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Knowledge Acquisition and Development for Formwork Selection System

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Abstract: The selection/design of a formwork system for a project is influenced by the building design, site constraints, available resources, the contractor's experience with different systems, and their availability. Typically, the selection of a formwork system is made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience. This experience may limit the selection of a system to one that is not the optimum. This paper describes the development and knowledge acquisition of an expert system developed to assist the formwork selector/designer in making that decision. This tool was developed by systematically capturing the expertise of people involved in all phases of the life of the formwork, from design through erection and concrete placement to its removal. The three stages of the knowledge acquisition, familiarization, elicitation, and organization, are described. The iterative process of building a microcomputer-based expert system is presented.

Introduction

Formwork is the largest single cost item in reinforced concrete structures, representing 35–60% of the cost of a concrete skeleton. Any real opportunity for cost saving can be realized by focusing on reducing the cost of the formwork system. Choosing the appropriate formwork system has a great influence on reducing materials and labor cost, improving the quality of the produced concrete, and achieving a faster floor cycle. Selection of the optimum formwork system requires years of experience in formwork analysis and design. This task is usually undertaken by a senior member of the contractor's organization. Selection criteria have not been formalized or encoded in the literature. This paper describes the development and knowledge acquisition of an expert system to assist the formwork selector/designer in making that decision (Hanna 1989). This tool was developed by soliciting the expertise of practicing professionals knowledgeable in the analysis and design of formwork systems.

Formwork Systems for Reinforced Concrete Structures

A formwork system is defined as "the total system of support for freshly placed concrete, including the mold or sheathing that contacts the concrete as well as supporting members, hardware, and necessary bracing" (Hurd 1981). Formwork systems for buildings are classified as either horizontal or vertical formwork. Horizontal formwork systems are those used to form the horizontal concrete work (slabs or roofs), while vertical formwork systems

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are those used to form the vertical supporting elements of the structure, e.g., columns, core walls, and shear walls.

The literature and field study reveal seven horizontal forming systems that can be used to support slabs and roofs: conventional wood systems (stick forms), conventional metal systems (improved stick forms), flying truss systems, column-mounted shoring systems, tunnel systems, joist-slab systems, and dome systems (Jensen 1986; Hanna 1989). It should be noted that joist-slab and dome forms are usually placed above plywood sheathing. As a result, they are considered special cases and will not be treated as separate systems. Two of these systems, the conventional wood system and the conventional aluminum system, are classified as hand-set systems. The remaining ones are classified as crane-set systems. Joist forms and dome forms can be handled by hand or attached to the surface deck of the flying form and "flown" into place.

Five vertical formwork systems are currently used in forming columns and walls. These are conventional, gang, slip, jump, and self-raising forms. Three of these systems (conventional, slip, and self-raising) are crane-independent, i.e., the crane is used only for material handling and placing concrete. The remaining two (gang and jump forms) are crane-set systems; the crane serves the dual functions of erection and dismantling forms, as well as delivering materials (Hanna and Sanvido 1990).

Overview of Formwork Selection

The formwork selection system has been divided into two stand-alone modules. Wallform and Slabform are the names chosen for the expert systems developed for the vertical and horizontal formwork systems, respectively. The vertical formwork expert system is separated from the horizontal one because the information required to select each system is not the same, and they both have different functions. This allows the user of the expert system to enter information relevant to the selection of either the vertical formwork system or the horizontal formwork system. The compatibility between each vertical and horizontal system was considered when building the expert system.

The two systems have been developed using the EXSYS Professional shell. The knowledge base has been built from a combination of published literature and intensive interviews with several experts. Knowledge is loaded into the shell directly in the form of if-then rules. The system asks the user for inputs in a multiple-choice format, and uses these inputs to make inferences and reach conclusions. At the end of each run, each system displays the selected type of formwork followed by "probability=" and a number from zero to 10, which indicates the confidence that the choice is correct. The systems also provide expert advice with regard to the type of sheathing, shoring, and reshoring employed, and recommend some manufacturers.

KNOWLEDGE ACQUISITION PROCESS

The process of building an expert system starts by selecting the appropriate domain for expert-system development. After deciding on the type and scope of problem, the expert system developer or the knowledge engineer (KE) starts the process of knowledge acquisition. The techniques for efficiently extracting knowledge and creating the knowledge base fall into three stages:

1. Familiarization stage.

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2. Elicitation stage.
3. Organization and presentation stage.

Fig. 1 shows these stages along with their purposes and methodologies. A detailed description of each stage follows.

Familiarization Stage

The purpose of this first stage is to explore the scope and complexity of the problem domain. This stage also identifies whether the initial goals, determined earlier in the process, were sufficiently narrow and self-contained. Familiarization includes a literature review and unstructured interviews.

Literature Review

In addition to the knowledge engineer's background in the problem domain, published works provide an overview and orientation to the subject. Texts, magazine articles, technical papers, and papers presented at conferences provide the primary source of the literature.

Basic formwork textbooks give a comprehensive description of the formwork systems used in concrete buildings. However, they contain little information describing the circumstances under which each system should be used. In addition, they omit a number of formwork systems that are relatively new to the construction industry, e.g., self-raising, jump, column-mounted shoring, and tunnel systems.

Another source of public knowledge consists of articles published in technical periodicals such as *Concrete Construction*, from 1980 to 1989; *Concrete International*, from 1970 to 1989; *Engineering News-Record*, also from 1970 to 1989; *Construction Methods and Equipment*, from 1970 to 1980. These articles describe case studies of successful application of specific forming techniques. Site conditions, cost savings, safety features, and the resulting quality of concrete are featured.

In the present study, approximately 30 rules were developed by carefully studying these sample projects. The writers feel that the articles found in the aforementioned technical periodicals offer an alternative to the induction technique for knowledge acquisition. These real-world case studies provide a training set, since relevant factors or attributes are frequently given (Hart 1985).

Unstructured Interviews

Three unstructured interviews were conducted with two major concrete contractors and a structural designer in the Washington, D.C., area. Also, each of the two contractors arranged three site visits in the area. The KE conducted another set of unstructured interviews with the project manager of each site. The outcome of these interviews was a complete classification of formwork systems available, as well as the main features that affect the selection of each.

In unstructured interviews, the KE does not have an organized list of detailed questions to ask. Rather, broadly focused questions are asked. An extensive set of rules was extracted using this technique. For example, the following is an excerpt from a dialogue that was recorded in the summer of 1988 with a formwork expert (FE) working for a major contractor in the Washington, D.C., area (Ladd, personal communication, 1988, 1989; Covarrublas, personal communication, 1989).

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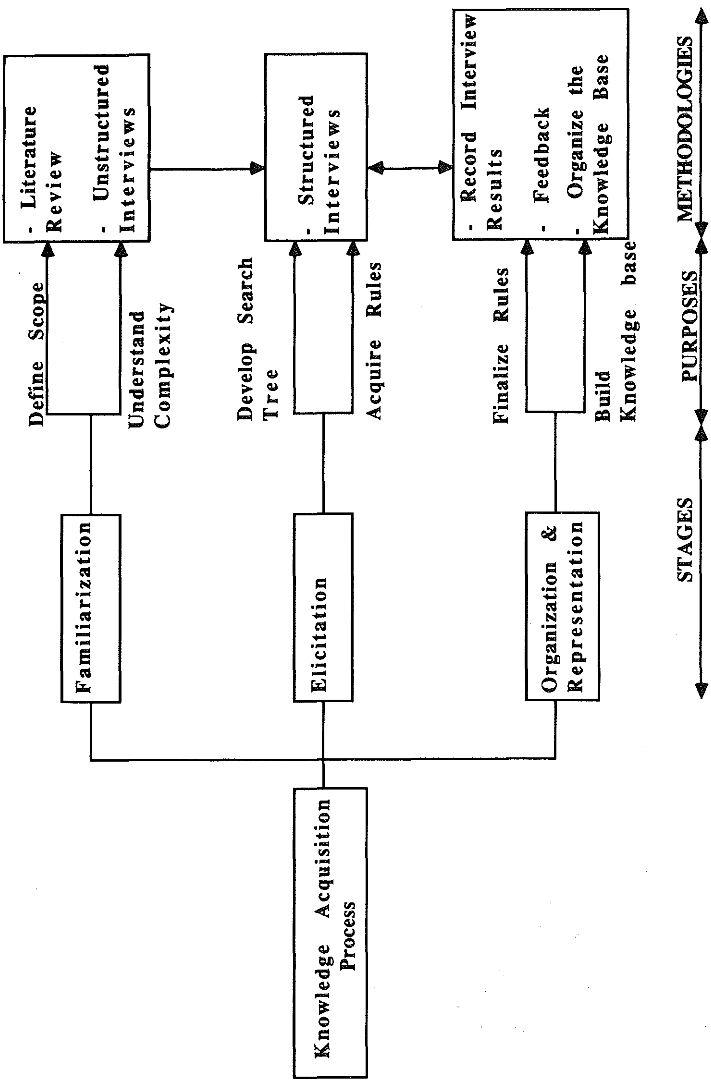

FIG. 1. Knowledge Acquisition Process (Hanna 1989)

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KE: "What type of formwork systems does your organization use?"
FE: We are using 1.6-cm plywood sheathing, supported by aluminum joists and stringers, which in turn are supported by a steel shoring system.
KE: Why?
FE: In the Washington, D.C., area, building heights are restricted to 10–13 floors high, because the local code prohibits any building higher than the top of the Capitol. Also, most of our buildings are small to medium-size and are located in urban areas that lend themselves to this type of forming system.
KE: You said small to medium-size buildings. What is your definition of small, medium, and large buildings?
FE: Small-size buildings have a 10,000-m^2 or less "footprint," medium-size buildings are between 10,000 and 20,000 m^2, large buildings are more than 20,000 m^2.

From this dialogue, the following points were extracted:

1. In response to the first question, the expert described the conventional aluminum system.
2. In response to "Why?" the expert cited some conditions that could be outlined in the form "(condition)–then (action)": if building size is small or medium, and building height is between 10 and 13 floors, and site condition is urban (restricted), then use conventional aluminum forming system.
3. The knowledge engineer used the expert's own answers to expand the discussion. For example, the expert said "our buildings are small." The KE then expanded the dialogue by asking, "What is your definition of small size?"
4. The success of this technique is critically dependent on the time that the domain expert can devote to the interview and the ability of the KE to expand the discussion in the proper direction.

Similar unstructured interviews were conducted concerning other horizontal formwork systems. These interviews provided the basis for establishing a comprehensive set of questions for more structured interviews.

Elicitation-Stage Structured Interviews

This stage has two purposes: to develop the search tree that enables the KE to efficiently build the knowledge base and to extract the required knowledge in the form of rules that can be refined and later encoded in a selected development environment.

Many expert systems have been developed using information obtained exclusively from books and other published works. As a result, they have limited usefulness. The strength of expert systems is derived in part from their ability to capture and represent the expert's knowledge. In an undocumented field such as formwork selection—notably in the selection procedure and some formwork systems—this private knowledge cannot be entirely obtained from technical literature. The knowledge engineer uses structured interviews to capture the expert's approach to the problem, to elicit his knowledge of the rules used to solve the problem, and to determine the certainty factors attached to the rules.

The elicitation stage is directed at developing an organized procedure to structure the data acquisition before actually conducting an interview. Fail-

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ure to prepare carefully for this stage will result in acquiring irrelevant knowledge. This step includes: (1) Preparing the questionnaire; (2) identifying the domain expert; (3) establishing an interview kit; (4) developing an organized set of questions; and (5) preparing an interview record that can be filled in quickly during the interview session. Some of these steps will be explained in some detail in the following sections.

Prepare Questionnaire

Based on the unstructured interviews and literature search, a comprehensive set of questions was developed. The questionnaire expanded the unstructured interviews to obtain detailed information about specific aspects. For example, during unstructured interviews, the knowledge engineer asked the expert about the circumstances in which the flying truss system could be used. The expert answered, "You should have a uniform modular building." Thus, when preparing the questionnaire, the knowledge engineer developed a set of questions in an attempt to define what the expert meant by the word *modular*. As a result, the questionnaire contained questions about beams, columns, walls, cantilever balconies, and openings, as well as questions concerning how the changes in the size and/or location of each of these elements affected the expert's definition of modular buildings.

Prepare Interview Data-Collection Forms

A key part of interviewing is to record quickly the information acquired from the expert. To accomplish this, interview data-collection blank forms were prepared in a matrix format, where the rows represented the different forming systems, and the columns represented the influence factors. Several blank columns and rows were provided to accommodate any new information that the expert might provide.

Conducting Structured Interview

Twenty structured interview sessions were held over the course of preparing the knowledge base. Twelve interviews were conducted in person. Eight follow-up interviews were conducted by telephone. It was found that an average of 2 hours per interview session was quite sufficient. Some experts were available for several interviews. In follow-up interviews, the KE summarized what was discussed in the previous meeting and presented his understanding of the rules that he had derived. The expert then agreed with or modified the approach and clarified the problem areas.

It was found that experts were not interested in the actual computer implementation; thus, they were never shown the actual knowledge source code. Two experts did, however, show interest in reviewing the search tree and, as a result, provided valuable comments about it.

The outcome of this stage was the development of the search tree shown in Fig. 2. The factors affecting the selection of formwork system are shown in this tree and are classified as follows:

1. Factors related to building architectural and structural design, which include slab type, lateral supporting system(s), and building shape and size.
2. Factors related to project (job) specification, which include concrete appearance and speed of construction.
3. Factors related to local conditions, which include area practice, weather conditions, and site characteristics.
4. Factors related to the supporting organizations, which include available

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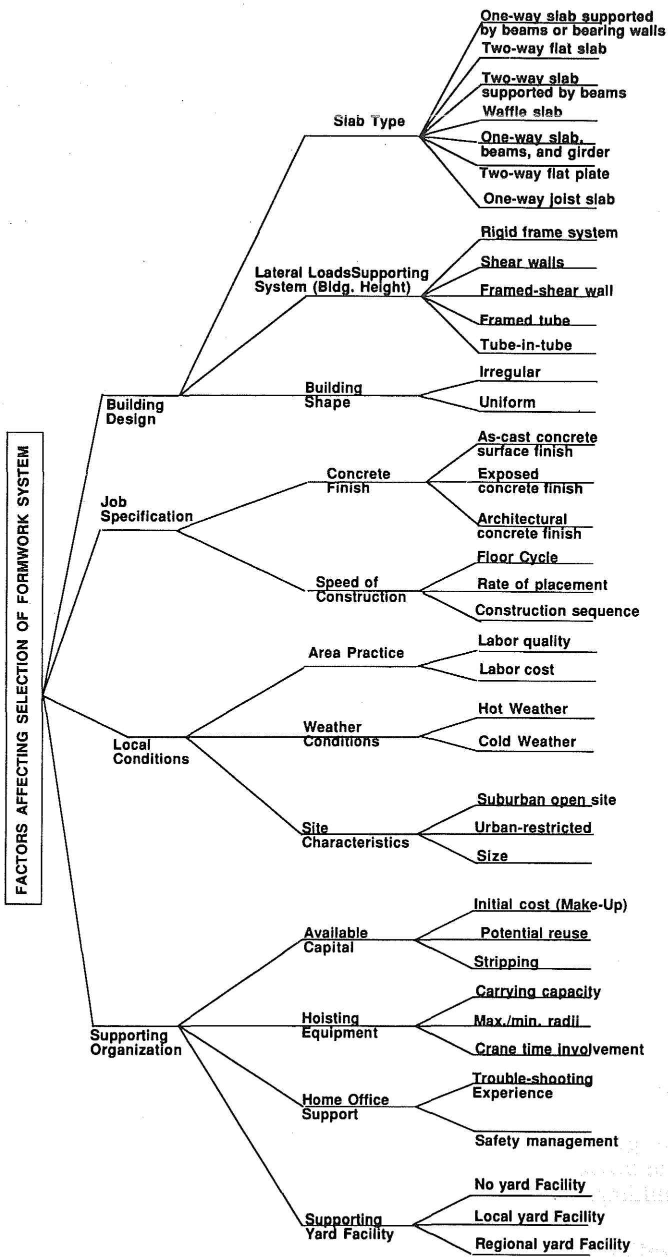

FIG. 2. Factors Affecting Selection of Formwork System (Hanna 1989)

capital, hoisting equipment, home-office support, and availability of local or regional yard supporting facilities.

Hanna (1989) has provided a comprehensive overview and explanation of these factors. The presented classification is based on a literature search and numerous interviews with formwork experts.

Interview Problems Encountered and Solutions

While interaction with an expert was the major source of knowledge for the knowledge base, several problems were encountered with this particular method of knowledge acquisition. Some of these problems, with alternative solutions designed to overcome their negative impacts, are discussed in the following.

Inaccessibility of Cost Data

Cost is a major factor in selecting a particular forming system for buildings. Due to the competitive nature of the construction industry, and the confidentiality of the cost information, an accurate cost comparison could not be obtained. It is interesting to note that for one of the interviews, the KE was asked to sign a legal document that prohibited him from releasing any information resulting from the interviews without the company's consent. However, some experts said that the factors affecting the selection of formwork systems stated in the search tree (Fig. 2) were directly correlated to the cost, and could be easily transferred to dollars. They felt that the final selection based on these factors reflected to a great extent the cost comparison of the formwork systems.

Interview Bias

To avoid bias, detect conflicts, and achieve completeness, it was important to coordinate a diversity of expertise with regard to each system. At least two interviews were conducted for approximately 70% of the formwork systems contained in the knowledge base. Due to the diversity of the forming systems included in the knowledge base, however, only a single expert was interviewed for the self-raising–form and the jump-form systems. The KE was fortunate to have interviewed the person who developed and introduced the jump form to the construction industry.

Experts' Conflict

Another example of conflict occurred when the knowledge engineer asked two experts about their definition of small, medium, and large buildings. The knowledge engineer received two different answers. One expert said that a small building is 7,000 m^2 or less, while the other expert defined a small building as 12,000 m^2 or less. A follow-up interview did not resolve the conflict. The knowledge engineer then asked a third expert, who specified 10,000 m^2 or less. In this case, the knowledge engineer decided to use the average of the three answers, which is approximately 10,000 m^2. A similar approach was followed with regard to the definition of medium and large buildings.

Organization and Representation Stage

The purpose of this stage is to structure the key concepts, rules, and knowledge, and transform them into a representative scheme suitable for the selected expert-system shell. The outcome of this stage was a comprehensive detailed knowledge base. Table 1 shows a condensed form of the

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knowledge base for vertical formwork systems. Table 1 follows the same organization structure as Fig. 2. The influence factors provided in Fig. 2 are listed in the first columns of Table 1. The effect of these factors on different formwork systems are then explained in the main body of Table 1. For example, slip form is used if the building's lateral supporting system is shear wall with a height around 400 ft (122 m). Table 1 was prepared by following the steps explained in the following.

Record Interview Results

Blank forms representing the tabular knowledge base shown in Table 1 were used to document the interviews. After several interviews had been conducted, these forms were cross-checked to detect areas of conflict or agreement. If the expert's answers were compatible, the relevant cell was recorded and finalized. If the expert's answers were incompatible, the knowledge engineer conducted a follow-up interview to resolve the conflict.

Conduct Feedback Interviews

The purpose of this step is to eliminate contradictions, assure completeness, and avoid repetition. As mentioned previously, the matrix format was used to present the knowledge base. As this matrix evolved, several gaps were spotted. Experts were then asked to fill in these gaps and to review other relevant information. For example, one expert that was interviewed stated that "in order to use the flying form systems (flying truss or column-mounted), all columns, beams, and walls should be of the same size and location from floor to floor," while another expert said that a difference in size and location between 10% and 20% is permissible. As a result, the knowledge engineer conducted a follow-up interview with the first expert, asked him about the 10–20% difference in column size and location, and explained the other expert's reasons. He agreed with the second expert, and the matter was resolved.

Organize Knowledge Base

Once the knowledge acquired in stage 2 has been recorded, it must then be analyzed, categorized, and organized. This is accomplished by completing a tabular format that relates the different formwork systems to the controlling factors.

Formwork Knowledge Base

Table 1 can be used to directly help the formwork designer/selector choose the appropriate formwork system even if he does not use the expert system developed as a part of this paper. Table 1 shows the relationship between the factors affecting the selection of formwork systems and the different forming systems available for vertical concrete work. The user must first list all the known major components of his project and then compare them to the characteristics listed in Table 1, under each forming system. The best formwork system can then be identified when the project features agree with most of the characteristics of particular system.

The following example shows how Table 1 can be used to identify the best formwork system for vertical concrete work.

Project Description

Tabor Center is a 1,300,000 sq ft (121,000 m^2) (or 20,000 sq ft/floor[1,860 m^2/floor]), multi-use facility in the center of downtown Denver, Colorado

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TABLE 1. Factors Affecting Selection of Vertical Formwork Systems (Hanna 1989)

	Formwork Systems				
Influence factor (1)	Conventional column/wall form (2)	Ganged forms (3)	Jump form (4)	Slip form (5)	Self-raising form (6)
(a) Building Design					
Lateral support					
Lateral support system	Most suited for frames and retaining walls	Shear walls; bearing walls; retaining walls	Shear walls; frames and framed shear wall	Shear walls	Shear walls; tube systems; tube-in-tube
Building height	Up to 120 ft (36.5 m)	Up to 350 ft (107 m)	Up to 350 ft (107 m)	Average = 400 ft (122 m); minimum = 60 ft (18 m); maximum = 600 ft (180 m)	At least 300 ft (91 m); no maximum
Building shape					
Column/wall size and location	System can handle variation of column/wall size and location	System can handle variation of column/wall size and location	System can handle moderate variation of columns/wall size and location	Walls should be of the same location; walls size variation can be accommodated	System can handle reasonably modular design
Openings/inserts	System can handle openings/inserts of different sizes and locations	Variation in openings' size and location can be accommodated at additional cost	Openings/inserts should be regularly occurring from floor to floor	Should be minimum; too many openings/inserts make this system impractical	System can handle moderate variations in openings' sizes and locations
(b) Job Specification					
Speed of construction					
Concrete finish	As-cast concrete finish	Produces smooth exposed concrete finish; tie pattern and number should be designed; form liners can be used to produce architectural concrete	Produces smooth exposed concrete finish; tie pattern and number should be designed; form liners can be used to produce architectural concrete	System produces rough concrete finish; no ties	Smooth concrete finish; form liners can be used
Construction sequence	Slabs and walls are placed concurrently	Slabs and walls are placed concurrently; walls can be placed ahead of the floor slab	System is used when no floor slab is available	Typically walls are placed entirely or at least several stories ahead of the floor	Walls are ahead of the floor; other method is used for the first two to three stories
Cycle time	One floor per week	One floor every three to four days	One floor every two to three days	One floor every day; rate of placing = 8–20 in/hr (20–50 cm/hr)	One floor every two to three days

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(*c*) Supporting Organization

Cost					
Stripping	Hand strip; high stripping cost	Crane is used to strip the system; high stripping cost	Forms are equipped with mechanism for stripping; minimum stripping cost	Forms are stripped at the end of the project; minimum stripping cost	Forms are equipped with mechanism for stripping; minimum stripping cost
Reuse	Less than 10	Between 40 and 50; reuses could be horizontally or vertically	Between 15 and 30	Between 50 and 100 (i.e., between 200 ft [60 m] and 400 ft [120 m] high)	At least 30 reuses should be available vertically
Hoisting equipment					
Location of adjacent building and obstruction	Generally not a factor	A major factor, system must have a free space to be moved from floor to floor	A major factor, system must have a free space to be moved from floor to floor	Minimum free space should be available for crane movement	Not a major factor; system can be used in downtown restricted areas
Crane time	Not a factor; system can be hand set	Crane-dependent system; sufficient crane time is a must	System substantially reduces crane time; average crane time pick = 20 min	Crane is used only for materials delivery and concrete placing	Crane-independent system
Operating system	Hand-set system; crane increases system efficiency and reduces cost	Crane-set system; crane serves two functions, lifting and supporting the forms	Crane is used only to lift the forms; crane is not used for forms dismantling	Motion is provided by electric or hydraulic jacks climbing on smooth steel rods	System is lifted by hydraulic, electric, or pneumatic lifters
Safety management					
Safety	No special safety features is required	Special care for handling the large ganged units by crane	Safe, guarded platform; no one needs to be on the form during crane handling	For hydraulic systems, special safety precautions must be taken to prevent fire several hundred feet (or meters) above ground	For hydraulic systems, special safety precautions must be taken to prevent fire several hundred feet (or meters) above ground
Yard facility					
Supporting yard facility, supplier or make-up area	Not a major factor, but system is more efficient, if a local yard facility is available	A major factor; system must have an adequate make-up area or close-by supplier	System is rented or purchased	Continuous materials delivery; uninterrupted concrete placement must be ensured	System is preassembled; make-up area is not a factor

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TABLE 1. ***(Continued)***

(1)	(2)	(3)	(4)	(5)	(6)
(d) Local Conditions					
Area Practice	More efficient in areas of high-quality, low-cost labor force	Works best in high-cost, low-quality labor force	System is easy to learn and adapt; learning curve is quite shcrt	System can be learned in two to three weeks	System requires high-quality supervision
Weather	Generally not a major factor	A major factor, walls should have sufficient strength before stripping, which is largely influenced by weather condition; high winds limit crane movement	A major factor, walls should have sufficient strength before stripping, which is largely influenced by weather condition; high winds limit crane movement	Hot or cold weather affect the concrete rate of setting, which slows the rate of rise	In cold weather, forms should be protected and concrete should be heated
Site characteristics					
Access to site	Generally not a factor for loose forms	Can be a major factor if the system is preassembled in a local yard facility	Site must be accessible, forms up to 16 ft (4.9 m) high and 44 ft (13.4 m) wide	System must have a limited access for material delivery	Minimum site access is required for concrete placing and rebar delivery
Site size	Not a factor	Can be a major factor if the forms have to be built in site	Not a major factor; forms are preassembled and unloaded directly	Not a major factor, system can be used in restricted small sites	Not a major factor, system can be used in restricted small sites

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(Burkhart 1987). It consists of twin office towers of 32 and 40 stories. The tower structure is composed of three elements: the exterior wall, the central core, and the interior deck area that ties the two together (tube in tube). The core is structural steel with a concrete diaphragm (infill walls) up to floor 12 to resist part of the lateral loading. The deck area is also structural steel with a metal deck and concrete fill. The exterior wall consists of closely spaced columns (tube system). A study showed that the crane time is not adequate for hoisting formwork, and it will only be used for material handling and concrete placing. Architectural concrete is required for the exterior walls.

The fact that a slip form is used for a building supported laterally by shear wall makes the slip form an inappropriate choice. It should therefore be eliminated. Ganged form and jump form are also eliminated because of the restricted site characteristics in downtown Denver and the inadequate crane service. As a result, the choice is limited self-rising form. A review of Table 1 reveals that several cells were accountable for selecting the self-rising form. These are:

1. The self-raising form is suitable for buildings higher than 25 stories.
2. It can accommodate architectural concrete requirements.
3. The self-raising form is a crane–independent system.
4. The self-raising form can accommodate restricted site conditions.

Expert-System Development

The actual development of the computer system involves an extensive iterative process of transforming the knowledge base into a format suitable for the selected environment. This requires restructuring, refinement, and testing. Some of the major activities in the process used to develop Slabform and Wallform are explained in the following.

Selection of Appropriate Development Tool

Fig. 3 shows the relation between the ease of expert-system development and the flexibility of the developed system. The level of flexibility is represented on the horizontal axis and ranges from inflexible (limited choice in input and output) to very flexible (unlimited choice in input and output). The ease of development and use is represented by the vertical axis and ranges from easy to develop and use (only general computer knowledge required) to difficult to develop and use (good programming skills required). The use of expert systems shells are only appropriate for the corner of the graph representing uses for specific circumstances. Shells are used when the ease of use and rapid development are highly desirable and the flexibility is a lower priority.

The primary users of the proposed expert system for the selection of formwork systems will be general contractors and formwork subcontractors, where little or no knowledge of programming languages is expected. The development tool must therefore be capable of providing a user-friendly interface to the contractor. As a result, the selection of an expert-system shell is appropriate for the system development.

Four major considerations were important to the development team when the expert system shell was selected. First was the user-friendliness of the system, since the intended users of the system have little or no experience in programming. Second was the flexibility of the system—the ability to

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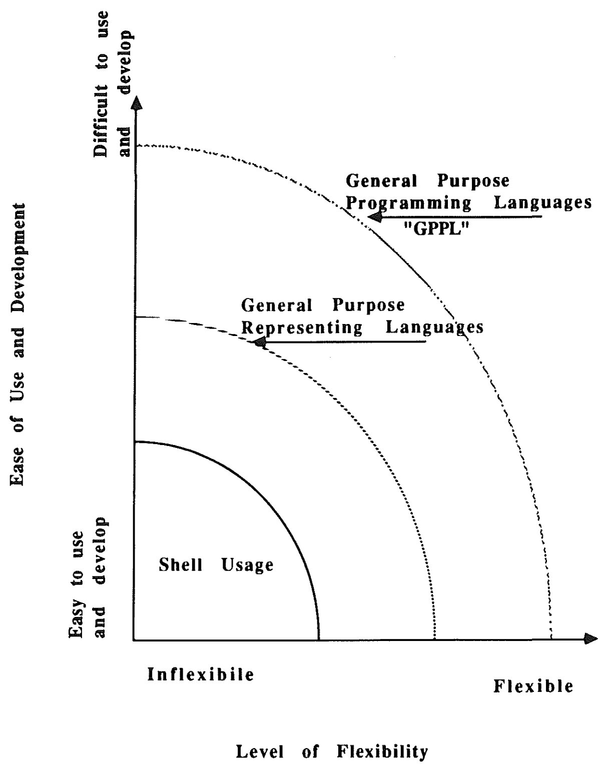

FIG. 3. Appropriate Use of Expert-System Shells (Hanna 1989)

modify and expand the system. Third was the adaptability of the system to run on an IBM personal computer (or compatibles) with a single high-density floppy disk drive. Fourth was the capacity and ability to handle a large knowledge base. EXSYS Professional therefore was chosen as a robust shell that is capable of handling up to 3,000 rules.

Shell Features

Fig. 4 shows the basic structure of the selected expert-system shell and its relation with the domain expert, knowledge engineer, and end user. The cycle starts with the interaction between the domain expert and the knowledge engineer. The knowledge engineer extracts the expert's knowledge and uses it to build the knowledge base. The shell has a built-in inference engine. The control mechanism of the inference engine uses the input data and facts, and attempts to search through the knowledge base to reach a conclusion. The user inputs information by selecting from a number of alternatives. The user may inquire as to why a question is being asked and how the expert system reaches its conclusion. The explanation facility also provides the user with a numeric rating of the level of confidence in the selected systems and some recommendations that should be followed in particular situations.

The thick lines in Fig. 4 represent the feedback process. The user accepts the result and stops, changes the input data and reruns, or completely rejects

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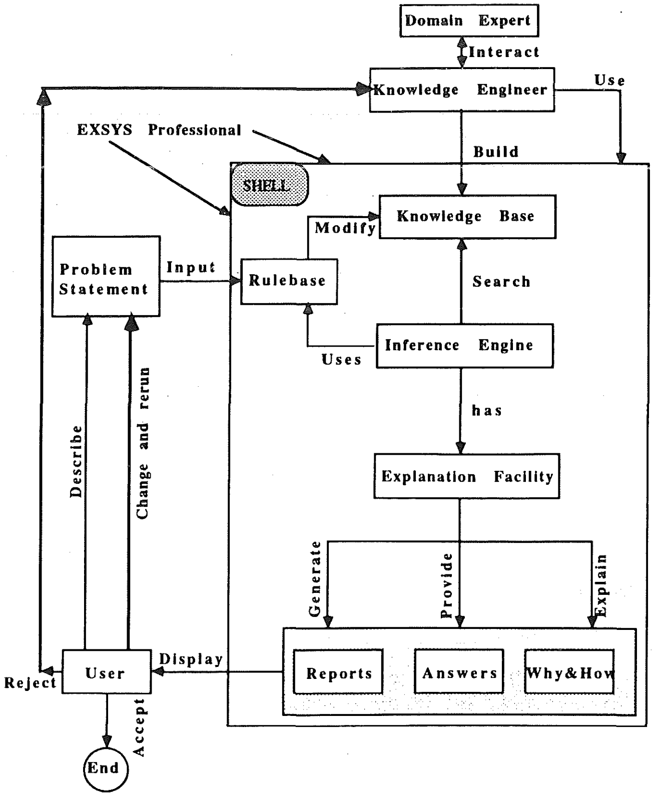

FIG. 4. Basic Structure of the Expert-System Shell (Hanna 1989)

the result. The last case requires the system developer to restructure the system to provide satisfactory conditions.

Representing Formwork Knowledge

As information relevant to the problem was initially acquired, much thought was given to the method of presenting this knowledge. The following procedure was developed to represent the acquired knowledge in a simple, organized, effective format. It is also well suited for the selected shell. It is included here as the bridge to the development of the expert system.

Develop Search Tree

This step starts with the creation of a list of all the relevant factors that affect the selection of formwork systems. By conducting interviews and reviewing literature, a complete list of all the relevant factors was established (Fig. 2). The final list included 40 different factors. These factors were further classified into a group of similar features and represented in a hierarchical tree format. Several versions of this tree were prepared and reviewed by two experts.

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Prepare Tabular Knowledge Base

The influence factors as well as all the possible solutions for horizontal and vertical forming systems were arranged in a table with columns representing all the possible solutions, i.e., the different types of forming systems, and the rows showing the effect of the influence factors on each forming system (Table 1). The tabular knowledge representation format proved to be very effective in facilitating the task of the knowledge engineer (Hanna and Sanvido 1990). The following advantages were noted during the preparation of these tables:

1. This format facilitates the recording of data received in an interview. Several blank sheets were prepared beforehand, and the knowledge engineer filled in the cells directly during the interview.
2. During the preparation of the final comparative analysis between different formwork systems, vacant cells representing knowledge gaps could easily be detected. As a result, follow-up interviews were short, narrowly focused, and could even be conducted by telephone.
3. Vertical and horizontal repetition of cells could be easily observed and recorded. The detection of this repetition was helpful in defining the subgoals, as will be explained in next section.

Building Prototype

Extract Rules/Subgoals from Tabular Knowledge Base

Figs. 5(*a*) and 5(*b*) show how the rules were extracted from the tabular knowledge base. These tables were also used to create subgoals. For example, in developing the expert system for the horizontal formwork system, there was a subgoal called adequacy of hoisting equipment. This subgoal is a synthesis of availability of crane and crane time involvement, existence of adjacent buildings and other obstructions, and adequacy of crane carrying capacity.

Transform Rules into Format Compatible with Shell

Knowledge was loaded directly into the shell in the form of if-then rules. The rules are developed by creating a series of qualifiers. A qualifier has two parts: the first is an incomplete sentence ending with a verb, and the second is associate values representing all the possible relevant situations to the qualifier. The "if" part of the rule consists of one or more of the qualifier's values and conditions that can occur. The "then" part consists of another qualifier value or variable or choices (possible solution to the rule), and represents actions that must be taken.

Develop Prototype System

The prototype system is a structurally complete expert system, but on a smaller scale, i.e., with a smaller number of rules. The purpose of developing a prototype is to ensure that the system is complete and capable of producing valid results. Accordingly, 23 rules were entered into EXSYS to represent a prototype for the selection of horizontal formwork systems. The 23 rules represent the major deciding factors that affect the selection of horizontal formwork systems. These factors were building design (uniform or irregular), hoisting equipment (adequate or inadequate), and site characteristics (restricted or unrestricted). These deciding factors were represented and

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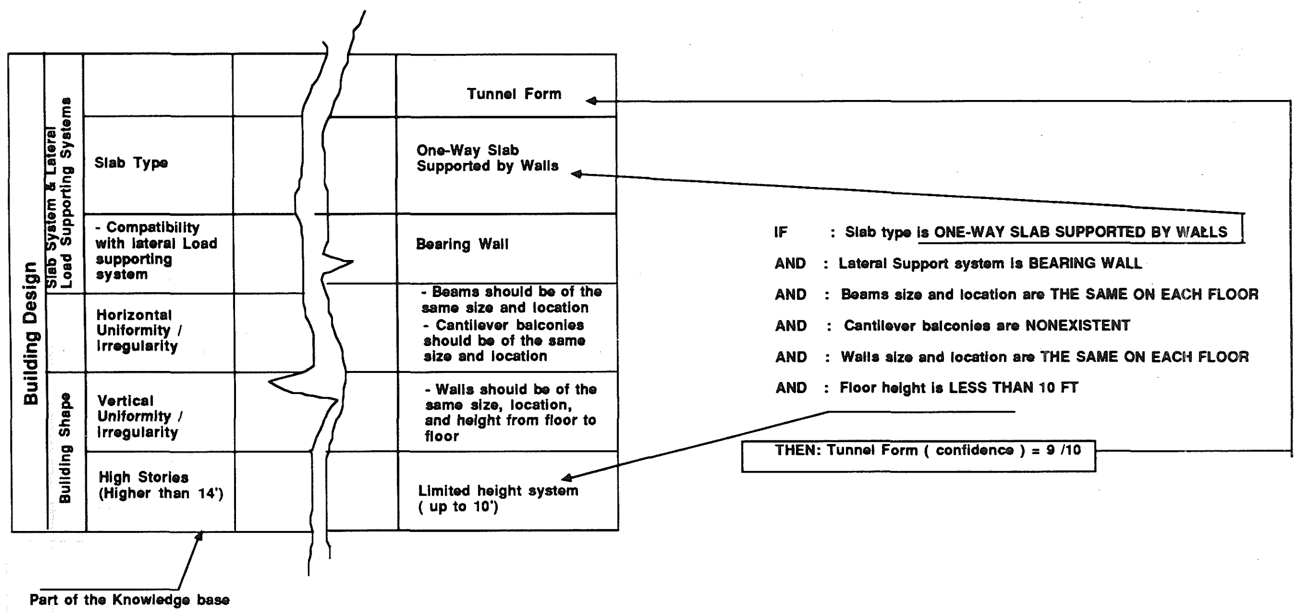

FIG. 5 (a). Example of Extracting Rule from Tabular Knowledge Base

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	Influence Factor	Conventional Wood System	Conventional Metal System	Flying Truss System	Column-Mounted Shoring System	Tunnel Form
Hoisting Equipment	Availability of Crane and crane Time Involvement	- Can be hand-set - Less expensive if crane is available	- Can be hand-set - Crane is necessary if made into panels	Adequate hoisting equipment must be available		
	Adjacent Building, Traffic, and other Obstruction	Generally, not a factor	- Generally, not a factor - May be a factor if system panelized	A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building		
	Adequacy of Crane Carrying Capacity	Generally, not a factor		Crane should have adequate carrying capacity at maximum and minimum radii.		

Subgoal "Adequacy of Hositing Equipment"

IF Crane is available with enough crane time involvement
AND Adjacent buildings, traffic, and other obstruction are nonexistent
AND Available crane has a sufficient carrying capacity at different radii

THEN Hoisting equipment is adequate
ELSE Hoisting equipment is inadequate

FIG. 5 (b). Use of Tabular Knowledge Base to Develop Expert-System Subgoals (Hanna 1989) entered into the system in abstract or qualitative terms. For example, in the prototype system, building design was classified as uniform and irregular in abstract terms without any attempt to quantify what is meant by uniform or irregular. In the completely developed system, building uniformity is a synthesis of three subgoals: horizontal uniformity, vertical uniformity, and miscellaneous uniformity. Each subgoal in turn is a synthesis of items. For example, a horizontally uniform building is achieved by satisfying three conditions: regular slab type, identical beam size and location, and regular reoccurrence of cantilevered balconies.

Test Prototype System

The prototype system developed for the selection of a horizontal formwork system was then tested on hypothetical projects. The prototype system was designed to give results in abstract terms. For example, the horizontal formwork system was divided into two main categories: hand-set systems (conventional wood and metal systems) and crane-set systems (flying truss, column-mounted shoring systems, and tunnel forms). The test was first conducted to ensure that the system is capable of classifying the selected system into hand-set or crane-set. Rules specific to two formwork systems were then added, and the expert system was tested. It provided valid results with an appropriate certainty factor.

Development of Complete Expert System

As mentioned previously, the prototype system was designed to process rules and produce output in abstract terms. The process of developing the complete expert system consisted of three steps.

The first step was to incrementally increase the number of rules to cover the full scope of each subgoal. For example, when developing the prototype, site characteristics were classified as either restricted or unrestricted. In the complete system, a number of rules were entered to completely define restricted or unrestricted site characteristics. These included the existence of adjacent buildings, nearby traffic and power lines, site accessibility, and availability of storage and make-up areas. This process was repeated to add the rules that define design uniformity or irregularity, and adequacy of hoisting equipment.

The second step was to add the rules that distinguish each formwork system. There are some intermediate rules added to the system to enable the system to determine whether the selected formwork system is hand-set or crane-set. The next step added the rules that characterized each formwork system. For example, the following rule was added to distinguish between the selection of the flying truss formwork systems and the column-mounted shoring system: if story height is higher than 6 m, and the story height varies on the same floor, then column-mounted shoring system (confidence) = 9/10, and flying truss systems (confidence) = 1/10.

The third step was to add the "stationary" rules. After the implemented expert system chose a specific formwork system, it also provided the user with some advice. For example: if the selected system is the flying truss system, and the clear distance between columns in the facade is more than 9 m, then divide the flying truss panels into two, each of width = clear distance between column (or 9 m)/2.

This rule is stationary and specific to the flying truss formwork system. Other stationary rules were added concerning the other formwork systems.

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System Capabilities/Limitations

1. Slabform and wallform are rule-based expert systems, designed to assist formwork designers/planners in selecting the optimum formwork system. Slabform selects the horizontal (floor) formwork, shoring, and reshoring systems; advised the user in a unique situation; and recommends some formwork manufacturers to contact. Wallform selects the vertical formwork system and recommends some formwork manufacturer's products.

2. The primary users of these systems are general contractors and formwork subcontractors. The system assumes that the user has some knowledge about formwork. The user is expected to be at an early phase in the development of the project, with some information available about building shape, site conditions, and resources.

3. In multipurpose high-rise buildings, each set of floors has certain functions and features that may result in the use of different formwork systems for each section. In this situation, the user is advised to run the system more than once to determine the optimum system for each part of the building.

4. The two systems were developed as a result of intensive interviews and a literature search. However, some information was extracted from a single source of expertise, and no safeguard against bias was therefore present.

Conclusion

The knowledge acquisition and development of a knowledge-based expert system for the selection of formwork for concrete buildings are described. Three basic stages were followed to acquire knowledge: familiarization, elicitation, and organization and representation. Each has its purposes and methodologies.

In developing slabform and wallform, a number of issues were observed. First, an expert-system shell is proven to be an effective tool for rapid and easy development. Second, the tabular knowledge base facilitates the process of presenting, organizing, and transforming the acquired knowledge into a format acceptable to the selected shell. The tabular knowledge base allows the knowledge engineer to conduct effective feedback interviews by locating empty cells. These tables also show the effect of influence factors on each formwork system. Third, the iterative process of building prototype, incremental improvement, and testing has led to a successful system development.

Appendix. References

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