by its height, perimeter (or perimeters of the floor outline changes), distribution of loads on the floor area, and the possible division of the floor into sections which must, or may be, served by separate cranes. It will also include the necessary duration of crane employment on the site or its individual buildings as determined in the schedule.

An important facet of information involves the permissible crane locations around the buildings, in the buildings (for climbing cranes) or between the buildings (for rail-mounted cranes). This should be obtained from the user in an interactive querying process while alerting him with appropriate comments to the pertinent size, load or access constraints.

All this information may be represented in a parent frame with a slot or a set of slots for each of the above-mentioned parameters. If the site under consideration includes several buildings, a building divided into sections, or a building with changing floor layout, children frames may be initiated for each building or building section – horizontal or vertical (in case of a changing shape). Other pertinent building data, constraints or explanations may be attached to this frame system by means of additional slots, assertions or text comments. Some of the slots may refer to a graphical representation of the site layout and the shape of individual buildings.

The second part is the data with main characteristics of the cranes to be considered. Those cranes may be part of the user's equipment stock, belong to a particular rental company, or represent the total population of available cranes on the market. The data includes general characteristics – name, code, reach, payload (or, payload profile), weight, maximum height, space dimensions, cycle time, cost per day or hour, transfer and installation cost. It may also include special characteristics of individual crane types, i.e. fixed or movable cranes – on tracks or wheels, climbing cranes, cranes on rails. The data may again be stored in a hierarchical frame system with a separate frame type for each equipment type, with specific parameters, constraints or requirements as needed.

A similar frame system may be established for auxiliary equipment – hoists, elevators, concrete pumps – which may affect the requirements from cranes, or substitute for some or all of their activities.

The information into the equipment frames may be input by each particular user, in view of his available stock of cranes, or taken from a universal data base representing specific rental possibilities on the market.

The third part of the knowledge base includes decision algorithms or 'operators'. Two operators of this kind are most important. One generates the possible solutions of cranes' allocation to the buildings. The other evaluates these allocations and selects from them the optimal solution.

The solutions generator generates the possible solutions, each suggesting a different equipment set-up for the particular site under consideration. If the site consists of a single building, a solution may include a 'no crane', i.e. lifting done by other equipment, a single crane, or several cranes, each attached to a particular building section. If the site is composed of several buildings, a 'site' solution may consist of: (a) individual 'building' solutions; (b) composite solutions in which one crane serves several buildings; (c) hybrid solutions, where other types of equipment are also taken into account. The generator may enumerate *all* plausible equipment combinations subject to various rules, which would *a priori* obviate solutions unacceptable for physical (load, reach) or economical reasons, or otherwise undesirable to user. Alternatively, the generator may consider only those solutions which are suggested by the user.

The solutions may also be housed in appropriate frames with each frame 'inheriting' the pertinent site features and also the characteristics of each type of equipment involved in the solution.

The solutions evaluator, written in any language, determines: (a) the optimal location of the equipment selected for each particular solution; (b) the cost of the solution considering all transfer, installation, usage/rental and operation expenses involved with the project; (c) effectiveness of the solution based on any other criterion selected by the user.

After evaluating in this manner all the generated solutions, a recommended solution or a set of solutions may be suggested to the user based on minimal cost or other criteria.

General observations

Some general observations, with respect to the applicability of expert systems to construction decisions, may be drawn from the discussion of crane selection systems in the former sections.

In general, an expert system will be most helpful to a potential user when it can assist him in obtaining a 'good' solution in situations involving a large number of controlled and non-controlled factors. A system would serve that purpose if it will be able to identify all these factors, assess them, and offer effective solutions, with an aid of reliable decision rules. Such system will be applicable to a large number of users, or perhaps to all potential users if all of its rules would be derived from 'universal knowledge', i.e. knowledge based on proven nature laws, clear cause–effect relationships, and generally accepted norms.

Various systems, based mostly on such rules, can be applied to construction problems. Some typical examples involve interpretation of codes and regulations, selection of building components for a particular use, identification of details and specification for production or construction, maintenance and repairs of equipment, etc. Naturally, such systems will be reliable only to the extent that their knowledge base reflects the current state of pertinent laws and norms, if these may change with time or circumstances.

The validity of the system, for any given situation or user, must however be carefully examined if it requires risk assessment or employs heuristic rules.

Risk assessment is required if some important decision parameters can be identified, but their value cannot be estimated with a reasonable certainty. Almost all expert systems and expert system shells offered on the market include special features for dealing with uncertainty. For this purpose, the user is asked to cite the certainty of value of each parameter requested in the context. An uncertainty can be treated within the expert system if, and whenever the user can realistically assess, in some manner, the amount of risk involved with each decision parameter. A risk assessment is, however, very difficult for practitioners, and for this reason various probabilistic features of planning devices (e.g. those of PERT) were very seldom applied in practice. A subjective risk assessment by an inexperienced practitioner, if insubstantiated by experience, may lead to wrong decisions.

Heuristics must be used whenever all pertinent decision parameters cannot be identified, or assessed with certainty, or whenever a cause–effect relationship cannot be established.

Heuristics reflect a certain experience, or statistics based on larger or smaller population of cases, products, occurrences, etc. A system may, therefore, not be applicable to a particular situation of the user, or it may be applicable only under certain circumstances.

Heuristics may, however, be useful in situations when they reflect the experience or the preference of a particular user. For example, an expert system for crane selection may be very useful in a company which has at its disposal a large stock of own cranes, and can form the selection rules based on their characteristics and its own policy with regard to their employment. An expert system may also well serve a company which rents cranes and, as an extra service, may advise its clients how to employ them in a most efficient manner. Another similar example involves an expert system for selection of precast elements with which a given building has to be assembled. Such system could satisfactorily serve its purpose when it applies to elements produced with a well defined method.

It follows that an expert system, using heuristics, can be very effective if it serves a particular user, or users group, for which those heuristics actually always indicate the most preferable alternative. Development of an 'in house' expert system, for each particular user group, is therefore advisable, when the system cannot be based solely on 'universal knowledge'. This is possible today in view of the variety of expert 'shells' offered on the market, but still requires much time, resources and a considerable expertise for selection and adaptation of the shell, construction of knowledge base and validation of the system.

A possible compromise between the two extremities–building of universal expert systems and their 'in house' construction–would be a two-stage procedure. This will call for construction of a so-called 'domain shell' adapted to a particular application. The shell will employ a knowledge structure, an inference procedure and an interface with user appropriate to the particular problem, and also all universal rules which could be safely applied, under all circumstances, by all possible users. Finally, it will contain a checklist of problems which should be addressed by rules, relevant to a particular user or users group, to make the system an effective tool for any non-experienced practitioner. Such rules may deal, in the case of crane selection, whether and when to use a crane, with a preference for the various types of cranes under different conditions of site, building shape, load, etc., and other similar problems. The planner will be then guided to his final decision in full agreement with the accepted practice of the company experts.

Another important question involves reliability of an expert system when applied to complex planning decisions. Such decisions, which involve a very large number of controlled and non-controlled factors–many of them particular to each project–are usually taken care of by a decomposition into separate planning tasks. The interdependence between the individual tasks, which was illustrated in the case of crane selection, is provided for by a human expert with an iterative approach, with constraints which are implicitly introduced or relaxed within the planning process. The success of such planning procedure depends very much on the size of the project and the experience and ingenuity of the planner. An expert system may perform successfully under one task planning situation in the following cases:

1. if the particular planning task can be entirely separated from others. This may be true if the task is so central that it will completely dominate all other planning tasks. For example, if the selection and location of the crane will determine all other project decisions–organization, scheduling, etc. It may also be true–if the particular planning task will be carried out in view of explicit constraints superimposed by other functions. The construction of a knowledge base, in such case, is more difficult because it must envision the possible constraints, and requires more involvement on the part of the user.

2. if the projects follow several main and predictable types, and the various interrelations can be amply modelled. Such situations can happen within a certain company, which engages in predetermined type of projects and employs, for their planning, well established routines.

Finally, it must be noted that an expert system can be useful to a construction planner, not only as a problem solver, but also as a base with relevant and easily accessible knowledge in a particular decision making domain. Thus, for example, the knowledge,[8] even if not translated into data driven operational rules, can be useful to an inexperienced decision maker. The data may thus be useful to him, compiled about different crane types, provided that it is periodically updated. In this sense, the system may be used very much as a sophisticated handbook or reference manual.

An expert system may be even useful as an effective facility for storage of information about a particular context, i.e. a project to be designed or constructed, to a decision maker, designer or planner.

It may be summarized, therefore, that an expert system can be used for construction planning under these circumstances:

1. as a general purpose tool–when all rules are based on 'universal', objective knowledge.
2. as a tool developed in view of the specific needs of a particular company.
3. as a 'domain shell' to be supplemented by the specific rules of a particular company or a group of companies.
4. as a general 'reference manual' for a particular domain.

Conclusions

The advantage of an expert system, with respect to a conventional computer program, is its ability to handle non-structured and uncertain information. An expert system seems to be a useful decision making tool in the construction planning process; however, its limitations in real life applications should be clearly perceived.

An expert system can be most advantageously applied for construction planning in the following cases:

1. for problems which can be solved using 'universal' knowledge, i.e. nature laws, clear cause–effect relationships, and accepted norms and regulations.
2. for problems which require also heuristic rules, if the system is used by a company or a group of companies with a similar experience and approach to decision making.
3. as a general purpose 'domain shell' which can be adapted to the specific needs of each user by insertion of his own characteristic rules.
4. as a general purpose 'manual' containing operative knowledge about a particular domain.

Special consideration must be given, when building an expert system for a construction planning task, to its dependence on the other planning tasks.

References

1. Brandon, P.S. (1987) Expert Systems–Modelling Professional Expertise? Fifth International Symposium on Organization and Management of Construction, London.
2. Cornick, T.C. and Bull, S.P. (1987) Expert Systems Integrated with CAD for Component Assembly. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
3. Delcambre, B. and Halleux, D. (1987) Elaboration de maquettes de systems experts appliques au domaine du batiment. Fifth International Symposium on Organization and Management of Construction, London.
4. Diekmann, J.E. and Kruppenbacher, T.A. (1984) Claims analysis and computer reasoning. *Journal of Construction Engineering and Management*, **110**, 4, 391–408.
5. Finn, G.A. and Reinschmidt, K.F. (1986) "Expert Systems in an Engineering-Construction

Firm", in Expert Systems in Civil Engineering, edited by Celal Kostem and Mary Lou Maher, ASCE, April.
6. Furusaka, S. and Gray, C. (1984) A model for selection of the optimum crane for construction sites. *Construction Management and Economics*, **2**, 157–76.
7. de la Garza, J.M. and Ibbs, C.W. (1987) Issues in Construction Scheduling Knowledge Representation. Fifth International Symposium on Organization and Management of Construction, London.
8. 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**, 121–44.
9. Gray, C. (1987) Crane Location and Selection by Computer. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
10. Halleux, D. (1987) Assistance to Technical Choices or Controls in Building Projects: Three Expert Systems Prototypes. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
11. Harmon, P. and King, D. (1985) *Expert Systems–Artificial Intelligence in Business*. John Wiley, New York.
12. Hayes-Roth, F., Waterman, D. and Lenet, D. (1983) *Building Expert Systems*. Addison-Wesley, Reading, Mass.
13. Hendrickson, C. (1987) An Expert System for Construction Planning. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
14. Hendrickson, C.T., Martinelli, D. and Rehak, D. (1987) Hierarchical rule-based activity duration estimation. *ASCE Journal of Construction Engineering and Management*, **113**, 88–301.
15. ISI Limited (1985) The SAVOIR Expert System Package User Manual. Version 1.3, November.
16. Kano, N. (1987) An Expert System for Planning in Robotized Construction. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
17. Kostem, C.N. and Maher, M.L. (Eds) (1986) Expert Systems in Civil Engineering. American Society of Civil Engineers, New York, NY.
18. Levitt, R.E. (1986) HOWSAFE: A Microcomputer-Based Expert Systems to Evaluate the Safety of a Construction Firm. In *Expert Systems in Civil Engineering*, Celal Kostem and Mary L. Maher (eds) ASCE, April.
19. Levitt, R.E., Kunz, J. and Kartam, N.A. (1987) Using Artificial Intelligence Techniques for Automated Planning and Scheduling. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
20. Levitt, R.E. (1986) Expert Systems in Construction, In Survey of the State-of-the-Art Expert/Knowledge Based Systems in Civil Engineering, Special Report P-87/01, US Army Corps of Engineers, DACW88-85-D-007.
21. Mohan, S. (1987) Expert Systems Technology in the Domain of Construction. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
22. Nay, L.B. and Logcher, R.D. (1985) An Expert Systems Framework for Analysing Construction Project Risks. Research Report R85-4, Center for Construction Research and Education, Department of Civil Engineering, Massachusetts Institute of Technology, February.
23. O'Connor, M.J., De la Garza, J. and Ibbs, W. (1986) An Expert System for Construction Schedule Analysis. In *Expert Systems in Civil Engineering*, Celal Kostem and Mary L. Maher (eds), ASCE, April.
24. O'Connor, M.J., *et al.* (1987) Workshop on Expert Systems for Construction Scheduling, US Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Ill.
25. Peled, N. (1987) An Expert System for Crane Selection and Location on a Building Site. Thesis presented to Technion, Israel Institute of Technology, Haifa, Israel, in partial fulfillment of the requirements for the degree of Master of Science.
26. Rodriguez-Ramos, W.E. and Francis, R.L. (1987) Single crane location optimization. *Journal of Construction Division, ASCE*, **109**, 4.

27. Seren, K.J. (1987) Expert Systems for the Manufacturing Process in Precast Concrete Building Component Factories and Concrete Construction. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
28. Tommelein, I.D., Levitt, R.E. and Hayes-Roth, B. (1987) Using Expert Systems for the Layout of Temporary Facilities on Construction Sites. Fifth International Symposium on Organization and Management of Construction, London.
29. Trimble, G. (1987) Expert Systems in Construction: Their Potentials and the Methodology of Knowledge Acquisition. Fifth International Symposium on Organization and Management of Construction, London.
30. Warszawski, A. and Peled, N. (1987) An Expert System for Crane Selection and Location. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction, Haifa.
31. Warszawski, A. (1985) Decision models and experts systems in construction management, *Building and Environment*, **20**, 4, 201–210.
32. Warszawski, A. (1973) Analysis of transportation methods in construction. *Journal of Construction Division, ASCE*, **99**, 2.
33. Waterman, D.A. (1986) *A Guide to Expert Systems*, Addison-Wesley, Reading, Mass.