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Toward the development of a knowledge-based construction schedule planning system

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TOWARD THE DEVELOPMENT OF A KNOWLEDGE-BASED CONSTRUCTION SCHEDULE PLANNING SYSTEM

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ABSTRACT

This research attempts to model and prototype a knowledge-based system for use in the construction industry to accomplish the automatic generation of initial construction schedules. The schedule can be transformed into a logical network that provides a physical representation of the construction operations plan. The prototype system, which requires symbolic processing and reasoning, is developed based on an intensive modeling that rationally examines industry practice.

The model identifies work breakdown and precedence relationship as the two major concepts in schedule planning. Work breakdown is concerned with the identification of construction activities that result in the completion of project elements. Precedence relationship is related to the sequencing of construction tasks based on the constraints of scheduling.

The knowledge structure of the prototype system is composed of databases, heuristics and algorithms. The databases consist of facts used to represent the structured hierarchy of activities and the formalized task precedence relationships. The heuristics are rules used to determine the breakdown of activities into scheduling modules, the appropriate level of detail and the precedence conditions. The algorithms are procedures used for activity breakdown, task sequencing and task redundancy.

The current application, scheduling a reinforced concrete building, is specifically prototyped to evaluate the model and the effectiveness of the system. A knowledge system shell M.1 is used to prototype this schedule planning system.

The prototype has been evaluated by conducting a laboratory experiment on inexperienced schedulers. By measuring the quality and the time of performance, the results of this experiment have suggested that the system can be an effective productivity tool to construction schedulers and planners. The ability of the system to improve the quality of construction schedules further suggests that the model developed is rigorous enough to warrant its continued development into a production standard system.

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I. INTRODUCTION

A. BACKGROUND

Traditional management theory divides management into the functions of planning, organizing, staffing, leading and controlling (Koontz and Weihrich, 1988). These functions are also applicable to managing construction projects. It is through these functions that the project is transformed progressively through the various development phases. In construction projects, these development phases are identified as the evaluation and feasibility studies, conceptual engineering, detailed engineering and design, procurement, construction and finally operation (Barrie and Paulson, 1984, Clough, 1979, Clark and Lorenzoni, 1978). The management of all these phases is described as construction management. Construction management consists of that group of management activities that is distinct from normal architectural and engineering services (Stukhart, 1987). These phases are shown in Figure 1. When construction management functions are limited to the construction phase alone, then this assignment will be described as construction operations management. This terminology is used in this research in order to differentiate from the overall construction management functions. The person responsible for the construction operations management functions is the construction project manager.

Construction operations management is therefore described as the systematic integration of a number of construction technologies, human and material resources, and other construction related disciplines into an integrated

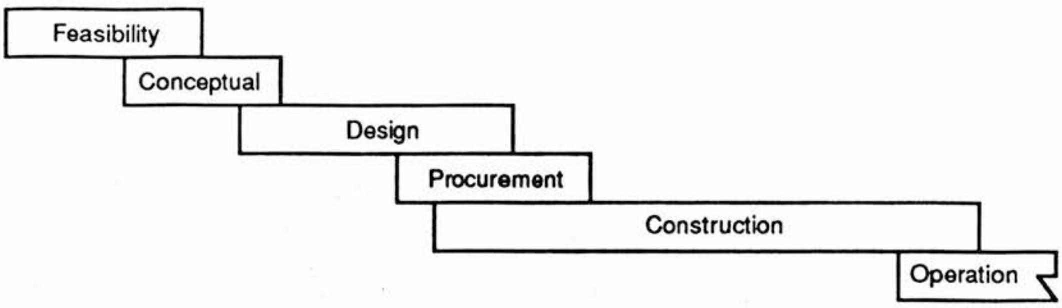

Figure 1. Construction Project Development Phases

entity toward the accomplishment of construction operations (Anonymous, 1986). It involves the management of every detail of construction activities immediately after the design is completed until the project is ready for use. Construction comprises a series of activities with one-of-a-kind tasks, having definable finish dates, finite duration and viewed as a single identity (Cleland and King, 1975, Kerzner, 1984).

Construction projects result in facilities to improve the well-being of mankind. These include facilities such as schools, hospitals, urban complexes, housings, apartments, roads, bridges, dams, water supplies, ports, airports, pipelines, plants, refineries and many other constructed structures. These projects are categorized into four major types of construction (Clough, 1981):

residential,

building,

heavy engineering,

industrial.

For these projects to be successful, their construction must be properly planned and controlled. According to Moder, Phillips and Davis (1983), planning is defined as the process of preparing for the commitment of resources in the most effective fashion, while controlling is defined as the process of making events conform to schedules by coordinating the action of all parts of the organization according to the plan established for attaining the objective. These planning and control functions are the two major functions associated with construction operations management.

Construction project organizations involve a hierarchy of people. Halpin and Woodhead (1976) identified four levels of hierarchy as shown in Figure 2. These are management personnel at organization, project, operation and task levels. The organizational level is primarily concerned with the overall success of the project by proper application of resources. The project level is concerned with planning and controlling the time and cost aspects. The operation level is concerned with the construction technology and the methods of construction. The task level is concerned with the identification, assignment and implementation of construction work.

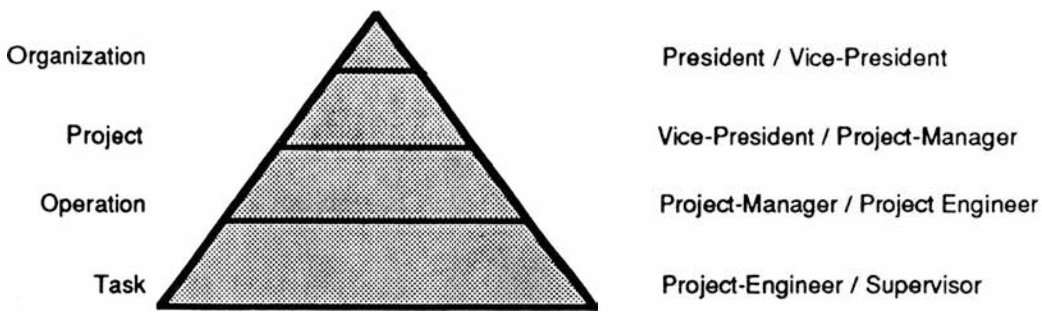

Figure 2. Construction Management Levels

Successful construction operations management is defined as having achieved the completion of the construction phase within schedule, cost and at the desired level of performance (Kerzner, 1984). This management focus is illustrated in Figure 3. To achieve the desired level of performance, the construction project must be designed and constructed with conformance to specifications (Leon, 1983). While maintaining this performance, management attention must also be given to the planning and control of construction schedules and costs.

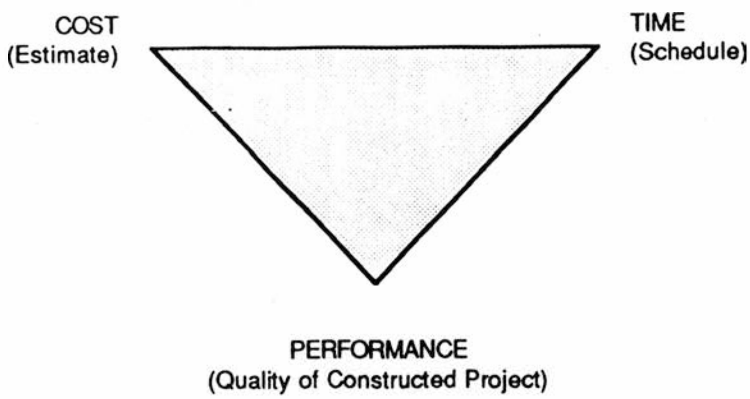

Figure 3. Construction Management Focus

The construction industry has been sluggish in adopting modern management systems to plan and build projects (Chalabi, 1986). This has caused long delays in schedule and big cost overruns. What are needed are more accurate and timely controls over planning and scheduling. This requires more extensive use of computers, graphics and project planning and control systems (Wager, 1985, Popescu, 1987). Scheduling systems have been used in the construction industry since the 1950's, yet the majority of construction contractors failed to fully use this tool effectively (Birrell, 1980, Jaafari, 1984). The problems in implementing these systems were partly due to schedulers being very strong in critical path scheduling theory but lacking the experience needed to develop realistic plans. Those with substantial project experience but short on planning theory tend to develop network plans that include basic logic as well as specific time sequencing deficiencies (Ponce-Campos, 1975). Therefore a new type of construction management tool is required to help project managers plan and control their construction schedules and costs effectively. This tool is a decision support system that could be developed within the context of construction planning and control.

Various presentations of critical path scheduling systems have recently been proposed (Kapur, 1978, Chalabi and Emerson, 1984, Markevicius and Rouphail, 1986) and their software are currently available (Moder, Phillips and Davis, 1983, Teja, 1987). These software do not provide the needed flexibility and efficiency as a project-oriented tool-kit (Passanisi, 1985). Passanisi (1985) suggests including automatic schedule generation and work breakdown structure into these tool-kits. The structure is rigid and does not allow for unstructured problems commonly encountered in construction operations.

As a supplement to the conventional programming techniques, a new approach in decision support is being proposed. This approach would utilize techniques developed from the artificial intelligence area known as knowledge-based systems. The proposed knowledge-based system would represent a part of the overall integrated project information system that would provide reliable data necessary for decision making. It would incorporate a knowledge base which contains data, information, rules and procedures related to construction planning and control. The system would be flexible enough to solve unstructured and judgemental problems commonly encountered in construction.

B. CONSTRUCTION OPERATIONS SYSTEM

1. Functional Phases. Construction operations are so inherently dynamic and complicated that the general approach has been to rely upon experience and to use intuitive approaches. The construction processes are so ill-structured and complex that only experienced project managers can plan and control construction operations effectively (Kangari, 1986a, 1986b, Gartland and Hendrickson, 1985, Maher, 1987). Since these experienced project managers are scarce and costly, a system that could help new and less experienced project managers perform these functions would be an excellent decision-making aid. Furthermore, the fully developed system would be useful to experienced managers and top management to support their decisions with quality and timely information. This therefore has led to the development of knowledge-based systems in construction operations management (Kangari, 1986b). This development will be described in detail in the literature review.

In developing a system for construction planning and control, the overall management of construction operations is broken down into four functional phases as shown in Figure 4. These phases are planning, scheduling/costing, monitoring and control. Each of these phases can benefit from the development of a knowledge-based system. The following activities are typically associated with each phase:

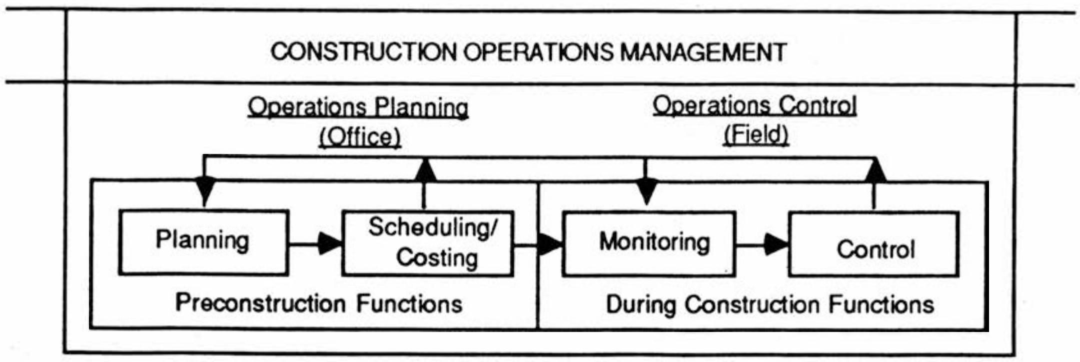

Figure 4. Construction Management Functions

Before Construction (Planning)

Phase I - Activity Planning

1. Determine work breakdown structure
2. Define appropriate level of activities
3. Ascertain precedence relationships
4. Schedule the relationships into a network

Phase II - Scheduling and Costing

1. Estimate activities duration
2. Estimate activities cost
3. Perform scheduling computation
4. Summarize estimated costs

During Construction (Control)

Phase III - Progress Monitoring

1. Measure physical progress
2. Maintain record of cost data
3. Report physical and cost progress

Phase IV - Performance Control

1. Evaluate and analyze progress
2. Appraise deviations
3. Determine corrective actions
4. Update plan and progress

Detailed treatment of the issues related to the above four phases is presented by Clough (1979, 1987), Halpin and Woodhead (1980), Barrie and Paulson (1984), O'Brien (1984), Peurifoy (1985), Mueller (1986) and Willis (1986).

a. Planning. This preconstruction function would cover the activity planning and scheduling and costing phases. The output from the scheduling and costing phase could be fed back into the activity planning phase to improve the planning function.

(i) Activity Planning: Construction planning is concerned with the devising of a workable scheme of operations which is designed to accomplish construction activities successfully when applied into practice. Activity planning begins with the generation of a work breakdown structure based on the output of detailed design. The techniques depend on the the trades of construction concerned (Ponce-Campos and Ricci, 1978). After the initial breakdown, the construction project might be further broken down into an appropriate level of activities, consistent with the scheduling and costing objectives. Traditionally, activity planning for the schedule is independent and separate from the cost. However, in order to increase the effectiveness and efficiency of construction control, an integration of cost and schedule activities should be considered (Sears, 1981, Hribar and Asbury, 1985, Stevens, 1986). This approach is an attempt to devise a scheme which allows a common description of job-site construction activities in cost and schedule.

An activity is defined as the lowest common unit of work for integrated cost and schedule control. The breakdown addresses the required details for scheduling purposes. Consequently, the same unit of work can be summarized into work packages appropriate for costing purposes. These work packages are common units of work described in the work breakdown structure. The breakdown of activities is prepared with the maximum detail required for either costing or scheduling purposes, bringing activities to the level at which control could be asserted. The activities selected are sufficiently short in duration and well-defined to be performed by a particular construction trade.

When all the activities involved are identified, these activities should be presented in an output form suitable for scheduling. The accuracy and usefulness of the breakdown and relationship are dependent mainly upon intimate knowledge of the construction, judgement and skill in planning. The construction of the breakdown and relationship is based on the physical and resource dependencies among activities. Application of logic tends to result in a breakdown and relationship that represent the technical dependencies of the operation.

(ii) Scheduling and Costing: When activity relationships have been developed, the next step is to estimate the duration and the cost of the activities. A construction schedule is a time-phased plan of construction activities that is necessary to complete the operations. Based on the breakdown established during the planning phase, the time required to carry out each activity is estimated. The duration of these activities can be established by any method appropriate to the scheduling process (Ayyub and Haldar, 1984). Someone experienced and familiar with the type of work involved is required or consulted when the activity times are estimated. Alternatively, some kind of database system could be accessed that would provide these activity duration estimates. This activity duration represents the elapsed time based on the organizational normal level of manpower, equipment and any other resources.

The schedule then becomes the basis for time control during construction operations. Using these time estimates, the time period required for construction completion is computed. This computation also determines the time period in which each activity must be accomplished if project completion time is to be met. Traditional scheduling methods such as Critical Path Method, Project Evaluation and Review Technique or Precedence Method may be utilized, since they deal with the construction of the project on the basis of activities. Variations to these methods that were of special use in construction projects were suggested by O'Brien, Krietzberg and Mikes (1985), Arditi and Albulak (1986), Chrzanowski and Johnson (1986) and Handa and Barcia (1986).

When estimating the cost of construction, the activities are summarized into appropriate work packages which are detailed enough for cost control purposes. The cost is a financial obligation that would be incurred when work has been done. This work package assignment is based on the practice of the construction industry concerned (ASCE, 1985). The estimating process begins with the preparation of a quantity survey of all the activities within the work package. This survey is a detailed compilation of the nature and quantity of each activity. After work quantities have been obtained, cost is ascribed to each activity and summed up into the work package. Similarly, some kind of database system could be accessed that could provide unit costs to these activities. These costs are associated with labor, material, equipment and subcontract. A summation of work package costs provides the estimated cost for construction. These detailed estimates of the individual work package then become the basis for cost control during construction (Neil, 1985).

b. Control. During construction this function covers the progress monitoring and performance control phases. The output from the performance control phase can be fed back into the progress monitoring phase to improve control function.

(i) Progress Monitoring: After plans and schedules have been devised, the next phase is to implement the project plan in the field and monitor the construction operations. Construction monitoring therefore involves the process of measuring the physical progress, reporting the progress from the job and recording this information in a format convenient to its comparison with the planned progress. These progress reporting and recording functions are based on the activities developed earlier.

The progress of any given activity can be measured in several different ways. It depends upon the mode of operation and the determination of field costs. However, a commonly used method is the estimated percentage completion of the activity, which measures the rate of progress at a given time period (Seiler, 1983). Various techniques have been used to measure this time-rate of progress in order to achieve a reasonable accuracy. One of the techniques is to make use of the S-curves, instead of the straight line relationship between time and work accomplished (Kerridge, 1979). In order to associate production costs with work achieved, progress is measured periodically. This periodic measurement of work accomplished includes all activities achieved by labor, material, equipment and subcontract.

Actual work performed is measured to determine the percentage of completion. With unit rates known, the related expenditure for each activity can be calculated. The main sources of data for field costs are labor and equipment time sheets, field survey of quantities of work in place, and procurement bills and invoices. These data are used to compute the actual unit rates of work and are reported for cost control purposes. Progress reporting is accomplished by listing the activities in progress and indicating the progress measurement for each activity. It is concerned with the stage of advancement of the field work. These reports are used for progress tracking and overall construction control.

(ii) Performance Control: Integrated cost and schedule control is the process of influencing the outcome of cost and schedule trends to conform with planned or expected performance. Its application is based upon construction cost estimates and time schedules developed for the operation, and using primary and contemporary information systems to routinely compare expected with actual performance. The information received from the monitoring phase measures, evaluates and reports the job progress. By comparing this information with planned performance, the nature and extent of any cost and schedule deviations would be appraised.

Overall cost control should be integrated with schedule control. Cost control is designed to measure construction cost status against budget. It is developed and administered at the job site. Evaluation of plan changes, claims and other change-order requirements is also done at the job site. When production costs are excessive, corrective action must be taken. Any efforts to improve field production must be based upon an investigation of the facts that cause these deviations. The effectiveness of cost control efforts depends largely upon the ingenuity and resourcefulness of the people involved. Various techniques have been developed to evaluate cost status, such as the earned value technique (McConnell, 1985).

As construction proceeds, progress reports keep coming in. After evaluating and analyzing these work activities, the progress status is determined. When critical activities are delayed, some corrective action must be taken to forestall overall project delay. One procedure is to increase the resource availability levels in order to meet the project's required completion date. The other approach is to extend selected activities by considering time-cost trade-off (Moder, Phillips and Davis, 1983, Minieka, 1978). As progress is updated, new activities are added to the network and certain original activities are deleted. New activity durations are estimated. With this information, the revised schedule and project cost are recomputed, updated and projected to completion. This process continues as the construction operations are monitored until construction is completed.

2. Systems Integration. A complete construction system would require the integration of all the development phases from project evaluation to operation. A method to enhance the use of computers in all phases of the life of a constructed facility has been proposed by Sanvido (1988). His proposed method identifies the functions required to manage, plan, design, construct, operate and maintain a facility. In another development, an integrated environment of processes and information flows for the vertical integration of architectural design, structural design and analysis, and construction planning has been reported by Fenves, Fleming, Hendrickson, Maher and Schmitt (1988). Raymond (1987) has presented a framework for understanding the the nature and role of an information system within a project management system. His data modeling approach, which focuses on building a conceptual data model of an object system, is no doubt a useful strategy when designing a total construction system.

From the four construction operations phases described earlier, it is apparent that a huge amount of data would be generated. These data are needed for feedback into the planning and control cycle. While most data desired might be computerized, simply having the data at their respective phases is inadequate. What is more important is that the appropriate set of data must be readily obtainable and can be easily transmitted from one phase to the other (Boyer, 1985). The output from the preceding phase should become the input of the proceeding phase. This would ultimately provide a system which is integrated, automated and interacts with the overall project planning and control as shown in Figure 5.

The complete construction planning and control system is therefore complex and highly interrelated. However, each of these phases could be developed separately and later be integrated. A knowledge-based system could provide an integration that directs the input/output operations and provides the decision support to the user. Butler, Hodil and Richardson (1988) have noticed that the trend in knowledge system technology is the embedding of knowledge-based systems directly into the traditional systems architecture as an adjunct to existing systems. In a knowledge-based construction system, the project domain would be identified before the system is designed. The output from the construction development phase could be used as a feedback into future design process.

Even though complete systems for construction planning and control would require the consideration of all the above four phases, this complete development was infeasible within the time limit available for this research. Therefore, this research focuses only on the planning aspect of the construction process covering activity planning for scheduling purposes. However, this

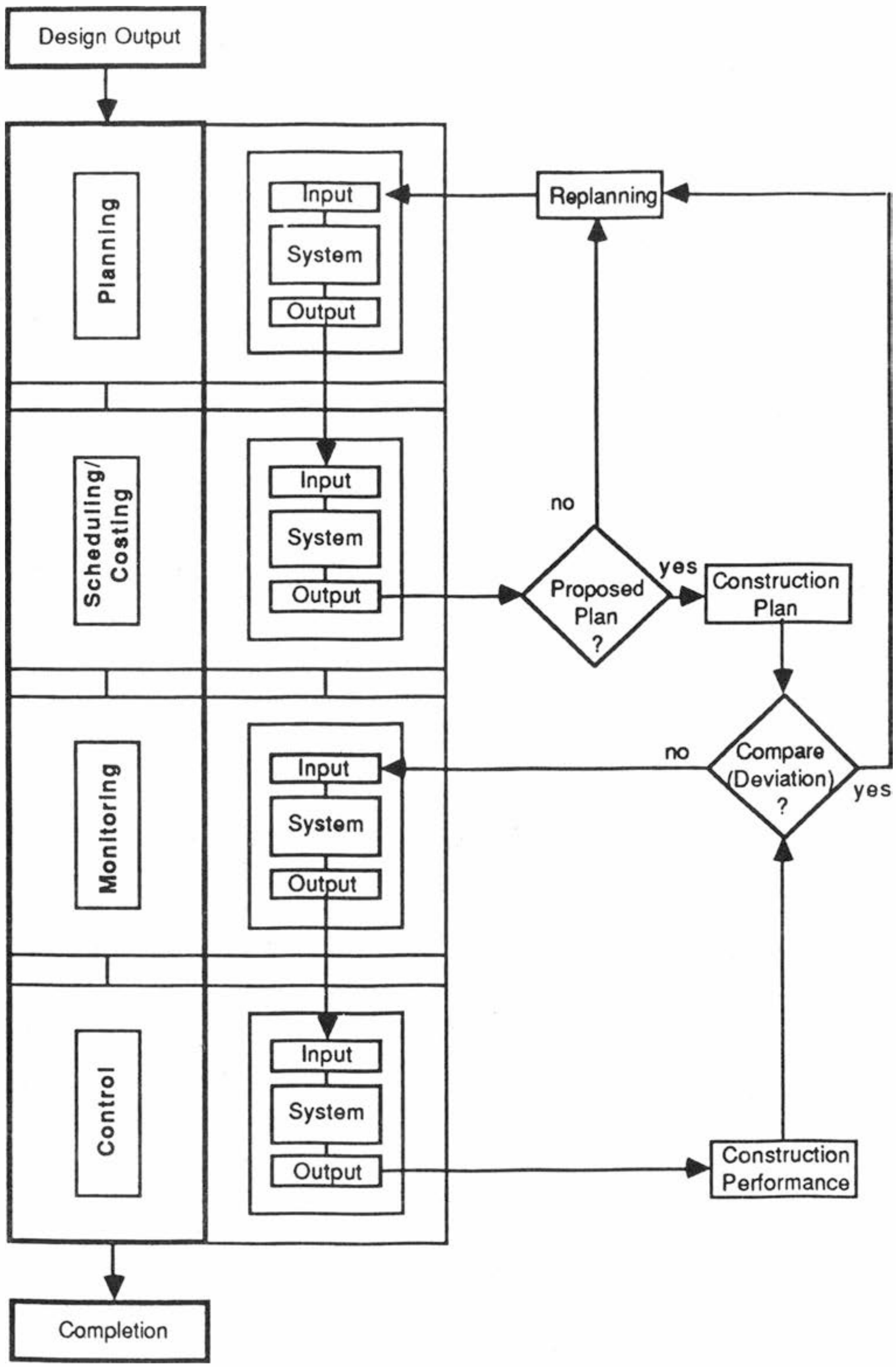

Figure 5. Construction Systems Integration

preconstruction effort is no less important than the actual construction control effort itself. This is because all network-based techniques depend on the existence of a sound initial project network which can only be developed through schedule planning considerations. Furthermore, generating a network is a complex heuristic process for which computationally efficient algorithms do not exist (Navinchandra, Sriram and Logcher, 1988). Since preparing a construction schedule requires experience and expertise, a system that can assist in undertaking this complex heuristic process is desirable. This knowledge intensive system requires symbolic processing and reasoning. As the advent of artificial intelligence can provide this requirement, it has proliferated a knowledge-based system's application in construction schedule planning.

C. RESEARCH OBJECTIVE

Cost and schedule controls are the two major ingredients to successful construction operations. They are two significantly different planning areas, though they can be integrated. As mentioned earlier, various scheduling and costing modules are incorporated in project management software that is widely available in the market today (Davis and Martin, 1985, Teja, 1987). However, in order to use these programs, the user first needs to prepare the work breakdown of activities and their precedence relationships, estimate their unit costs and determine each activity's duration. The scheduling and costing programs basically perform the computation after the content, duration, unit cost and dependencies of all activities are input into the system. The problems in using these programs are therefore in visualizing the construction activities, in preparing the work breakdown and their relationships, in estimating the costs and the durations, and finally in interpreting the output.

Computer programs such as Harvard Total Project Manager, Primavera, Microsoft Project etc. (Fersko-Weiss, 1987) have been used in the construction industry for scheduling purposes. However, in order to further improve schedule planning, a construction scheduling program which could automatically generate an initial network is needed. This research therefore attempts to develop a program for automated network generation through the application of knowledge-based system techniques. It represents a methodology for scheduling the construction process. The system would utilize the databases from the engineering design phase and the knowledge base of the construction scheduling phase, thus integrating design and construction.

The primary objective of this research is therefore to develop an integrated model that would utilize engineering design output and construction scheduling knowledge in an integrated construction planning program. This model would ultimately provide the structure for knowledge-based system development that could provide an initial construction schedule to be used as an input to the well established network scheduling programs. The system would provide information pertaining to the types of construction activities and the relationship among these activities. This information is normally expected during construction planning. Consequently, this research would provide an insight into the suitability of knowledge-based system applications in construction operations management in general and construction schedule planning in particular. A knowledge-based system development tool is selected and used to prototype the system in this research.

D. SIGNIFICANCE OF THE RESEARCH

This research is expected to provide a better understanding of the construction scheduling process. This is achieved through modeling and knowledge acquisition. Since knowledge is formalized during system development, this enables the researcher to consider the various aspects of construction scheduling. Unstructured scheduling processes are transformed into formalized instructions and methodology. By modeling the schedule planning process, a methodology has been devised to direct system developers to develop a computer-based construction scheduling system.

The ultimate knowledge-based system as perceived by the researcher would be useful to project managers, planners and schedulers in particular, and the construction industry in general. Since it is an application system that represents real systems and processes, the benefits would be immediate. The system would help users plan and ultimately control their construction better. This system would also encourage more people in the construction industry to use a computer-based schedule planning system because of its perceived simplicity and ease of use. Consequently, delays and errors in construction operations would be reduced.

This research would provide the impetus for further development and refinement in the problem domain being captured. However, the required strategy and structure would have been identified and could be employed in future enhancements. Further development and refinement would be required concerning the knowledge base. As knowledge-based systems provide this knowledge updating capability, the system would provide the basis for future enhancements.

Finally, this research provides insight into the suitability of knowledge-based systems in construction planning applications. In particular, it examines the robustness of knowledge-based system methodology as applied to construction scheduling applications. Through prototyping and system evaluation, this research demonstrates the practical application of a knowledge-based system tool to solve construction schedule planning problems previously inhibited by conventional programming techniques. These findings have provided directions for future knowledge-based developments, thus leading towards production standard systems.

II. LITERATURE REVIEW

A. RESEARCH NEEDS IN CONSTRUCTION

1. Overview. Construction engineering and management is a fast growing discipline of civil engineering that has not been well founded on theories and mathematical analyses. Considering the importance of construction as an industry and the lack of well-defined knowledge, it is important that basic research needs in this area be identified. However, it is difficult to develop a theoretical framework since this discipline has not reached its maturity yet. Therefore current research should be devoted to structuring the knowledge of construction into a well-defined process (Carr and Maloney, 1983).

2. NSF Sponsored Workshops. To encourage construction research, the National Science Foundation (NSF) has sponsored three major workshops during the 1982-87 period. The first workshop was held in 1982, the second in 1985 and the third in 1987.

a. Construction Engineering Basic Research. This first workshop was held at the University of Michigan, Ann Arbor in 1982 (Carr and Maloney, 1983). The purpose of this workshop was to discuss basic research needs in the construction industry. The topics identified and recommended for further research were related to Construction Engineering Management, Construction Engineering Analysis and Design, Construction Engineering Uncertainty and Construction Engineering Human Resource Management. Specific issues in

Construction Management were Project Planning, Estimation, Measurement and Control. From the above recommendation, it is apparent that project planning needs to be researched. This involves the development of techniques for analyzing construction engineering management problems of work breakdown structures, computer estimating, computer tracking, computer graphics, data bases and simulation models.

b. Computerized Applications to Construction Engineering and Management. This workshop was held at the University of Illinois, Urbana-Champaign in 1985 (Ibbs, 1985, 1986). Its purpose was to determine new computer applications and technologies related to construction engineering and management processes. Four important topic areas were developed for research. These topics were Project-Wide Databases and Communications, Knowledge-Based Expert Systems, Simulation and Robotics.

In Knowledge-Based Expert Systems, the potential of artificial intelligence concepts and viable applications to construction were evaluated. Specific issues by which expert system and knowledge-based models could be used in the construction industry were of great concern. Important application areas were identified as monitoring/forecasting applications, classification and evaluation, planning and design, diagnostic, qualitative simulation and interpretation across varying levels of data accuracy.

Again, from this workshop, the application of a knowledge-based expert system in construction was suggested. In particular, it was felt that potential applications should be directed towards developing integrated decision support systems for construction projects that address cost and schedule planning, monitoring and control.

c. Construction Automation: Computer-Integrated Construction. This workshop was held at Lehigh University in April 1987 (Wilson, 1987). The goal was to set directions in exploring increased and effective automation and systems integration in the construction industry. Systems integration is required among the activities of design, construction and operation. Six kinds of issues and priorities were considered important by the workshop participants. These issues were System Architecture and Organizational Structure, Structure, Formalization and Classification of Knowledge, New Languages and Representation Techniques, Intelligent Interfaces, Designing for Automation, and Sensing and Monitoring.

Knowledge-based systems were needed to provide assistance to design tasks. Research should be directed to develop an understanding of the core knowledge and underlying structure of these tasks. Knowledge-based systems were also needed to interface computer applications and databases, translate data elements, and provide intelligent pre- and post-processors to existing algorithmic packages. Interfaces were also needed to interpret design output into construction planning.

From this workshop, it was observed that knowledge-based systems were the focus of computer-integrated construction. Knowledge-based systems were needed for the evaluation and monitoring of designs. Even though knowledge-based methodology has been explicitly identified for application in the design phase, it should be equally applicable to the planning, monitoring and control of the construction operations.

B. EXPERT SYSTEMS DEVELOPMENT

1. Knowledge-Based Expert Systems. Expert Systems and Knowledge-Based Systems both fall under the general category of Knowledge-Based Expert Systems (Harmon and King, 1985, Fenves, 1986). However, a distinction is made by Turban (1988) to distinguish between the two types of systems. The difference is in terms of how the knowledge is acquired. Expert Systems' knowledge is acquired from real human experts while in Knowledge-Based Systems, knowledge is acquired from sources other than the human experts and documented sources such as books and journals. Similarly, a system would be considered as a Knowledge-Based System as it is developed and consequently refined. When the system has reached a performance level which is comparable to the performance of human experts or better and its knowledge has been supplemented by experts' knowledge, then the system is considered to be an Expert System. However, the steps in the development process are basically the same for the two types of system. The development and uses of expert systems have been extensively reported in the literature (Karna, 1985, Karna, Parsaye and Silverman, 1986, Antonisse, Benoit and Silverman, 1987).

a. Perspective. The development of knowledge-based expert systems is one of the areas of artificial intelligence activity. Others include natural language systems (interface, communication) and perception systems (vision, speech, touch) (Rauch-Hindin, 1986). According to Feigenbaum (Harmon and King, 1985), an expert system is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. Knowledge necessary to perform at such a level, plus the inference procedures used, can be thought of as a model of the expertise of the best practitioners of the field.

Conceptually, a knowledge-based expert system attempts to model an expert and his expertise so that this knowledge is always readily available to users for the purpose of decision making, consulting, diagnosis, learning, planning, research and many more. Its applications are suitable to model tasks about which people become knowledgable and perform a lot better through years of experience. Tasks that require extensive judgement, lack formal structure and are poorly defined are well-suited to the application of expert systems.

According to Rauch-Hindin (1986), most expert systems have the capability to update their knowledge easily, have flexible problem-solving strategies, exhibit high performance in terms of their ability to solve their assigned problems correctly and have the capability to explain what they have done and why. Expert systems are limited to domain-specific knowledge rather than to general problem solving techniques. For the system to be efficient and effective, the problem domain should be specific and narrow.

Conventional computer programs are basically structured instructions that use algorithms to direct computations. They usually provide a single correct answer. Their knowledge is declarative and the system produces solutions based on calculations. Declarative knowledge is firm, fixed and formalized. In contrast, most authors including Mishkoff (1986) and Harmon and King (1985) agree that knowledge-based expert systems use search computations as well as direct computations. They enumerate possible solutions using their knowledge. Their knowledge is both declarative and procedural. Procedural knowledge is subjective, ill-codified and judgemental. It produces conclusions based on reasoning. Declarative knowledge is usually referred to as facts while procedural knowledge is normally associated with a set of instructions and rules.

b. Expert Systems Architecture. There is no absolute architecture for a knowledge-based expert system. However, based on the review of some currently available books and literature on artificial intelligence and expert systems (Hayes-Roth, Waterman and Lenat, 1983, Weiss and Kulikowski, 1984, Rauch-Hindin, 1985, Linder, 1986, Levine, Drang and Edelson, 1987), a generic knowledge-based expert system should consist of at least these two major components:

the knowledge base, and

the inference engine.

Other minor components include the user interface, the explanation subsystem and the knowledge acquisition subsystem. Many other variations are possible as the system varies from a high level language to a low end development shell. The characteristics of these major components are by no means exhaustive.

(i) Knowledge Base: The knowledge base contains all the knowledge about a certain problem domain which has been entered or extracted from the human expert. This knowledge is a collection of facts (data and information) and rules (heuristics and procedures) gathered by a knowledge engineer directly from the expert and through observations and publications. In some cases, the expert himself is the knowledge engineer. The expert is supposed to have a high level of performance in the domain being captured. The knowledge base is separated from the inference engine. This allows the flexibility in updating the knowledge and to add knowledge incrementally. It also allows substituting a new knowledge base while retaining the same inference engine for a new problem domain.

Knowledge representation is the method of encoding or structuring the knowledge (data, information, heuristics and procedures) and its relationships in the knowledge base. The most common conceptual representations of the procedural knowledge are in the form of rules, semantic networks and frames. These representations can be used alone or in conjunction with the other two to build the system. Within the knowledge base, individual rules, semantic networks and frames are modularized.

Rule-based representation is also known as the production system (Harmon and King, 1985). It is of the form IF a set of conditions (expressions) are satisfied THEN a set of consequences can be inferred. The IF expressions consist of the object-attribute-value composition, followed by a logical operator (and/or). Through the implementation of the rules, the qualitative and quantitative knowledge used in decision making are represented. When representing qualitative knowledge, certainty factors (confidence levels) may be assigned to the consequences. Knowledge that is to be translated into rules can be entered into the system knowledge base by typing into a text file or interactive rule-editing memory, depending upon the kind of tools used.

A semantic network is a collection of nodes connected together by links or arcs (Harmon and King, 1985). The nodes represent the object (actions, events) or the value (descriptors). The links between the nodes represent the attributes (predicates) that define the relations between one node (object) and the other node (value). It is of the form is-a, has-a and many more similar relations. The network enables a knowledge system to infer information about the object as described by the value through the attribute relationship. This inference relationship establishes an inheritence in the network. It refers to the ability of one node to inherit the characteristics of other nodes higher up in the hierarchy that are related to it. Network representations are flexible allowing new nodes and links be defined as needed. They are useful to represent knowledge in domains that use well-established taxonomies to simplify problem solving.

A frame is a description of an object that contains slots of related knowledge associated with that particular object (Harmon and King, 1985). The slots may contain attributes, rules, procedural attachments, instructions or subprograms. The attributes store values and the instructions infer new knowledge into the slot. The subprograms point and link the slots of one frame to the other frames. This link creates an hierarchy of relationships between frames and other frames or subframes. Since related knowledge is grouped together, frames representation structures knowledge in a more organized and manageable manner that mimics the way experts remember and reason objects. It is particularly useful for specifying all the important features of an object.

(ii) Inference Engine: The inference engine is a program that uses the knowledge base and the problem representation to draw logical conclusions. It performs two major tasks. First, it provides access to the knowledge base, examines the existing knowledge and adds new knowledge when possible. Second, it decides which portion of the knowledge base to apply and the order in which inferences are made. Inferences are made through reasoning and justification. The inference engine therefore conducts a consultation with the user. The conclusion can be deduced in a number of ways depending on the structure of the inference engine.

The inference engine structure determines the reasoning methods and the control strategies of the system, using the inference mechanism and the control mechanism respectively. The inference structure depends on both the nature of the problem domain and the way knowledge is represented and organized in the base.

The inference mechanism determines the inference strategy used in the system. It contains the reasoning methods that determine how to interpret and manipulate the knowledge. The most common methods of inference strategy are the forward chaining and the backward chaining. A control mechanism within the inference engine organizes and controls the strategies taken to apply the inference process. The control mechanism contains the general problem-solving knowledge.

In a forward chaining or data-driven strategy, the premises of rules are examined to see whether they are true or not, given the information on hand. If they are true, the conclusions are added to list of rules, and the system examines the next rule. Then the inference mechanism will make the appropriate assertions. A goal is reached when no more rules are left to be examined. This strategy is appropriate for data-driven problems in which a substantial accumulation of facts is available and possible conclusions are progressively validated based on supplied information.

If possible outcomes are known, then a backward chaining or goal-driven strategy is used. In this strategy, an initial hypothesis as to the validity of a conclusion or goal is selected for evaluation. Inferencing starts with the goal and works backwards through the subgoals in an effort to choose an answer. The reasoning process attempts to prove the validity of the goal by successfully testing whether the prerequisite conditions are true or not. The conclusion is reached when the prerequisite conditions are satisfied. This strategy is dependent on the feasibility of making an initial hypothesis.

2. Civil Engineering Applications. In recent years, expert systems have attracted many researchers in civil engineering seeking a solution for problems that were previously insoluble by conventional computer programming. This is evidenced by the publications of various research papers and proceedings devoted to expert systems development (Karamouz, Baumli and Brick, 1986, Kostem and Maher, 1986, Lenocker, 1986, Will, 1986, 1988, Palmer, 1987, Maher, 1987). In civil engineering research, knowledge-based expert systems provide an environment to conduct investigations in areas related to construction engineering and management, structural engineering, geotechnical engineering, water resources engineering, environmental engineering and transportation engineering. Various researchers have described how expert systems could be used to prototype civil engineering applications (Maher, 1988, Rasdorf and Parks, 1986, Rasdorf and Wang, 1986, 1988, Wong, Dong, Boissonnade and Ross, 1986, Cohn, Harris and Bowlby, 1988).

Potential applications of knowledge-based expert systems in civil engineering fall under the following related areas (Fenves, Maher and Sriram, 1984a, 1984b).

a. Interpretation:

The system may be used for interpretation of existing conditions such as the structural and load capacity of structures based on observations, and for the interpretation of traffic conditions and demands for transportation improvements. It may also be used to interpret field conditions in geotechnical engineering. As an intelligent modeling tool, the system can serve for problem identification and in result interpretation where powerful analytical tools are available.

b. Diagnosis:

In failure diagnosis, the system may be used to identify the most likely cause of failure for landslides, rockslides, building failures and construction schedule failures. It may also be used to perform remedial diagnosis of existing civil engineering systems to determine potential failures and dysfunctions.

c. Monitoring:

The system may be used for performance and process monitoring. With microprocessors and sensors providing input to expert systems, real-time monitoring may be performed on structures, foundations and construction equipment. In monitoring design and construction processes, the system is used to control costs and durations.

d. Planning:

In project planning, the system may assist in the planning of design and construction projects with many possibilities to consider. It may be used in macro-planning of large capital projects where various requirements are to be considered.

e. Design:

Knowledge-based expert systems could be used for the initial synthesis of system function or configuration, selection of initial design parameters, modification and redesign of unsatisfactory project.

In water resources engineering, expert systems have been built for snowmelt runoff modeling and forecasting (Engman, Rango and Martinec, 1986), reservoir management and planning (Kangari and Rouhani, 1986), advice for the QUAL2E water quality model (Barnwell, Brown and Marek, 1988), parameter estimation for the USGS modular groundwater model (Lennon, Mikroudis, Rumbaugh and Tanem, 1988) and hydraulic data fusion (Scarlatos, 1988).

At present significant prototype systems have been built for applications in structural engineering related areas. Some of these systems were reported by Evan and Mulert (1986), Kostem (1986), Krauthammer and Kohler (1986), Naeim and Martin (1986), Adeli and Balasubramanyam (1988), Jones and Saouma (1988) and Ovunc (1988). Among the more successful prototypes are HI-RISE (Maher, 1984), SACON, SPECON, HICOST, DESTINY, SICAD and KADBASE (Rehak, Howard and Sriram, 1986, Howard, 1988). These prototypes represent the components of an integrated knowledge-based structural engineering system. A similar architecture may be developed for an integrated knowledge-based expert system in construction engineering and management.

3. Construction Engineering and Management Applications. Since most construction engineering and management activities are not well-defined and are ill-structured, experimentation with expert systems through the formalization of concepts and processes may lead to the development of related theoretical frameworks (Fenves, Maher and Sriram, 1984). As the determination of these theories and principles by conventional research may well lie ahead in the unknown future, expert systems may become a stepping stone towards the incremental discovery of the theory and principles for construction.

a. Research Status. In construction engineering related areas, knowledge-based expert system prototypes have been developed for pump repair, well selection, change order evaluation, quality control, claim analysis, construction risk analysis, construction process design, duration estimation, machine diagnostic, power system operations, welding procedure selection, welding defect analysis and others (Kangari, 1986b, Finn and Reinschmidt, 1986). Other systems include an expert system for risk assessment of concrete dams (Frank and Krauthammer, 1986), a knowledge-based consultant for construction inspection (Kangari, 1986c), an expert system for selecting bid markups (Ahmad and Minkarah, 1988), an expert system for the management of low volume flexible pavements (Aougab, Schwartz and Wentwork, 1988), an expert system for the evaluation of rail/highway crossings (Faghri, Joshua and Demetsky, 1988), CONSITE: a knowledge-based expert system for site layout (Hamiami and Popescu, 1988), DISCON: a differing site conditions claim advisor system (Kraiem and Diekmann, 1988) and an expert system for contractor prequalifications (Russell and Skibniewski, 1988).

A recent survey by Ashley and Levitt (1987) has indicated that construction planning, engineering, management and maintenance were receiving increasing attention as potential application domains for knowledge-based expert system. In their report, the authors have described ten systems that were currently under development. These systems included: (1) CPO-ES, an expert system designed to systematize some of the planning processes for construction project organizations, (2) ICT, time estimating system to provide time and cost estimates for projects whose scope was very loosely defined, (3) an expert system for repeating construction project successes that uses the developed knowledge base and other relevant data to seek opportunities for improvement in new projects, (4) IRIS, an intelligent construction risk identification system designed to help construction professionals with the first important task of risk identification, (5) SITEPLAN, a layout of temporary construction facilities that designs a siting plan and updates the plan continuously as project time progresses, (6) IPMS85/2, a system that performed the evaluation of project personnel based on progress data available from a typical project time/cost monitoring system data base, and (7) Maintenance Advisor for old elevators, a system that encodes much of its knowledge about the diagnosis and repair of older-model elevators for use by less-experienced mechanics. Three other systems by Kangari (1986), O'Connor, De La Garza and Ibbs (1986), and Levitt and Kunz (1985) will be described in greater detail later.

A prototype expert system for masonry construction duration estimation, MASON, was described by Hendrickson, Martinelli and Rehak (1987). This prototype makes estimate of masonry construction time and provides a variety of explanations and advisory facilities. The knowledge is limited to concrete block and brick construction. An expert system for cost estimating was reported by Biegel, Bearden, Dickerson and O'Donnell (1986). Their system, PAINTER, is a rule-based cost estimating program for house painting. The program was written in a version of C language that runs on IBM PC microcomputers.

b. Systems Under Development. For construction management applications, current research focusses on the planning, scheduling, costing, monitoring and controlling of the construction process. The integration of these otherwise isolated processes could result into an efficient and effective project planning and control system. However, most of these systems are still in the developmental and conceptual stages. These systems are described below.

(i) Monitoring And Control Systems: One of the earlier developments in construction management was a system for construction project monitoring. McGartland and Hendrickson (1985) have introduced the potential of knowledge-based expert systems for cost control, time control, and purchasing and inventory control. However, at the time their report was published, the proposed system had not yet been developed. Only conceptual ideas were presented. For cost and time control, the proposed system would analyze the times associated with each construction activity and also verify the values related to percent complete and expenditure to date. For application in purchasing and inventory control, the system would aid project managers to determine the appropriate levels of inventory and to minimize overall material costs. This project monitoring expert system would be executed after the project network was run through a CPM or similar project scheduling system. All the activities related to the project and the initial schedule were prepared and input by the user.

Nay and Logcher (1986) described the proposed operation of an expert computer system designed to analyze causes of construction project work package variance from planned objectives. However, the system had not been implemented at the time their paper was reported. Only the conceptual design of the proposed expert system was described. The perceived system was designed to analyze construction project risks. The system assumed that work packages and project plan had been defined, the project was in progress, and the performance review data was being collected.

Another application of expert systems in the area of construction monitoring was in decision-making and risk analysis. This risk management prototype expert system was developed by Kangari (1986) for decision making under uncertainty. The system was developed using INSIGHT 2, a microcomputer knowledge engineering tool for rule-based representation. The system was designed to help contractors to identify uncertainty factors and provided a risk index for the overall project. The knowledge base contained a general description and classification of construction risk, in terms of hypotheses, data and intermediate reasoning concepts. Project risk was classified into categories relating to project design, contract language and actual construction. During consultation, the user would provide input concerning construction work conditions, sources of uncertainty, confidence levels, cost and economic data, type of contract and information about subcontractors. The system was expected to provide management with the capability to monitor projects more effectively through managing and forecasting the uncertainty factors.

(ii) Scheduling Systems: Two separate reports were available in this problem area. Levitt and Kunz (1985) have developed a knowledge-based system for updating engineering project schedules. Their technique was used to modify activity lists and schedules using explicit knowledge of a particular construction domain and project management. They have demonstrated the use of a knowledge-based system to represent in the computer much of the knowledge of construction and project management. This knowledge was normally used by the project manager to create the initial schedule and update activity schedules as the project progressed. The knowledge and data derived from activity completions could explain the basis for schedule updates and the impacts on activity durations. A prototype model was built for the design and construction of an offshore concrete gravity type oil drilling platform. The platform model was built using the KEE system software development environment on Xerox 1108 dedicated AI workstation. However, the system was unable to generate activities and design network logic for particular tasks in this model. Initial schedules were provided as input to the system by the user before consultation.

In another development, O'Connor, De La Garza and Ibbs (1986) have developed an expert system for the analysis and evaluation of construction scheduling networks. This construction schedule analysis prototype was developed to help project managers analyze and evaluate initial as well as progress construction scheduling networks. The system combined both the rules and frames architecture and was implemented on a microcomputer-based expert system shell called Personal Consultant Plus from Texas Instruments. The knowledge base was provided with scheduling decision rules and construction knowledge. The initial schedule or the project progress data were provided by the user and were first processed by Primavera, a commercial microcomputer-based project management system. The data output from this software was automatically loaded onto dBASE III, a microcomputer-based relational database management system. Data from this database system, user supplied project-specific information and the knowledge base provided the necessary input to the expert system shell. A statistical module was incorporated to contrast project progress data against the original project plan. Since the creation of an initial schedule was not part of the system, the authors suggested that future research should look into the automatic generation of construction networks.

(iii) Planning Systems: The development of a knowledge-based expert system for construction planning was reported by Hendrickson, Zozaya-Gorostiza, Rehak, Baracco-Miller and Lim (1987). Their perceived system is a knowledge-intensive expert system that generates project activity networks, cost estimates and schedules. These includes the definition of activities, specification of precedence, selection of appropriate technologies, and estimation of durations and costs. Their prototype, CONSTRUCTION PLANEX, is a knowledge-based system that emulates the complete construction planning process. The system is implemented in KNOWLEDGECRAFT on a Texas Instruments EXPLORER computer. This system was developed by a group of researchers at Carnegie Mellon University.

The system has three essential parts: (1) the Context, (2) the Operator Module, and (3) the Knowledge Base. The Context contains information on the particular project being considered such as the design elements, resources, element activities and project activities. The Operator Module contains operators that create, delete or modify the information stored in the context. The Knowledge Base contains a large number of knowledge sources represented by rules, heuristics and calculation functions that provide relevant information to the Operators. However, their present prototype is not capable of cost estimating. The current application is to plan modular high-rise buildings and the knowledge sources are coded to perform technology choice, duration estimation, precedence setting and activity identification in the domain of office buildings.

Another prototype related to construction planning was reported by Navinchandra, Sriram and Logcher (1988). This work was undertaken at Massachussetts Institute of Technology. Their system GHOST is part of a larger integrated knowledge-based environment for construction planning called CONPLAN. The system does not use its knowledge to build a construction network but only to criticize it. The prototype takes a set of activities as input and produces a schedule as output by setting up precedents among the activities.

GHOST knowledge base is made up of four knowledge sources called critics. These knowledge sources are: (1) Knowledge about the physical nature of the work, (2) Knowledge about construction, (3) Knowledge about inheritance and hierarchical refinements of the network, and (4) An operations research technique that checks for redundancy of the network. The prototype starts with a network with all the activities in parallel and modifies it to produce a temporally better network. This algorithmic approach is used uniformly over all stages of plan generation.

C. RESEARCH EFFORTS IN SCHEDULE PLANNING

Hendrickson, Zozaya-Goristiza, Rehak, Baracco-Miller and Lim (1987) and Navinchandra, Sriram and Logcher (1988) have reviewed the literature of artificial intelligence that addressed the general problem solving of planning. Planning has been a part of artificial intelligence research since the early 1960's. Early work in planning was performed on a system called NOAH. Other systems include NONLIN, DEVISER and MOLGEN. Scheduling systems ISIS and CALLISTO developed a general system of activity representation for job-shop scheduling. A conceptual design for a knowledge-based system as applied to production planning problem was described by Duchessi (1987). Bradley, Buys, Elsawy and Sipes (1985) developed a microcomputer-based intelligent project planning system to assist managers in planning the life cycle for automating their information systems. Another prototype expert system, Interactive Planning Assistant (IPA), was reported by Levene (1987). The scope of functionality for the IPA was defined to be applicable to project planning, process planning and job-shop scheduling.

These artificial intelligence-based planning systems offer some useful conceptual tools that were not without significant limitations. This is because (Hendrickson, Zozaya-Gorostiza, Rehak, Baracco-Miller and Lim, 1987),

1. Construction requires numerous distinct tasks for completion,

2. Construction planning involves the selection of appropriate resources to apply,

3. Construction planning has to consider time constraints and cost and resource trade-offs between technology and activity duration,

4. Efficient algorithmic scheduling tools may be required since construction schedules include a large number of activities,

5. Construction planning is highly knowledge intensive. Therefore a different architecture is required for construction schedule planning systems.

Major research efforts in construction planning and scheduling are taking place at Carnegie Mellon University (CMU) and Massachusetts Institute of Technology (MIT). Their systems CONSTRUCTION PLANEX and GHOST respectively, have been described earlier. These systems were developed as a long term project undertaken by a group of researchers to represent a part of the larger integrated construction management system. However, their development is still in its infancy.

CONSTRUCTION PLANEX creates construction activities from geometric information about individual design elements. The program then develops the network. GHOST does not build the network but only criticizes it. In my proposed prototype, the system guides the user in creating the construction activities. These activities are described in plain English language rather than in geometric information. However, all these three systems have one thing in common. The output from each system is a construction schedule that specifies precedence relationships among activities.

The search techniques employed by CONSTRUCTION PLANEX and GHOST were not reported in the literature. However, my system is developed based on a data structure that uses three heuristic algorithms to derive the final precedence schedule. My system is implemented on a microcomputer while the other two systems are implemented on specialized AI machines. Even though my system represents a portion of the major work undertaken by CMU and MIT, it mimics the experts scheduling approach. The system is designed to be interactive.

III. RESEARCH METHODOLOGY

A. OVERVIEW

This research represents an initial investigation of the engineering design and construction operation system's integration. This integration is achieved through building a knowledge-based system. The proposed system was designed and built by the researcher as a knowledge engineer.

Even though a complete system for construction operations management would require the consideration of all the four phases of planning, scheduling/costing, monitoring and control with respect to cost and time, this proposed system focuses only on schedule planning as shown in Figure 6. It represents a methodology for devising a workable scheme of construction operations which is designed to accomplish the completion of construction in an efficient and effective manner. Schedule planning is concerned with the definition of construction tasks and the sequencing of these tasks into a logical construction schedule. An initial construction schedule would be generated from the system's output.

The scope of this research is dictated by the expected performance of the system and the intended users of the system. This may be described by the type of information required as an input to the system, the knowledge of the user and the sophistication of the output provided by the system. This architecture was influenced by the domain encoded into the knowledge base during system development.

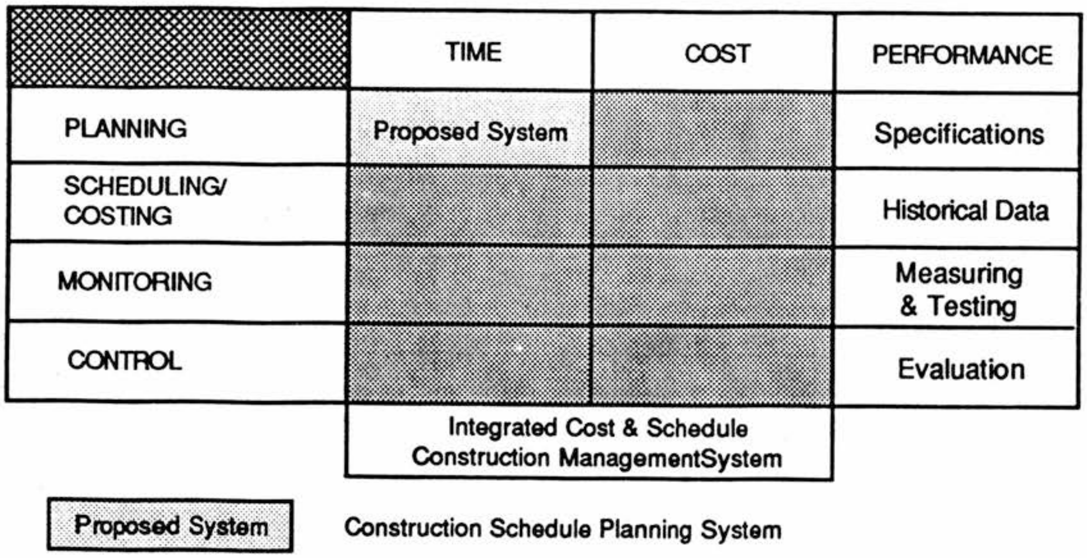

Figure 6. Construction Management Matrix

The input information was derived from engineering designs that have been completed to a stage that the project was ready for construction. The engineering design outputs consist of construction specifications, engineering drawings and data that provide a description of the project. For the current prototype, the users are expected to be conversant with the general terms of construction and building technology. It would be advantageous for the users to have some rudimentary knowledge of similar project designs and construction. However, these restrictions could be relaxed if more system development time were available to code the knowledge base with pedagogic instructions. This engineering design information would be requested from the user during interaction with the system.

The output provided by the system would depend on the quality and quantity of domain knowledge being coded into the knowledge base. For this initial system, the output will address construction scheduling. Therefore the knowledge to be coded into the system covers the knowledge of activity planning and scheduling. The output format depends on the capabilities of the knowledge system development tool selected for prototyping.

B. INDUSTRY INTERACTION

As part of the system development process, the assistance of two construction firms in St. Louis, Missouri area was solicited. The purpose of this interaction was to discuss the techniques employed by the companies' experts when preparing construction schedules, to observe how practitioners in industry prepared their construction schedules and to examine some of their past construction schedules in an effort to develop a construction schedule planning model and to prototype a typical knowledge-based construction schedule planning system.

The two construction firms visited were J.S. Alberici and McCarthy. Both companies were listed in The Top 400 Contractors which appeared in the ENR annual survey (Hannan, 1987, 1988). J.S. Alberici ranked number 47 in 1986 with total contracts of $480 million and number 48 in 1987 with total contracts of $506 million. Its construction specialties were in building, manufacturing, power, airport, highway/bridge, process and marine. McCarthy ranked number 18 in 1986 with total contracts of over $1 billion and number 33 in 1987 with total contracts of $806 million. Its construction specialties were in building, manufacturing, airport, highway/bridge and design. Two visits were made to J.S. Alberici and one visit to McCarthy, all to their scheduling departments. These were supplemented with a number of telephone interviews.

No questionnaires were distributed to these practitioners in an effort to solicit the knowledge. However, they were asked to outline the steps they took and the factors they considered when preparing a typical construction schedule. As the researcher himself is a civil engineer with prior knowledge in construction, this interviewing process ran smoothly. At Alberici, the Fort Leonard Wood Engineering School and St. Louis University Hospital projects were used as the basis for discussion. At McCarthy, the projects discussed were Fair Oaks Commerce Center, Winchester Medical Center and Mountainside Hospital. The discussions were centered around the structural, architectural, mechanical and electrical aspects of scheduling. Due to the confidentiality of the companies concerned, no cost aspects were revealed. However, these projects were large enough to warrant detailed planning.

Through these discussions, a construction schedule planning model was initiated. Pertinent scheduling information from their previous scheduling printouts was adapted into the prototype system knowledge base. Even though the prototype knowledge base was later adapted to the problem domain provided for use during system's evaluation, the knowledge acquired from these visits provided the basis for structuring the rules and facts related to scheduling a reinforced concrete building. However, to prototype a more comprehensive schedule planning system, more of such visits would be required in order to develop a high utility system.

From these visits, it was observed that no standard practice was adopted and made available to construction schedulers. The schedule planning techniques currently practiced by these schedulers were inconsistent, vague and idiosyncratic. They were meaningful for a particular scheduler but were not appropriate for general use. Therefore, a standardized system needs to be developed in order to provide a construction schedule which is comprehensible to all the practitioners in the industry concerned.

C. RESEARCH DESIGN

This research followed the procedures of building a typical knowledge-based system. It consists of five stages characterized as identification, conceptualization, formalization, implementation and testing (Waterman, 1986). However, for this construction schedule planning system development, the research is based on the design as shown in Figure 7. The milestones involved are Identification, Modeling, Prototyping, Testing, Evaluation and Evolution. It is an iterative process which requires various refinements to each step. This design philosophy is consistent with the above five stages. This approach is general enough that it might be used to develop any schedule planning system in different domains.

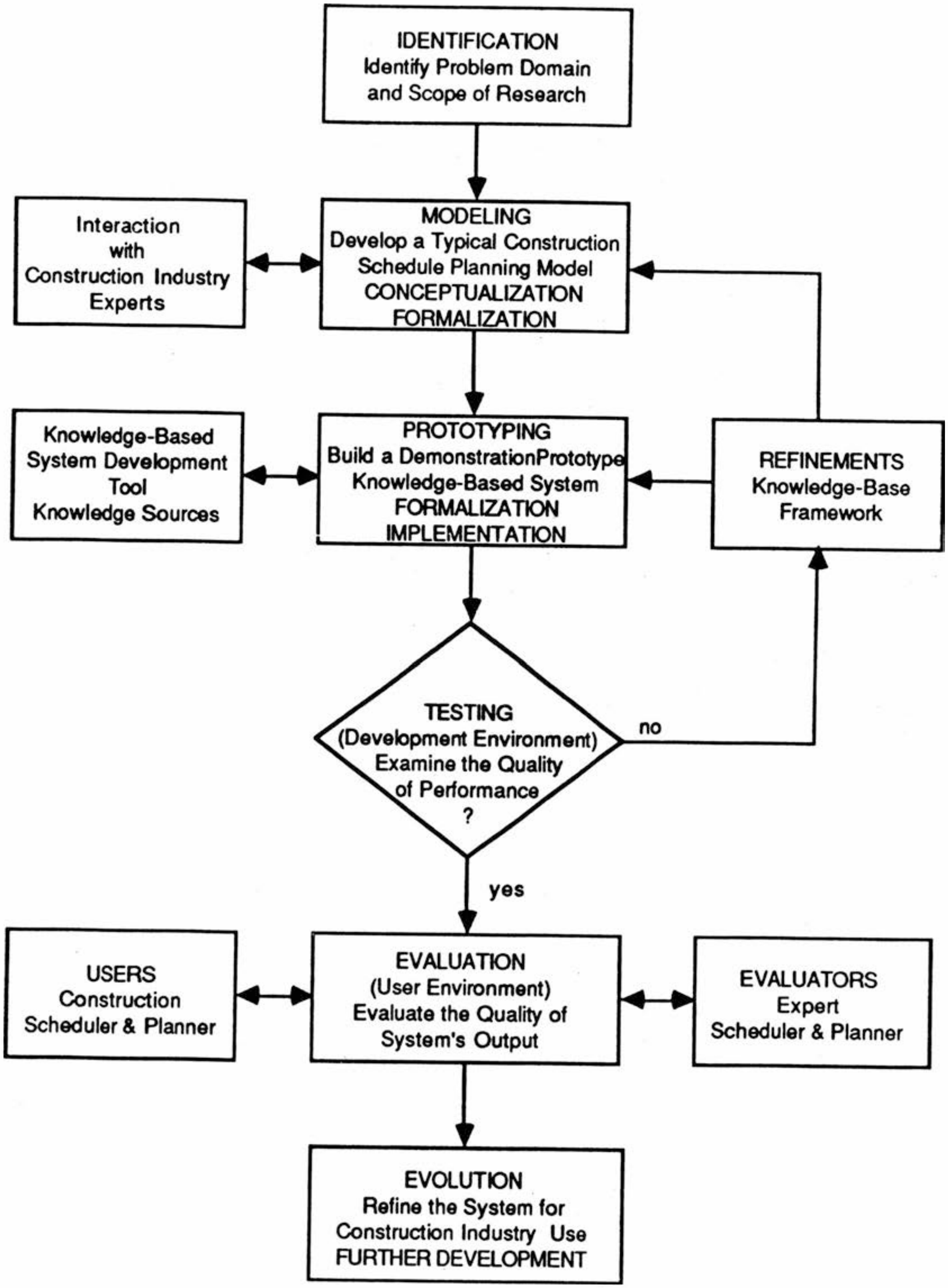

Figure 7. Research Design

1. Problem Identification. The first step is to identify the problem, its scope, how knowledge would be acquired, the sources of expertise and the resources needed. The problem was identified through a literature search and the researcher's own work experience. As mentioned above, the focus for this proposed system was to produce an initial construction schedule. The resources needed are predominantly the knowledge sources and the computing facilities. A microcomputer-based hardware and software was used in this development.

In an attempt to keep the problem domain narrow, this system was restricted to a typical building construction. A building construction consists of the tasks needed to complete the superstructure, which may be made of wood, steel and concrete construction, the substructure, which includes foundations, internal finishes and architectural work, and finally the sitework which includes landscaping, roads and any other external services. The superstructure in this research was limited to low-rise buildings initially, since the construction operations for high rise buildings are significantly different in terms of technology and equipment and it is important to keep the initial scope within feasible limits.

2. Development Procedure. Building a knowledge-based system requires the transfer and transformation of problem solving expertise from some knowledge sources to a program. This process of extracting knowledge from a source of expertise and transferring it into a knowledge system program is called knowledge acquisition. Potential sources of knowledge include human

experts, publications, textbooks, databases and one's own experience. The system was developed through modeling, prototyping and testing. This approach has been used by Willis, Huston and d'Ouville (1988) in information systems development. The outcome of this development was a prototype system that could be evaluated to determine its feasibility.

a. Conceptualization. The modeling phase conceptualized the schedule generation process and formalized it into a knowledge system framework. This modeling process was used to identify the variables and processes related to constructing a construction schedule. It was conceived by soliciting the practitioners in the construction industry as described above and studying the scheduling techniques as reported in various publications. This model was further refined as the system was prototyped and evaluated. A generalized model for construction schedule planning system was developed.

b. Implementation. The prototyping phase formalized the above model into a knowledge base framework and mapped out construction scheduling facts and rules into a knowledge system tool environment. The system needed to be flexible enough to provide preliminary construction schedules for the domain being captured. The system was designed to be interactive. The structure of the prototype system was based on the model developed earlier. Prototyping a knowledge-based system mainly involved coding the facts and rules into the shell environment.

The emergence of personal computers and wide availability of project management softwares have attracted more engineers and managers to use computer-based project management techniques (Davis and Martin, 1985). In this research, it was decided that the knowledge-based system prototype would be developed on a microcomputer. This choice was made because it was felt that microcomputers such as the IBM Personal Computers, IBM Personal System/2 and the compatibles are widely available at relatively low costs. Since this construction schedule planning system would be directed towards medium-sized contractors who have little or no access to specialized AI machines and mainframes, this choice seemed appropriate. While the feasibility of a construction planning system implemented in specialized AI machines has been demonstrated (Hendrickson, Zozaya-Gorostiza, Rehak, Barocco-Miller and Lim, 1987), it was anticipated that the desirability of knowledge systems implemented on microcomputers would be welcomed by the numerous medium-sized contractors in the construction industry world-wide.

The development of new knowledge-based systems is changing rapidly due to the ease of construction and time required, resulting from improved knowledge system building tools (Gevarter, 1987). Knowledge system tools for civil engineering applications have been reviewed by Ludvigsen, Grenney, Dyreson and Ferrara (1986) and Ludvigsen and Grenney (1988). These reviews revealed that knowledge system tools delivered on microcomputers are suitable for civil engineering applications. Furthermore, it was believed that the recent proliferation of knowledge-based systems was due to the increased availability of knowledge system development tools that could be built and delivered on microcomputers (Ortalano and Perman, 1987). A study by Wigan (1986) also indicated that many civil engineering applications including construction applications will be satisfied by current tools including the M.1 by Teknowledge (1985). He suggested that the attention of potential users of knowledge-based system should be directed towards the definition, extraction and implementation of the knowledge base rather than the tool itself.

This proposed system was therefore implemented in M.1, a microcomputer-based knowledge system software tool. This expert system shell was developed by Teknowledge (1985). This tool has been licensed to UMR Computer Science Department and has been used for instructional purposes. It was believed that this tool could effectively build a construction planning system since the knowledge of planning was based on heuristics which could be represented by facts and rules. Furthermore, the purpose of developing this prototype was to illustrate a modeling concept rather than development of a commercial production standard.

M.1 (Version 2.0, 1986) is implemented in C programming language. It provides a powerful and efficient development environment. The tool also has the utility to deliver the system for the production environment whereby the user has no access to examine the knowledge base. It has the capability to integrate with large databases of conventional software and the external function interface capability allows it to access procedures written in C or assembly language. The knowledge base could contain up to 1000 rules and facts. The representation of knowledge allows for the encoding of uncertain knowledge through uncertainty factors. The inference engine uses a modus ponens mechanism, which is a rule to derive new facts from rules and known facts (Harmon and King, 1985), and a goal directed depth first control to reach conclusions. This type of reasoning process is known as backward chaining.

c. Testing. The prototype was tested in the development environment and later tested in the user environment. The purpose of testing was to establish whether the knowledge representation scheme was adequate and to determine the accuracy of the embedded knowledge, within the presumed problem domain. To achieve this, the quality of output provided by the prototype system during development was iteratively evaluated by the researcher. This involved comparing the output with past schedules prepared by practitioners in construction industry.

3. Evaluation Procedure. After the demonstration prototype was developed and tested based on the expertise of the researcher and with the input provided by the industry practitioners, a laboratory experiment was conducted to run test cases based on actual engineering designs. The purpose of the experiment was to assess the quality of scheduling output provided by the system and the usefulness of the model as a decision-making aid. This experiment will be described in detail later.

The results of the evaluation suggested refinements to the knowledge-base structure and to the formalisms for the schedule planning model as developed by the researcher. They also confirmed the feasibility of using knowledge engineering technology in construction schedule planning system development and user environments.

D. SYSTEM EVOLUTION

Knowledge-based systems evolve through various development stages, depending on the quality of system's performance and the intended users. Waterman (1986) identified the system's stages as the demonstration prototype, research prototype, field prototype, production model and commercial system. The characteristics of these stages are shown in Table I. This proposed schedule planning system was developed through the demonstration and research prototypes. Further development would refine the system towards construction industry's use.

Table I. EVOLUTION OF EXPERT SYSTEMS

(Waterman, 1986, Page 140, Table 12.1)

Development Stage	Description
Demonstration prototype	The system solves a portion of the problem undertaken, suggesting that the approach is viable and system development is achievable
Research prototype	The system displays credible performance on the entire problem but may be fragile due to incomplete testing and revision
Field prototype	The system displays good performance with adequate reliability and has been revised based on extensive testing in the user environment
Production model	The system exhibits high quality, reliable, fast, and efficient performance in the user environment
Commercial system	The system is a production model being used on a regular commercial basis

IV. SYSTEM DEVELOPMENT

A. MODELING

A major step in system development is to conceive a working model that best represents the construction schedule planning process. This model cannot be conceptualized and formalized in a single step. Instead, it is developed steadily through a number of prototype iterations. Ultimately, a generalized model for construction schedule planning system is evolved. This model is shown in Figure 8 and Figure 9. This conceptual model consists of two parts,

1. Work Breakdown
2. Precedence Relationships

The basic features of the model are: (1) breakdown of the basic activities into horizontal and vertical modules, (2) breakdown of the parent activities into children activities based on a structured hierarchy of activities, (3) examination of the activities for appropriate level of detail, (4) sequencing of the tasks based on a formalized precedence relationship, (5) checking of the tasks for precedence conditions, and (6) identification and removal of redundant relationships.

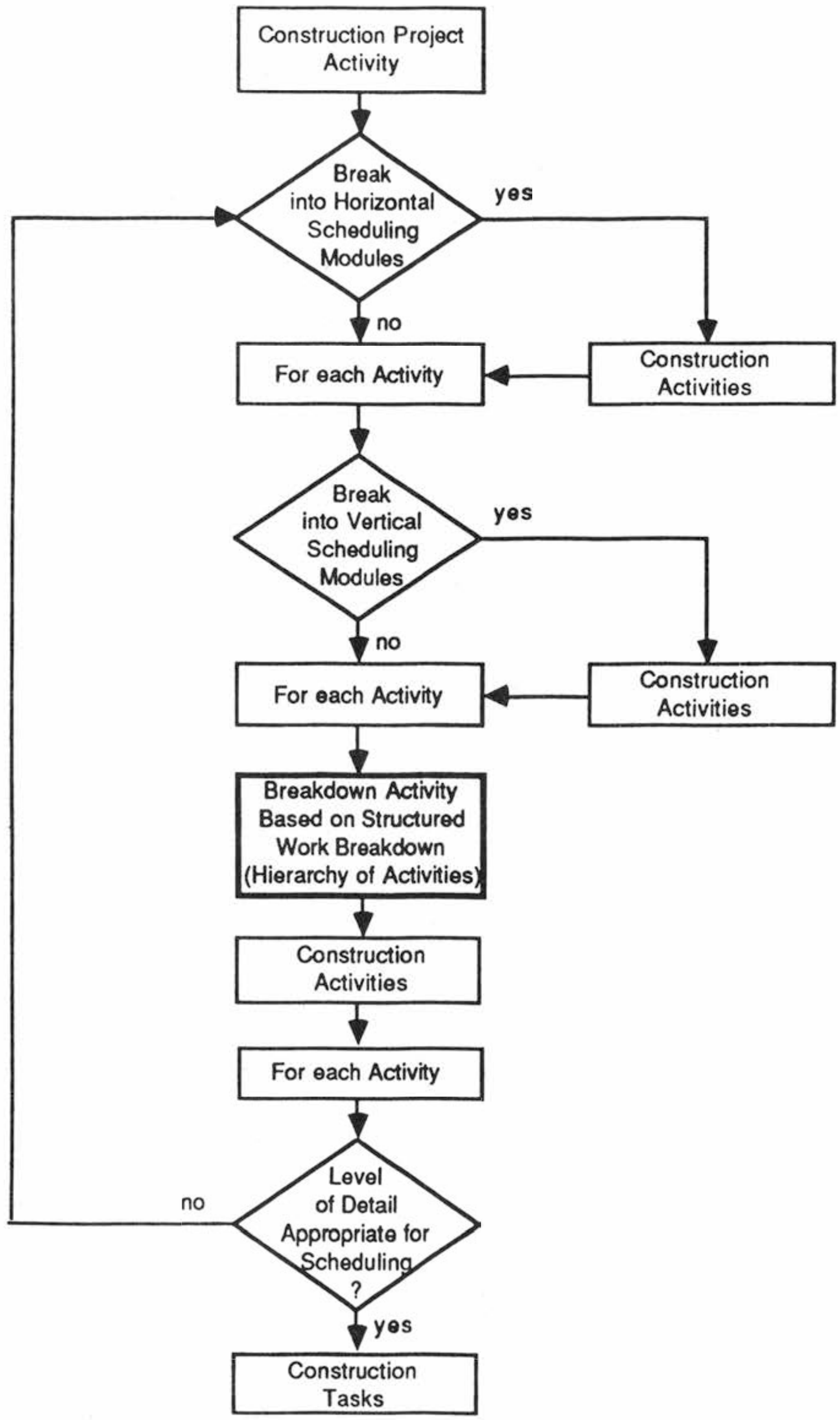

Figure 8. Work Breakdown Model

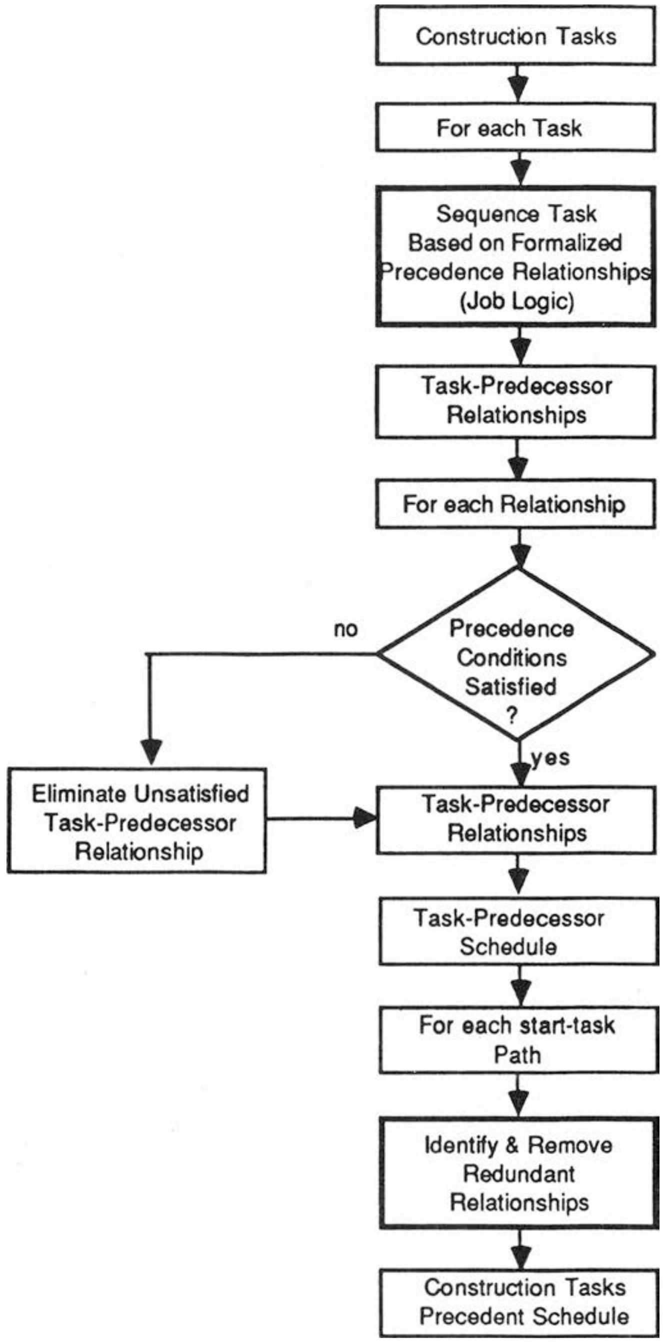

Figure 9. Precedence Relationship Model

1. Work Breakdown. Work breakdown is the identification of work activities that results in the construction and completion of work elements. These work activities are represented in a hierarchy that reflects the different levels of users. These users are the management personnel at organization, project, operation and task levels as described earlier. The model requires these activities to be structured for the needs of the lowest level user that the system is designed for. However, the model enables the system to generate activity breakdowns for all user levels higher up in the hierarchy by summarizing up these lowest level activities (Datz, 1986). This concept has been described by Kapur (1978) and Datz (Kerridge and Vervalin, 1986).

This breakdown decomposes the project into various activities. Project activities can be further broken down into more detailed activities. The higher level activity is called a work component while the lower level activity is called a work element. An activity is a description of work operation that would consume time and one or more resources of labor, equipment and material. Basic activities are described by the type of action to be performed (example: build), the characteristic of the work component (example: concrete), the name of the work component (example: column) and the name of the work element where action is to be performed (example: footing).

The lowest level activity considered during a schedule planning session is called a task. Thus, activities can be broken down into tasks that would be appropriate for any management level desired. An activity that is considered to be a task for a particular management level should be broken down further before it can be considered as a task for another management level which is lower down in the hierarchy.

The concept of work breakdown is therefore represented by three task generation stages as follows,

a. Scheduling Module Breakdown

b. Work Breakdown Structure

c. Level of Detail

a. Scheduling Module Breakdown. The purpose of the scheduling module breakdown is to break construction activities into horizontal and vertical component activities that would be suitable for scheduling the construction operations. This breakdown is essential mainly because of the difference in physical locations of the same activity involved when actual construction is undertaken. By decomposing the activities into different modules, a standard approach for schedule planning could be managed for all project sizes.

Activities are therefore completely identified by means of their horizontal and vertical locations together with their basic description. The structure of the basic activity description has been described earlier. The location needs to be specified since many activities are derived from the same basic activity description, the only difference being their locations. These location specifications are unique for each activity. A typical example of their identification is shown in Figure 10. The activity derived from this breakdown can be scheduled independently from other activities of the same basic description. These two activities normally have an implicit precedence relationship.

Location			Activity Description			
Horizontal	Vertical	Horizontal	Action	Characteristic	Component	Element
			Build	All works related to	Project	Construction
B1	3F	NW	Place	Concrete	Column	Reinforcement

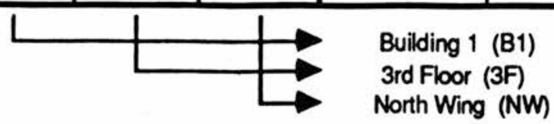

Figure 10. Activity Identification

In the horizontal scheduling module breakdown, the activity is broken down into subactivities because of distinct horizontal location and the constraints on resources. This situation arises because a basic activity could involve a huge amount of work at large locations. Therefore, it would be necessary to segment this activity into smaller quantities of operation, each representing a unique activity of the same kind. These activities could be scheduled sequentially one after the other. For example, if an activity called "pour concrete floor slab" would involve a very large floor space and the resources are limited, then it would be necessary to schedule this activity into "pour concrete floor slab - north section", "pour concrete floor slab - east wing" etc. kinds of activities.

In vertical scheduling module breakdown, the activity is broken down into subactivities because of distinct vertical location and the constraints on the physical implementation of the activities. For this situation, a basic activity could impose constraints to its work operation that would require segmenting the activity into a number of operations, each representing a unique activity of the same kind. For example, if an activity called "pour concrete floor slab" would involve different floor levels of a multistory building and the method of construction requires the completion of one floor after the other, then it would be necessary to schedule this activity into "pour concrete floor slab - first floor", "pour concrete floor slab - second floor" etc. kinds of activities.

When identifying the tasks that make up a construction schedule, a large number of tasks can be derived from the basic activity as described above. These basic activities are represented in the database of the work breakdown structure. Because of this requirement, a procedural knowledge to build up these derivative activities from the basic activities is incorporated into a construction schedule planning system. Therefore, complete identification of activities to include location specification and activity description were designed based on this concept. This activity identification process requires symbolic processing and data structure programming. Specific rules and practices to implement this breakdown concept need to be acquired and formalized.

b. Work Breakdown Structure. Each activity identified from above is broken down further into more detailed activities based on the structured hierarchy of activities and the activity breakdown procedure. Two kinds of activities could be identified, namely the element activity and non-element activity. An element activity is the activity that would always consume material resources to build while a non-element activity involves operations that would not consume material. Some examples are:

element activity:

place concrete column reinforcement
erect steel frame column
build concrete foundation footing.

non-element activity:

cure concrete column concreting
remove concrete beam formwork
excavate concrete foundation footing
demolish existing building structure.

For cost estimating, element activities are always considered but some of the non-element activities are not accounted for. This is because in cost estimating, the objective is to identify activities which have costs associated to it. In scheduling, however, the objective is to identify time consuming activities.

In cost estimating and construction specifications purposes, the construction industry has accepted MASTERFORMAT (CSI, 1985, 1986) as the standard format for its breakdown. This format is heavily material oriented and decomposes the project into elements breakdown. It is therefore not directly suitable for scheduling breakdown. Since no such standard format currently exists for scheduling purposes, it is suggested that a similar format that decomposes the project into a hierarchy of element and non-element activities be established as an industry standard. Like any other standard documents which are well-structured, comprehensive and coordinated, this standardization is required for the format to be accepted industry-wide (Davis, 1986).

A high-level activity breakdown format is proposed in this research. Such standardization would facilitate communications among the members of the construction industry when it is fully developed (Huff, 1987). Also a consistent framework is important when the system is directing towards automation. The activity breakdown format shown in Figure 11 is compared against MASTERFORMAT. This comparison is derived from UNIFORMAT and the Uniform Construction Index (Dell'Isola and Kirk, 1983). Currently, UNIFORMAT is the format available that most resembles the framework required for scheduling breakdown purposes.

Since the objective of work breakdown is to identify time consuming activities, an elemental approach is used. This structured hierarchy format involves the breakdown of construction work into its elemental parts of element or non-element activities. An element activity breakdown could be derived from MASTERFORMAT to create lower level element and non-element activities. However, a non-element activity could be broken down further to create only non-element activities.

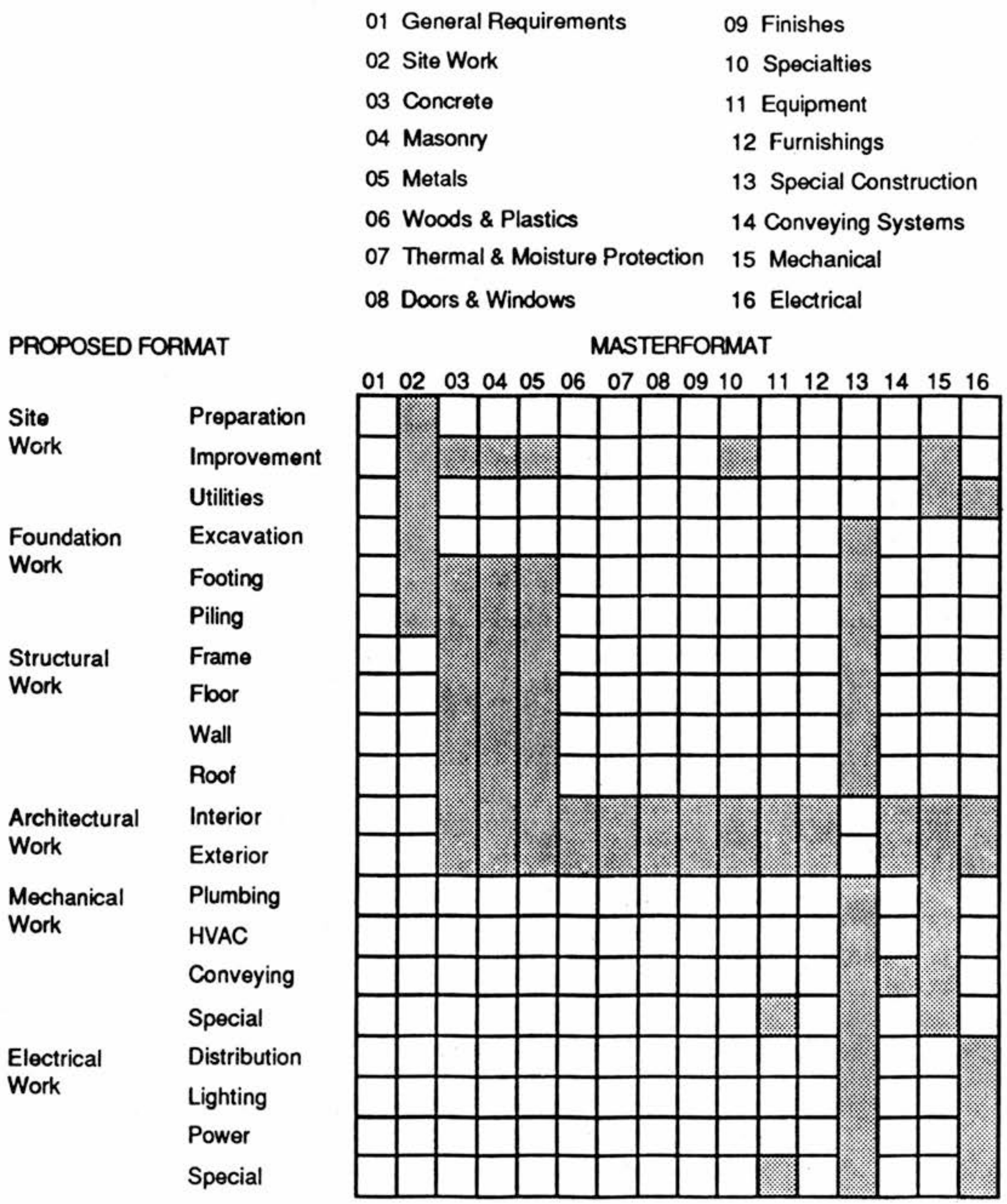

Figure 11. Proposed Format and Masterformat

A typical hierarchy is shown in Figure 12. This hierarchy is a tree-like structure that is made up of a parent activity and its children activities. The children are a more detailed breakdown of the parent. By structuring the activities into a hierarchy, any desired level of activity details can be presented. Only basic activities within a given domain need to be structured in this hierarchy. Complete identification of the activities to include location specifications would be created by the system from the basic activity based on the scheduling module breakdown concept. Similarly, basic activities currently not in the structure could be incrementally added to the knowledge base. The system should therefore be designed to incorporate this feature in order to make the system grow.

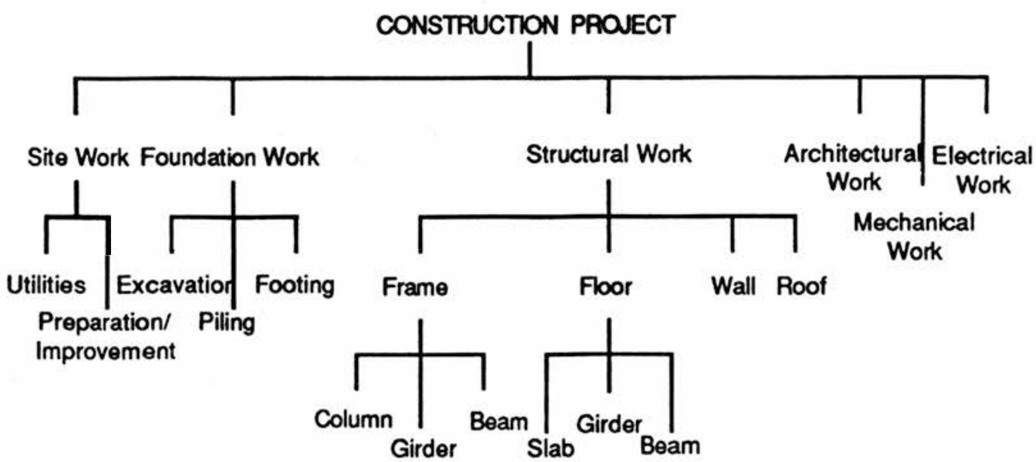

Figure 12. Typical Structured Hierarchy of Activities

A complete hierarchy of activities represents all the activities that make up a project within the given domain. However, a particular construction project under consideration might consist of only a subset of these overall activities. Therefore, a procedure is needed to identify these activities from a given hierarchy of activities. The concept is that if a parent activity is cut off from the breakdown, then all succeeding activities down the branches are automatically excluded. This procedure is described as the Activity Breakdown Algorithm. From this procedure, breakdowns of activities that represent the components of the construction project being scheduled are selected. The description of the algorithm is presented below.

Activity Breakdown Algorithm: This algorithm is formulated to identify the activities relevant to the project whose construction schedule is sought, based on the hierarchy of activities database structure. In the database, a list of activities that represents a more detailed breakdown of a given activity is coded. The routine for this algorithm will consider an activity and its children activities.

Details of this Activity Breakdown Algorithm are provided in Figure 13. It is made up of the following steps:

Step 1:

For a given activity under consideration, let's identify this activity as parent activity-P and the breakdown activities as children activities-C. All activity-P's considered by this routine have activities-C. However, if activity-P has no children activities-C explicitly specified in the database, then activity-P represents the appropriate level of detail and therefore would not be examined by this algorithm. Read the list of activities-C from the database.

Step 2:

Since all, some or none of activities-C could represent breakdowns for activity-P, it is necessary to determine which of these activities-C are parts of the current level breakdown. Identify each activity-C's that apply to the construction being considered from the activities-C list.

If activity-C under consideration is identified, then activity-P is replaced by activity-C as the appropriate breakdown and activity-P is removed from being an appropriate breakdown.

If activity-C under consideration is not identified, then activity-P may represent the appropriate breakdown until all activity-C's are examined.

Step 3:

After all activity-C's are examined, then determine the status of these activities.

If none of activities-C is identified to represent further breakdown, then the list of activities-C currently represented in the database is not complete to include one or more activities that seem to represent part of activity-P breakdown. Since the current system does not have the capability to build up these missing activity-C's, the present algorithm assumes that the user has to be satisfied with activity-P as the appropriate breakdown. Rename activity-P as task-P and go to Step 4.

If one or more activities-C is identified to represent further breakdown, then activity-P does not represent the appropriate breakdown. Activity-P has been replaced by one or more activity-C's from Step 2 and go to Step 6

Step 4:

Since task-P is designated as the appropriate breakdown, then it is reasonable to assume that all activities-C could be represented by task-P. This assumption is required to manipulate the task-predecessor relationships that have been explicitly built in the database. Read the list of activities-C that represents the breakdown for task-P from the database.

Step 5:

Examine each activity-C. For each activity-C under examination, rename it as task-P. Identify task-P children.

If task-P has children, then go to Step 4 to read the list of these children.

If task-P has no children, then further breakdown has not been explicitly stated in the database. Hence, all activities-C's down the tree breakdown from activity-P has been replaced by task-P and go to Step 6.

Step 6:

Finally, construction activities are identified as task-P or one or more activity-C's. Activities-C will be further examined for appropriate level of detail.

c. Level of Detail. After construction activities have been selected from the above procedure, each of these activities is examined to determine whether the activity represents the appropriate level of detail for scheduling. In this model, construction activities are broken down into various levels of detail based on the structured hierarchy of activities as described earlier. Due to the varying needs of users, the organizational level users would need less detailed breakdown than the task level users. However the system is designed for the most detailed breakdown that reflects the needs of the lowest level user and provides logical relationship among activities within the project domain selected for development.

The appropriate level of detail is achieved when logical relationships between activities can be specified for the need of the intended user based on the following principles (Willis, 1986),

Physical Constraints:

i. The activity under consideration could be started and go to completion without interfering with the start or completion of other preceding tasks.

Consider for example the activity "build concrete floor slab". Should there be no pipes or conduits to be placed within the slab, then the appropriate level of detail is achieved and no further breakdown is necessary. On the other hand, if there are pipes or conduits to be placed within the slab, then it would be necessary to break the activity further into activities such as "build concrete slab formwork", "place concrete slab reinforcement" and "pour concrete slab concrete".

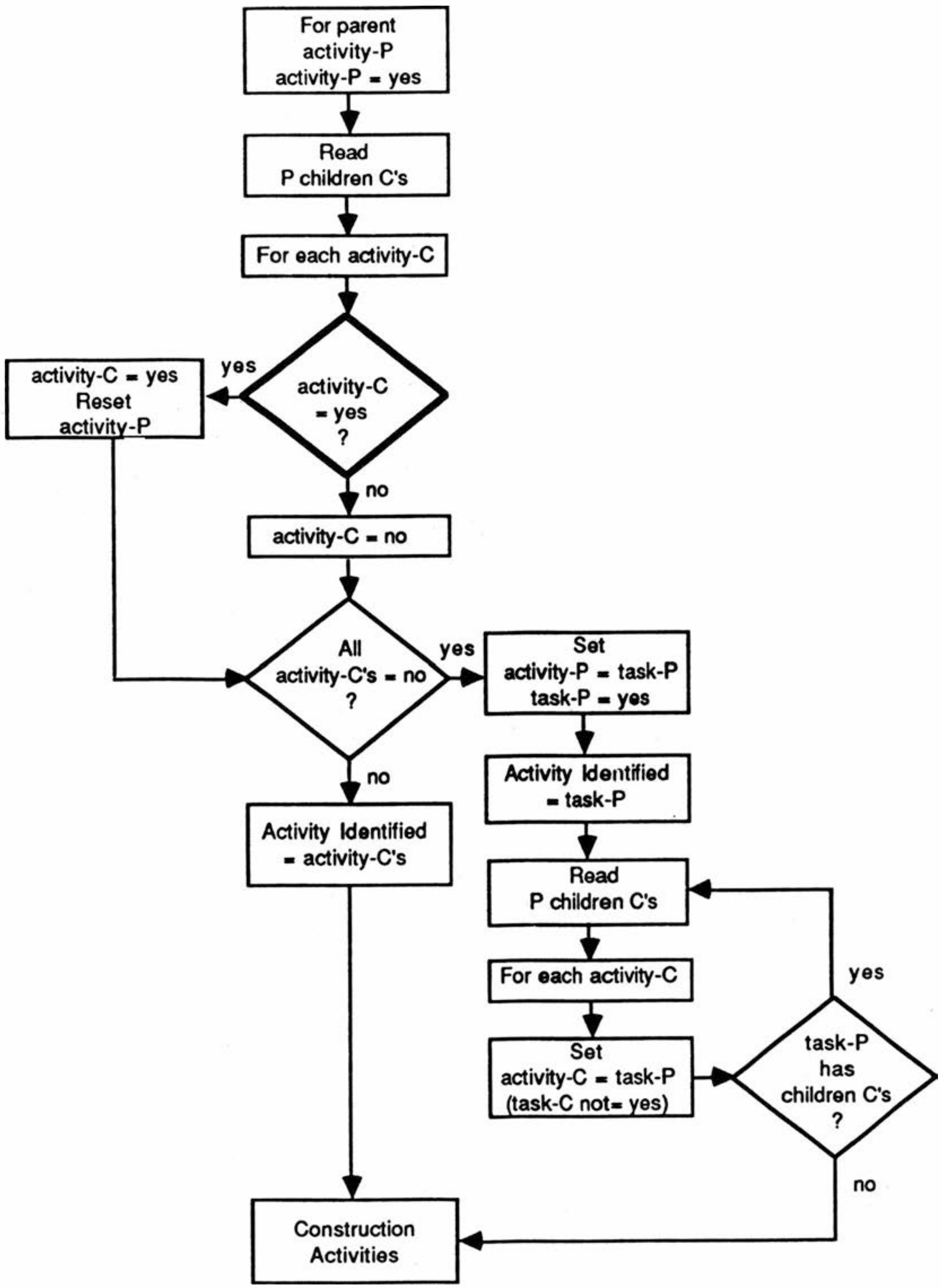

Figure 13. Activity Breakdown Algorithm

ii. The activity under consideration could be completed without being interrupted while other concurrent tasks are performed, or other succeeding tasks could be started immediately after its completion.

Consider for example the activity "build concrete floor slab". There are also pipes or conduits to be placed under the slab. Because of the method of construction used, these pipes or conduits could be placed only after the slab is completed. In such a situation, it would be unnecessary to break the activity further.

Physical and Resource Constraints:

iii. The duration of the activity under consideration is predictable. This implies that the activity is detailed enough to warrant further breakdown.

Consider for example the activity "build concrete floor slab". If this activity involves a large quantity of work, the resources are available and unlimited, the method of construction is well known and not physically constrained, then further breakdown is unnecessary.

Resource Constraints:

iv. The activity under consideration would not require different labor trades or equipment types other than what are currently being assigned to complete the activity.

Consider for example the activity "build concrete floor slab". If the operation requires different trades to complete, then it would be necessary to break the activity further into activities such as "build concrete slab formwork", "place concrete slab reinforcement" and "pour concrete slab concrete", each representing different trades of workmanship.

v. The activity under consideration would not be affected by the long lead-time of its labor, material and equipment resources.

Consider for example the activity "build concrete floor slab". If the operation requires a long lead time to procure wood and steel reinforcement but ready made concrete is available any time, then it would be necessary to break the activity further into activities such as "build concrete slab formwork", "place concrete slab reinforcement" and "pour concrete slab concrete".

If the activity under examination satisfies the above principles for scheduling, then no further breakdown is necessary and the activity is identified as a construction task. Similarly, if the activity is explicitly coded into the database without any children activities, then it is assumed that more detailed breakdown is unnecessary and the level of detail is appropriate for scheduling. This task would appear on the schedule planning output. Otherwise, the activity would be broken down further based on the concepts of the scheduling module breakdown and the structured hierarchy of activities.

2. Precedence Relationships. The next step is to establish precedence. Precedence relationships among tasks are established after considering the constraints on scheduling. These constraints are of two types: physical and resource. The physical constraint is related to the start of the proceeding task and the finish of the preceding tasks. It is based on the sequence of performing the tasks. Knowledge about the construction operations is therefore required. The resource constraint is related the availability of labor, equipment and material. It can also arise from organizational idiosyncracies. The output of schedule planning is a list that provides the description of tasks and their immediate predecessors. This relationship is needed for performing schedule analysis such as identifying the critical path.

Establishing precedence relationships among tasks could be modeled by three processes,

a. Job Logic Formalism

b. Precedence Condition

c. Redundant Relationship

a. Job Logic Formalism. Job logic is a sequential relationship that exists between tasks. It is represented by a logic diagram. This diagram is used to relate a task with every other task. There are three kinds of logical relationships. They are precedent, subsequent and concurrent relationships (O'Brien, 1969, Moder, Phillips and Davis, 1983, Willis, 1986). In this proposed system, the job logic is represented by a precedence relationship. A typical finish-to-start task precedence relationship is shown in Figure 14. This simple precedence relationship requires that before a task could start, then all tasks that precede this task must be partially or completely finished.

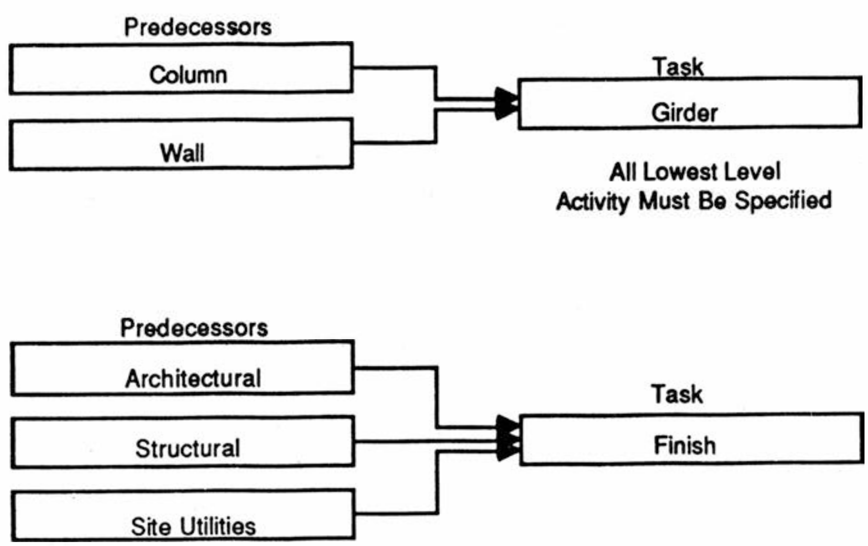

Figure 14. Typical Tasks Precedent Relationship

When the relationship between tasks is depicted by task nodes and an arrow, this representation is known as the Precedence Method. It is similar to the Activity-on-Node notation. In the Precedence Method, four types of precedence relationships could be established between any two tasks. These relationships are the finish-to-start, start-to-finish, start-to-start and finish-to-finish. Each of these relationships could also include a lag value. A negative lag value implies a lead. A zero lag value for finish-to-start implies that the proceeding task could start immediately upon the finish of the preceding activity. By manipulating the lag value, the finish-to-start relationship could implicitly represent the other three relationships. However, only finish-to-start precedence relationship with no lag is considered in this initial system.

For a given project domain, a large data set of predetermined task-predecessor relationships for every activity that make up the project can be established. When these relationships are acquired from knowledge sources, it is assumed that the resources of labor, equipment and material are not constrained. With the assumption of unlimited resources, these relationships then depend only on the physical constraints as to the finish of the preceding task and to the start of the proceeding task. Physical constraints are laws of nature that impose practical restraints on tasks based on the current construction technology. For example, a roof cannot be built until the supporting walls or frames are ready, irrespective of the availability of labor, equipment and material for its construction.

In capturing the task-predecessor relationship, it is desirable that each possible task that makes up the project domain under consideration is examined and all possible tasks that can precede this task are determined.

However, prospective predecessors must be specified for all the lowest level tasks present in the structured hierarchy of activities. If the precedence relationship for tasks higher up in the hierarchy are not explicitly specified, then it can be built up by the Activity Breakdown Algorithm. To avoid the possibility for any inconsistency in specifying this precedence relationship, each lowest level task must must be specified to be preceded only by other lowest level tasks. From the above example, a task such as "build roof" would have "build wall" and "build frame" as prospective predecessors. This would provide chunks of task-predecessor data. These data are structured into a database to facilitate retrieval.

However, a particular construction project under consideration might consist of a task preceeded by a subset of these predecessors. Therefore, a procedure is needed to identify these predecessors from the list of task-predecessors. Since these predecessors have been identified as relevant tasks during work breakdown, this procedure basically eliminates irrelevant tasks in the list. This procedure is described as the Task Sequencing Algorithm. The description of the algorithm is presented below.

<u>Task Sequencing Algorithm:</u> This algorithm is formulated to identify the task predecessors after the task has been identified from the Activity Breakdown Algorithm. This formulation is based on the precedence relationship database structure. In the database, a list of activities that represents predecessors to a given activity is coded. The routine for this algorithm will consider an activity and its predecessor activities.

Details of this task sequencing algorithm are provided in Figure 15. It is made up of the following steps:

Step 1:

Consider in turn each task identified by the Activity Breakdown Algorithm as being part of the project breakdown and at the appropriate level of detail. For a given task under consideration, let's identify this task as successor activity-S, the activities preceding this task as predecessor activities-R and the activities that represent this task breakdown in the hierarchy of activities as children activities-C. All task-S's considered by this routine have been determined to represent the appropriate detail of activity breakdown.

Step 2:

In the database, every lowest level activity appearing in the hierarchy of activities must have its immediate predecessors explicitly specified. Other higher level activities may or may not have their immediate predecessors explicitly specified. If an activity has no immediate predecessors explicitly specified, then the activity must have children activities specified in the hierarchy of activities. This step identifies these predecessors. Examine activity-S to determine its predecessors.

If activity-S has predecessors, then read the list of activities-R from the database and go to Step 4.

If activity-S has no predecessors, then read the list of activities-C from the database and go to Step 3.

Step 3:

When activity-S has no predecessors, then it has children activities-C. From the Activity Breakdown Algorithm, when activity-S is identified as the appropriate level of activity breakdown, then all children activities down the hierarchy from activity-S were replaced as task-S.

For each activity-C's, redesignate activity-C as new activity-S and go to Step 2

Step 4:

When activity-S has predecessor activities-R, examine each activity-R to find if it has been determined to represent part of the project breakdown.

If activity-R is part of the project breakdown, then examine activity-R further and go to Step 5.

If activity-R is not part of the project breakdown, then redesignate activity-R as a new activity-S and go to Step 2.

Step 5:

Each predecessor activity-R that is part of the project work breakdown will either be at the appropriate level of detail or have been replaced by a parent task-P during project breakdown that is at the appropriate level of detail. Determine the status of this activity-R.

If activity-R is at the appropriate level of detail, then designate task-R as a predecessor of task-S.

If activity-R is not at the appropriate level of detail, then designate task-P as a predecessor of task-S.

Step 6:

The algorithm repeats until all predecessor activities-R are designated for each task-S. Finally, task-S predecessor is identified as task-R or task-P.

b. Precedence Condition. From the above procedure, precedence relationships are established between a task and all the possible predecessors within a given project domain. However, for these task-predecessor relationships to exist, a certain set of conditions other than physical constraints must be satisfied due to the nature of the construction work involved. Consider for example, a construction work that is made up of a roof, a wall and a frame as tasks. In the task-predecessor database, it has been specified that a roof could have a wall and a frame as predecessors. However, a wall could be a predecessor to a roof only if it is a load bearing type and no frame exists. Similarly, a frame could be a predecessor to a roof only if there is no wall or the wall is a non-load bearing type. Even though both wall and frame have been identified as construction tasks and as possible predecessors, yet

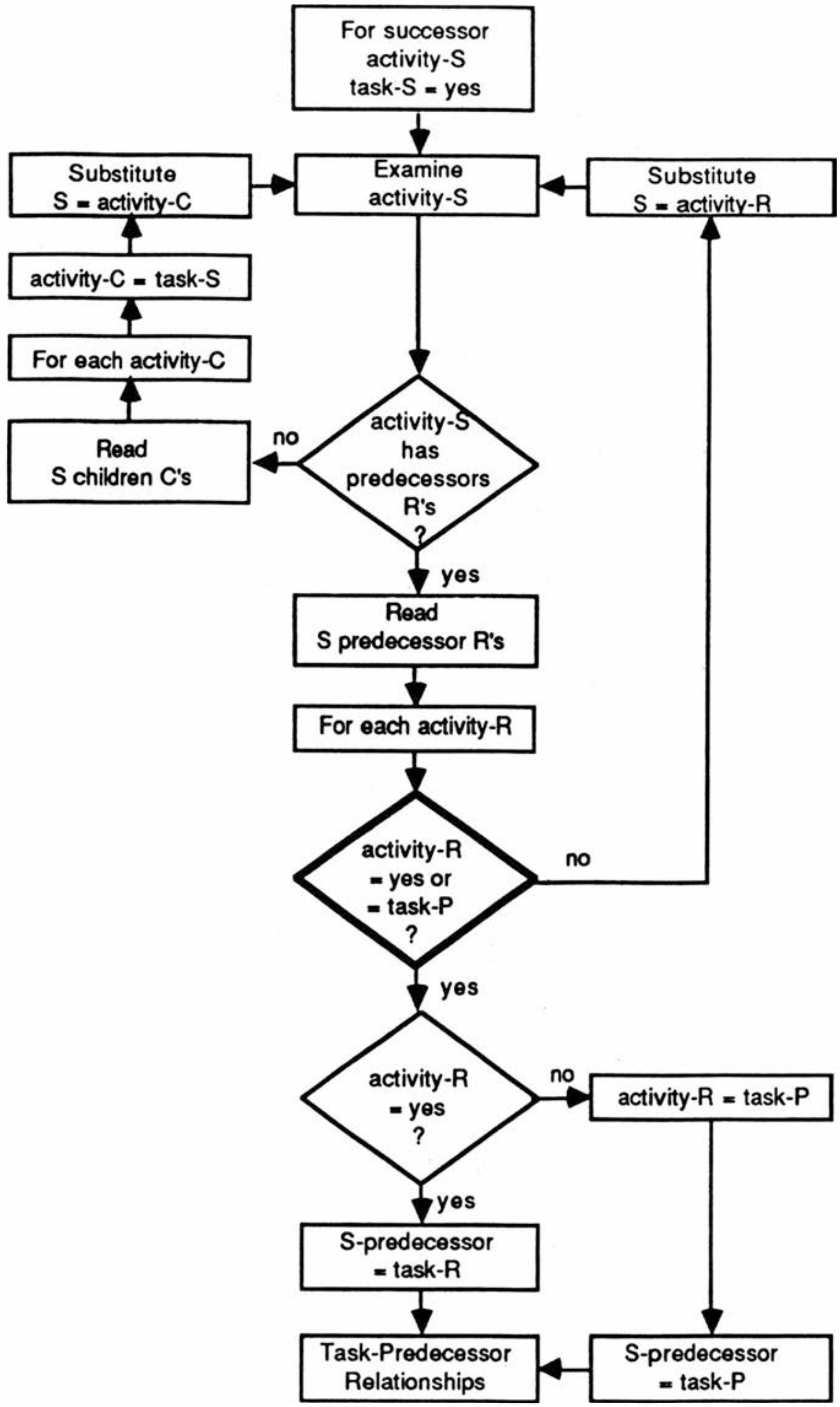

Figure 15. Task Sequencing Algorithm

they are not necessarily immediate predecessors to the task roof unless these conditions are met.

Similarly, other precedence conditions could be explicitly coded into the system and would be tested when encountered. Other conditions might include resource constraints and methods of construction. These conditions could be acquired based on the format shown in Figure 16. They are heuristics used by experienced schedulers to arrive at a feasible schedule. Predecessors that do not meet these conditions are eliminated. However, if there were no precedence conditions to be satisfied other than physical constraints, then no conditions need to be explicitly stated in the knowledge base. For all precedessors that satisfy their precedence conditions, a new set of task-predecessor relationships would be established.

c. Redundant Relationship. After all the task-predecessor relationships have been examined, a task-predecessor schedule is generated. This schedule lists all the task-predecessor relationships that have been identified by the task sequencing algorithm and later refined by checking against the precedence conditions. Due to the structure of the task sequencing algorithm, this task-predecessor schedule would include some precedence relationships that are redundant. This type of redundant relationship is known as implicit task-predecessor redundancy. Another type of task-predecessor relationship that could occur in the schedule is the logic loop relationship. The task-predecessor redundant relationship and the logic loop relationship are illustrated in Figure 17.

ACTIVITY	POSSIBLE PREDECESSORS	CONDITIONS FOR RELATIONSHIP TO EXIST
Roof	Wall	wall type = load bearing
		frame = no
	Frame	wall type = not load bearing
		frame = load resisting or structural

Figure 16. Establishing Precedence Conditions

(i) Logic Loop Relationship: This logic loop task-predecessor relationship exists when there is a path from a given task that traces through a number of other tasks and leads back to the same task. A logic loop relationship is similar to the task-predecessor redundancy except that the direction of the path is reversed. This relationship is created when a successor that has a predecessor (called task) is specified as the immediate predecessor to this task.

In a schedule planning system, logic errors are present because of the inconsistency in the stated task-predecessor relationships. These illogical relationships can be discovered by using a procedure that checks for the existence of logic loops. This procedure has been described by Weist and Levy

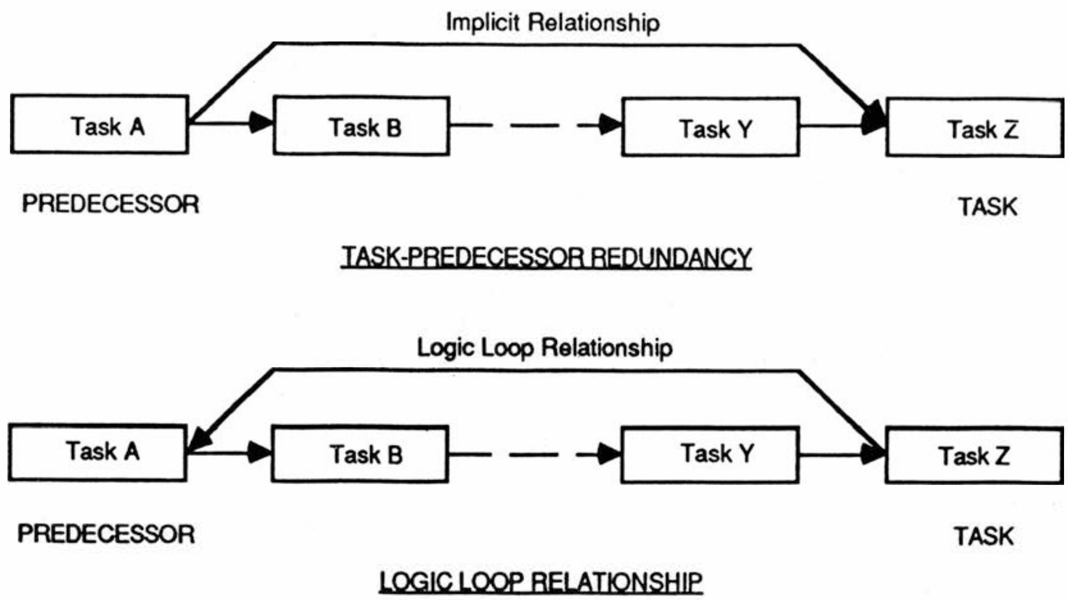

Figure 17. Redundant Relationships

(1977). The checking procedure can be done while building the task-predecessor relationships in the knowledge base during system development. Alternatively, this checking procedure can be applied after the task-predecessor relationships have been identified by the task sequencing algorithm and refined against the precedence conditions as described in the previous sections.

Logic loop relationships are more serious than the task-predecessor redundancies because they represent logical errors in the schedule. They must be removed before the schedule is examined to identify the redundancy relationship. While a procedure that checks for redundancy can check for the existence of logic loops, it cannot remove them per se except in an arbitrary fashion (Weist and Levy, 1977). This is because it is impossible for any algorithmic procedure to determine which task-predecessor in the loop represents a logic error except the scheduler who prepares the logic and knows the accuracy of the stated task-predecessor relationships in the schedule.

(ii) Task-Predecessor Redundancy: In an implicit task-predecessor redundancy, there is a path between two tasks, the successor and the predecessor, passing through a number of other tasks, and also there is direct path connecting these two tasks directly. This direct path is redundant since a precedence relationship has been explicitly specified through the longer path. Even though the predecessor seems to be the immediate task of the successor, it is infact a more distant one. Only explicit predecessors along the longer path need to be established in a schedule.

Removel of redundant relationships is desirable but not absolutely necessary since they do not violate the task-predecessor logic. However, they make drawing the network more difficult, clutter the network and increase computer time and expense. One method of removing redundancies was described by Weist and Levy (1977). This method makes use of topological ordering of activities into rows and columns. By examining these rows and columns in a particular fashion, redundant predecessors are identified and can be eliminated.

A similar algorithm to identify this redundancy could be developed. This algorithm would mimic the procedure used by experienced schedulers. An algorithm to eliminate task redundancy and identify logic loops was not completed and remains for further work. These deviations were instead removed manually from the systems output. After eliminating this redundancy, a logical task precedence schedule is produced. This schedule is a representation of correct job logic and can be transformed into a network. With this initial network, conventional network-based techniques that utilize Precedence Method algorithms can be used to complete construction planning.

B. PROTOTYPING

The knowledge-based system for construction schedule planning consists of a knowledge-based shell that provides both the development and delivery environments and a microcomputer that provides the environment for system prototyping and consultation. The structure of the prototype system is shown in Figure 18. The system shell consists of the knowledge base, the inference engine, the context, the explanation facility, the developer interface and the user interface.

The shell used in this research is M.1, a rule-based tool from Teknowledge. In a shell, the knowledge base is empty. Therefore, prototyping a knowledge-based system is predominantly coding the facts and rules into the

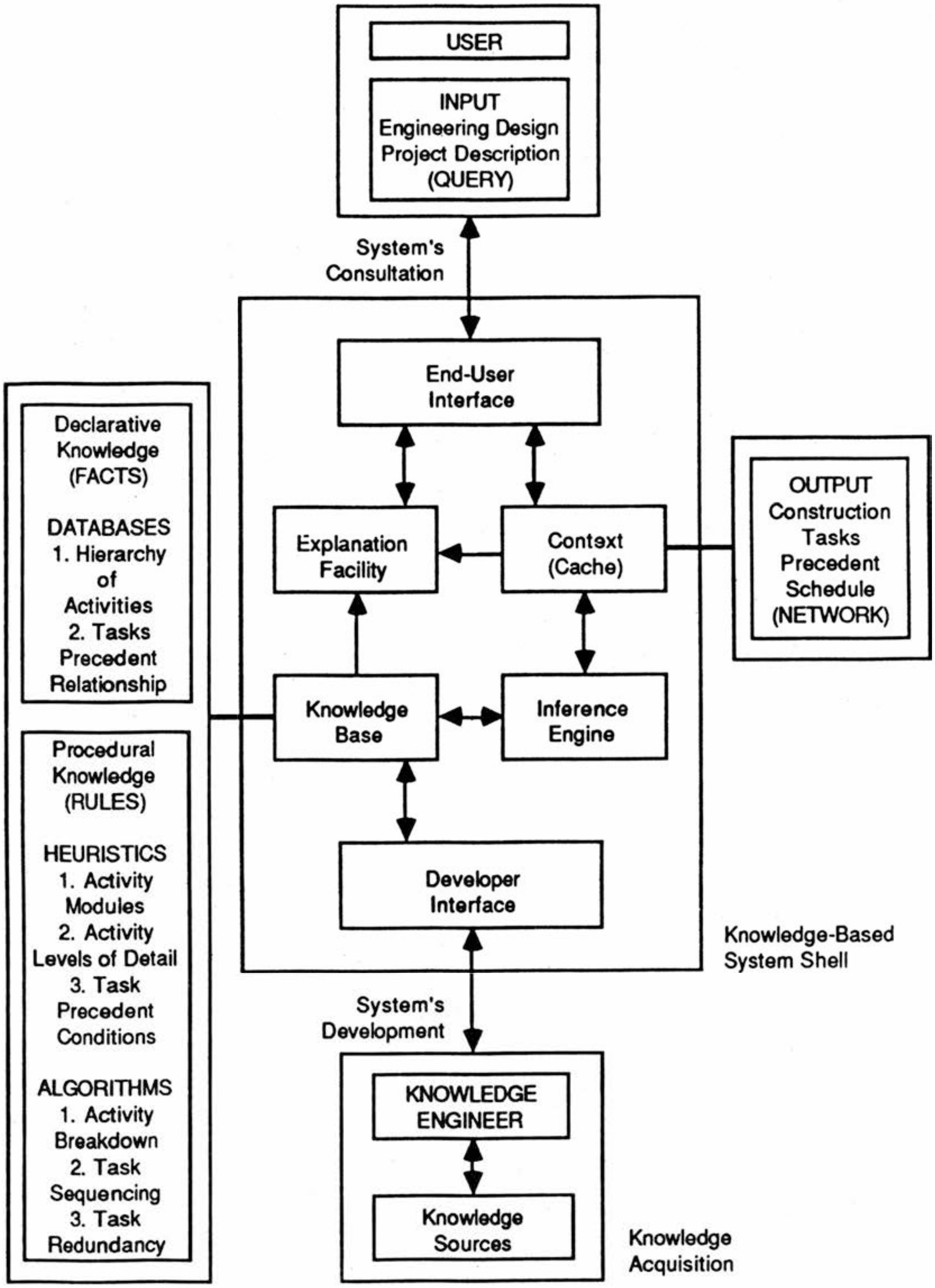

Figure 18. Structure of the Prototype

shell. The shell's inference engine provides the reasoning process. The developer interface provides the medium to build the system, the end-user interface provides the medium to consult the system and the explanation facility provides the responses to user query during consultation. The context or cache is the working memory that provides intermediate results and the system's output.

1. K owledge Base. The knowledge of construction schedule planning is structured based on the model as described earlier. In this context, the facts are declarative knowledge represented in the forms of databases and the rules are procedural knowledge represented in the forms of heuristics and algorithms. Complete listings of the knowledge base for this schedule planning system based on the project as described by the drawings in Appendix A and Appendix B are provided in Appendix C.

The present prototype system has the knowledge to plan a construction schedule for a particular type of reinforced concrete buildings described later. The overall knowledge base is made up of almost 400 lines of program code written in M.1 syntax. The system is able to identify and produce a schedule up to about 40 construction tasks.

In this rule-based system, the knowledge base consists of about 100 production rules, 74 facts that describe the different activities representing the project breakdown, 22 facts that describe the hierarchy of activities and 50 facts that describe the precedence relationships among activities. The production rules were used to write the algorithm codes and the heuristics needed to schedule a construction within the specified domain.

a. Databases. A database system has been developed to represent the structured hierarchy of activities and the formalized task precedence relationships. This database structure is consistent with the capability of the shell and the algorithmic procedures that utilize these data. In M.1, an activity and its members are represented by a list structure. A list structure is a data structure constructed from a functor that names the structure and its component.

Thus, in a structured hierarchy, the parent activity is the functor and the children activities are its components. An activity "frame" and its children "column", "girder" and "beam" are represented by

frame = [column, girder, beam].

Similarly, in a formalized precedence relationship, the successor task is called the functor and the predecessor tasks are its components. A task "roof" and its prospective predecessors "wall", "column" and "girder" are represented by

roof = [wall, column, girder].

A unique numbering identification system is used to differentiate a list structure that represents a structured hierarchy of activities from a list structure that represents a task precedence relationship.

Hence, these list structures that represent a hierarchy of activities and a task precedence relationship could be independently and incrementally built in the database. A list structure that represents the children activities of a particular parent activity could be acquired and represented without considering other list structures that represent different work breakdown. A similar argument applies to the list structures for task precedence relationships. This independency in list structure representation makes the knowledge acquisition formidable considering the vast amount of activities present in construction. Only basic activity breakdowns need to be acquired and be represented once in the database.

b. Heuristics. Heuristics are rules of thumb knowledge used by experts to schedule their construction. Three kinds of heuristics are identified for schedule planning based on the model as developed above. These heuristics are related to the breakdown of activities into horizontal and vertical scheduling modules, the examination of activities to determine the appropriate level of detail and the examination of tasks to satisfy the precedence conditions. These heuristics are the most difficult part of the knowledge base to acquire since they are mostly unstructured and idiosyncratic. Heuristics that are used by a particular scheduler in a given organization could be different from others due to variations in experience and practice. Therefore this knowledge could be proprietary but not necessarily be universal.

These heuristics are the crux of the system knowledge base. The quality of the system depends largely upon their precision. It is because of these complex heuristic processes that very little attention has been given to the development of schedule planning system. Some attempt was initiated in this research to capture this heuristic knowledge. Since the process of acquiring this knowledge is very time consuming, only specific issues related to schedule preparation were considered. However, the basic heuristics captured in this research were significant enough for the overall schedule planning process to be identified and prototyped.

Typical rules that represent these knowledge components are illustrated below. However some of these concepts were not explicitly used in the prototype system developed in this research because of the time constraints to solicit them.

scheduling module breakdown rule:

> if the building is two stories
> then break the activity "build floor" into
> "build floor level 1" and
> "build floor level 2".

level of detail rule:

> if pipes are embedded under slab
> then break the activity "build slab" into
> "build formwork and place rebars" and
> "place concrete".

precedence conditions rule:

> if wall is of shear or
> load-bearing type
> then activity "build girder" and
> activity "build floor slab"
> are to be preceded by "build wall".

c. Algorithms. Two algorithms were developed to manipulate the above databases and heuristics. They are identified as (i) Activity Breakdown Algorithm, and (ii) Task Sequencing Algorithm The description of these algorithms has been presented earlier. In this prototype system, the algorithms are presented in M.1 knowledge base by recursive rules which make use of variables. The M.1 program written for these algorithms was based on the following flow steps:

Activity Breakdown Algorithm

Step 1:
For each parent activity-P,
Activity-P = yes.
Activity-P has children activities-C.
Read activities-C.

Step 2:
For each activity-C until all activities-C are examined,
Is activity-C part of the project breakdown ?
If YES, activity-C = yes
reset activity-P.
NO, activity-C = no.

Step 3:
Are all activities-C = no ?
If YES, set activity-P = task-P
task-P = yes
activity identified = task-P.
NO, activity identified = activity-C
go to Step 6.

Step 4:
Task-P has activities-C.
Read activities-C.

Step 5:
For each activity-C until all activities-C are examined.
Set activity-C = task-P.
Does task-P have activities-C ?
If YES, go to Step 4.
NO, task-P has no activities-C.

Step 6:
Construction activities identified.

Task Sequencing Algorithm

Step 1:
For each successor activity task-S,

Task-S = yes.
Activity-S represents the appropriate detail of activity breakdown.

Step 2:
Examine activity-S.
Does activity-S have predecessors activities-R ?
If YES, read activities-R
go to Step 4.
NO, activity-S has children activities-C
read activities-C.

Step 3:
For each activity-C until all activities-C are examined.
Activity-C = task-S.
Substitute activity-S = activity-C.
Go to Step 2.

Step 4:
For each activity-R until all activities-R are examined.
Is activity-R part of the project breakdown ?
If YES, examine activity-R.
NO, substitute activity-S = activity-R
go to Step 2.

Step 5:
Is activity-R represent the appropriate detail of activity breakdown ?
If YES, task-S predecessor = task-R.
NO, activity-R = task-P
task-S predecessor = task-P.

Step 6:
Task-predecessor relationship identified.

However, these algorithms could also be coded by external procedures written in C programming language that could later be interfaced with M.1. These algorithms that were written in M.1 are reproduced in Appendix C.

2. Consultation. The process by which the user interacts with the system through a user interface is referred to as consultation. Since the system is interactive, consultation is by means of input and query dialog. The user is requested to answer questions that provide the project description as an input. The query session extracts information from the user in order to activate rules related to activity modules, appropriate level of activity details and precedence conditions. Currently, the output from the system consists of a listing of construct n activities that shows their precedence relationships.

A typical consultation session is given in Appendix D. This consultation is based on the projects used to prototype and evaluate the system. The description of the projects will be given in the next section. The drawings are shown in Appendix A and Appendix B.

V. SYSTEM EVALUATION

A. INTRODUCTION

During development, knowledge-based systems need to be tested and evaluated. Informal evaluations by domain experts and knowledge engineers have been used to test for program accuracy. Formal evaluations by potential users help to determine the utility of the system in addition to program accuracy. These evaluations focus mainly on the performance issues specific to the design and application of the system respectively (Buchanan and Shortliffe, 1985).

Some aspects of system's performance are more appropriately evaluated than others at a particular stage of its development. For a system that has reached completion, the evaluation warrants formal assessment in the following areas (Hayes-Roth, Waterman and Lenat, 1983):

1. Decisions, advice and performance

   Reliably accurate output is an essential component of a knowledge-based system. This is a measure of the quality of system's performance. Therefore, some approach to performance verification is required. However, the mechanisms for deciding whether the system output is appropriate or adequate may be difficult to define or defend.

2. Correct reasoning

   High level performance of the system may require heightened attention to whether the system is reaching decisions using reasoning equivalent to that used by comparable human experts. This mechanism of reasoning is required during the evaluation process.

3. Discourse (I/O content)

   A variety of parameters influence whether a system is acceptable by the intended users. The nature of the discourse between the system and the user is important. The parameters are the choice of words used in questions and responses, and the ability of the system to explain, assist and educate the user. These abilities will indirectly improve the system's performance in terms of output quality and time.

4. Hardware environment (I/O medium)

The interaction between the user and the system requires a hardware interface. This input and output medium, such as the graphics capability, needs to be evaluated.

5. Efficiency

Technical analyses of the system's behavior in the user's environment are also required. The efficiency of the system can be measured by the time committed during consultation. Other analyses include CPU power and disk space that indirectly affect the performance time of the system.

6. Cost effectiveness

This is applicable to marketable knowledge systems where the costs to purchase and maintain the system are weighed against its benefits.

Before evaluating the system in the user's environment, the domain expert and the knowledge engineer need to test the system in the development environment to determine the accuracy of the embedded knowledge and the correctness of the output provided by the system. Only then can an evaluation be conducted on potential users to determine the performance of the system in terms of program accuracy and utility. This procedure has been followed in this research. For this construction schedule planning system, the prototype was refined during testing and later evaluated in a laboratory environment.

Studies concerning the relative effectiveness of humans and computers to solve ill-structured problems were reported by Trybus and Hopkins (1980) and Cats-Baril and Huber (1987). The experiment conducted by Trybus and Hopkins (1980) compared computer solutions for plant layout problems with manual solutions obtained without the subjects having access to the values from computer solutions prior to their solution attempts. Results from the experiment showed the best computer solutions to be as good or better than the best manual solutions. The study by Cats-Baril and Huber (1987) examined the computer delivery of decision aids for addressing career planning problems against the use of paper/pencil as a delivery device. The findings concluded that whether or not the system was computerized did not have a significant effect on among other things the quality of user performance and productivity of ideas. A similar experimental design was devised for the evaluation of this schedule planning system.

Since this construction schedule planning system has not reached total completion, the prototype was evaluated strictly on its performance as a decision support productivity tool. This productivity evaluation is related to the quality and time of the system's performance. The quality of the system's performance was measured based on the accuracy and correctness of the scheduling output provided by the system. The time of the system's performance was measured based on the amount of time taken from the start of the consultation until the output was provided by the system. The quality of the scheduling output and the time required to produce the output are used as measures of the system's effectiveness. The laboratory experiment conducted in this research examined the effectiveness of the knowledge-based prototype computer system in the context of a construction schedule planner faced with an ill-structured scheduling problem in relation to manual scheduling.

The experimental attribute used in this evaluation study is construction schedule planning. The criteria relevant to this attribute are that the problem is relatively ill-structured, requires judgement to solve, is significant to the experimental subjects (novice schedulers) and important to the intended users (construction schedulers). Construction schedule planning requires the generation of construction tasks and the sequencing of these tasks into a construction schedule.

B. OBJECTIVES AND HYPOTHESES

The main objective of the experiment is to determine if the proposed computer scheduling method will improve the productivity of novice schedulers in comparison to manual scheduling. This improved productivity will measure the effectiveness of the knowledge-based system.

The computer scheduling method is the process by which novice schedulers will consult the prototype knowledge-based construction schedule planning system in an effort to produce a construction schedule. This prototype was developed in this research. The manual scheduling method is the process by which novice schedulers will use their own knowledge, skill and judgement in an effort to produce a construction schedule. The knowledge, skill and judgement are acquired through formal education and work experience.

The next objective of the experiment is to determine if there is any variability in productivity measures between two samples of novice schedulers. The samples are Civil Engineering students (CE sample) and Engineering Management students (EM sample) from the University of Missouri-Rolla (UMR). This variability will indicate if subjects from the two samples come from the same population.

The experiment was conducted to determine the correctness of the hypotheses that (1) novice schedulers using the computer scheduling method would provide scheduling output as good as or better than those from manual scheduling method, and (2) the time required to develop a schedule using the computer scheduling method would be as good as or better than manual scheduling method. Therefore, the hypotheses to be tested are:

QUALITY OF PERFORMANCE

Testing Population Means for CE Sample

Null Hypothesis:
The true mean in the quality of scheduling output for CE sample obtained with computer scheduling method is not greater than that obtained with the manual scheduling method.

Alternative Hypothesis:
The true mean in the quality of scheduling output for CE sample obtained with computer scheduling method is greater than that obtained with the manual scheduling method.

Testing Population Means for EM Sample

Null Hypothesis:
The true mean in the quality of scheduling output for EM sample obtained with computer scheduling method is not greater than that obtained with the manual scheduling method.

Alternative Hypothesis:
The true mean in the quality of scheduling output for EM sample obtained with computer scheduling method is greater than that obtained with the manual scheduling method.

Comparing Two Sample Variances for CE and EM Samples

Null Hypothesis:
The variance in the difference of the quality of scheduling output between computer and manual scheduling methods for CE sample is equal to that of EM sample.

Alternative Hypothesis:
The variance in the difference of the quality of scheduling output between computer and manual scheduling methods for CE sample is greater than that of EM sample.

TIME OF PERFORMANCE

Testing Population Means for CE Sample

Null Hypothesis:
The true mean in the time to produce scheduling output for CE sample obtained with computer scheduling method is not greater than that obtained with the manual scheduling method.

Alternative Hypothesis:
The true mean in the time to produce scheduling output for CE sample obtained with computer scheduling method is greater than that obtained with the manual scheduling method.

Testing Population Means for EM Sample

Null Hypothesis:
The true mean in the time to produce scheduling output for EM sample obtained with computer scheduling method is not greater than that obtained with the manual scheduling method.

Alternative Hypothesis:
The true mean in the time to produce scheduling output for EM sample obtained with computer scheduling method is greater than that obtained with the manual scheduling method.

Comparing Two Sample Variances for CE and EM Samples

Null Hypothesis:

The variance in the difference of the time to produce scheduling output between computer and manual scheduling methods for CE sample is equal to that of EM sample.

Alternative Hypothesis:

The variance in the difference of the time to produce scheduling output between computer and manual scheduling methods for CE sample is greater than that of EM sample.

C. METHODOLOGY

1. Tasks and Subjects. The assignment for each subject was to develop a construction schedule for a given construction project. The project description was based on a given engineering drawing that was prepared during the engineering design phase. The schedule preparation required the subjects to break the given project into appropriate tasks that would be suitable for construction operations and sequence these tasks into a task-predecessor schedule. This schedule would indicate the construction tasks and their immediate predecessors. This assignment did not require logical networks to be drawn as an output. However, the assignment required a high degree of judgement from the subjects.

Engineering students who were seniors or graduates taking the project management course (EMGT 361) in the Engineering Management Department and students taking the construction scheduling course (CE 401) in the Civil Engineering Department at UMR were selected for this experiment. Participation in the experiment, although voluntary, was strongly encouraged by the professors in charge of the courses concerned. Twenty-seven subjects from these two classes with a background in project or construction scheduling participated in the experiment.

This experiment investigated the effects of two treatments on two different samples. The treatments were manual and computer. The sample subjects were students with civil engineering background and students with engineering management background as described above. These students were assigned into two groups to represent two different samples based on their background. One sample group consisted of 13 students who had prior knowledge in construction scheduling while the other sample group of 14 students had prior knowledge in project scheduling.

Two different projects were selected, each representing a similar level and degree of difficulty in terms of construction planning and scheduling. These projects were the sand filters building for the wastewater facility improvement in Alton, Missouri and the wash water pumping station building for the water works improvement in Hibbing, Minnesota. The two buildings were designed by Crane & Fleming of Hannibal, Missouri and by Black & Veatch of Kansas City, Missouri, respectively.

Not every aspect of construction was considered in this experiment. Therefore, only one sheet of engineering drawing for each project was used to represent a particular aspect of construction operation. Each of these drawings described a typical reinforced concrete building to be constructed below grade. The construction activities related to this construction were:

* structural elements such as the floor, wall and roof

* architectural works such as waterproofing, dampproofing, finishes and related accessories such as ladders, hatches and railings

* mechanical installation of pumps, equipment and pipings

* foundation works such as excavations and backfills

* site works such as sidewalks, curbs and gutters

This construction work was envisaged to contain about thirty different construction tasks and could be conveniently scheduled within one hour and fifteen minutes.

2. Procedure. The experiment was conducted over a period of four weeks. During the first week, each subject from both groups was asked to schedule the project design manually. One of the two designs was randomly selected and assigned to each subject. After a lapse of about three weeks, each subject from the same two groups was asked to run and consult the prototype system in order to produce a construction schedule. However, the other design which was different from the one they had scheduled manually was assigned this time.

During the manual treatment, the subjects worked in a large room with enough space for spreading out the drawings. After a welcoming address and a brief overview, the subjects were each given one of the two engineering drawings and a set of instructions as shown in Appendix E. At the end of the session, the scheduling output sheets and the drawing given were collected. No time limits were enforced during the experiment. However, the subjects were advised to work within the time period allocated for the assignment. Each subject was requested to work independently, but was allowed to ask the researcher for any clarification. The time spent by each subject was recorded. The room conditions provided for a good working environment and distractions were minimal.

During the computerized treatment, each subject worked in an office environment room containing an IBM System 2 Model 50 personal computer. Each subject was given a questionnaire to fill out outlining his/her academic background and practical experience as shown in Appendix F. After a brief overview, each subject was given the other engineering drawing which was different from the one he/she used before and allowed access to the personal computer. The computer system had been set for the subject to start the consultation. All instructions were given on the screen. No paper or pencil was required. At the end of the session, the scheduling output was printed by the system's printer. This output and the drawing provided were collected. Similarly, the time spent by each subject was recorded.

3. Productivity Measures. As hypothesized earlier, the purpose of the experiment was to measure the effects on the scheduler's productivity when using the computerized system in comparison to manual performance. These effects would provide measures of the effectiveness of the construction schedule planning knowledge-based system as a decision support tool to improve productivity. The concept of productivity and designing effective management systems to improve productivity in construction industry has been described by Sanvido (1988).

The effects of these two treatments, computer versus manual, were assessed on two dependent variables that represented a measure of productivity. These variables are,

a. quality of performance

b. time of performance

These two variables warranted formal assessment as suggested by Hayes-Roth, Waterman and Lenat (1983) and Buchanan and Shortliffe (1985). At this stage of system development, it was felt that the quality and time of performance need to be evaluated in an effort to justify the effectiveness of the system as a productivity tool and to recommend further development.

a. Quality of Performance. The quality of performance of the individual subjects was assessed by Professor Kincaid, professor in Construction Engineering and Management at the University of Missouri-Rolla. He is a full-time faculty member and currently teaches construction engineering management courses in civil engineering department. With almost thirty years of construction engineering and management experience, he has had experience in cold regions construction, construction equipment repair and rebuild, topographic and geodetic surveying, operation and maintenance of millitary installation facilities, management of planning, design and construction of water resources, flood control and navigational facilities. He has also managed the operation, repair, construction and financial activities of a city department of public works and has worked as a resident engineer for the construction of a wastewater treatment plant. This professor volunteered to serve as an expert judge and knew about the experimental treatments but did not know which subject (student) was associated with each schedule he judged.

A systematic systems approach (Athey, 1982) was used for this assessment. The assessment of the quality for each subject's schedule output was based on three attributes chosen by Professor Kincaid. These attributes were,

i. Level of activity detail

Is the number of activities appropriate, that is, too many or too few? Are activities balanced, that is, too many small ones or too few large ones? Are too many minor steps spelled out?

ii. Completeness of the schedule

Are all significant work items included? Are items specific? Are extra items included?

iii. Network logic.

Is precedence shown? Is precedence logical? Is concurrence shown where practical? Is concurrence logical? Do relationships include logic loops and implicit redundancies?

These attributes were measured based on a scale of 0 to 10, with weights assigned to each attribute as follows: level of detail (1), completeness of the schedule (1) and network logic (2). These scales and weights were devised by the evaluator. Both outputs presented by each subject were evaluated. The total numerical rating assigned to each scheduling output was based on the evaluation matrix as shown in Appendix G. The maximum possible rating for each output was 40 absolute units.

b. Time of Performance. The performance time was measured directly using the amount of time spent by each subject to come up with a construction schedule for each treatment. This time was measured from the time the subject examined the drawing until an output was handed over to the researcher. The unit of measurement was in minutes. Each measurement was adjusted to the nearest minute.

D. RESULTS AND DISCUSSION

1. Analysis. A statistical analysis was performed on the data collected for the two productivity measures of quality and time of performance to determine their significance. Since the objective of the experiment was to examine increased productivity, that is the improvement in productivity measurement between computer and manual methods, absolute measures of ratings for quality and time were not of interest. Therefore, a randomized paired comparison design was used (Box, Hunter and Hunter, 1978). This design would analyze the difference in quality and time performance scores when scheduling assignments were performed manually and on computer. The difference would indicate the change in productivity. Since the experiment was based on small samples, student-t test procedures were used (Cass, 1980a, 1980b). The results were analyzed using the Statistical Analysis System (SAS, 1982, 1985) program on the mainframe computer at the university.

The appropriate statistical analyses conducted were:

> (1) Testing a specified population mean based on small sample method using the standard t-test procedure for significance testing. This test was performed for both the CE and EM samples.
>
> (2) The F-distribution to compare the variability of two samples using their variances. These samples consisted of the CE and EM subjects.

The variables considered were the quality and time productivity measures. Since the consequences of wrongly rejecting the null hypothesis are not serious enough, the 5% significance level is considered appropriate. However, a one-tail test was carried out at both the 0.01 and 0.05 significance levels for each of the above analyses. The computation for these tests are shown in Appendix H. The inputs to the SAS program were reproduced in Appendix I.

2. Findings. The results for the quality and time productivity measures are presented below.

a. Quality Productivity Measure. The results provided by the SAS output for the quality of performance are shown in Appendix J for both the subjects with civil engineering and engineering management backgrounds. From this appendix, it is observed that the average scores for the civil engineering samples were 27.31 and 33.92 for the manual and computer methods respectively, an improvement of 24 percent. For engineering management samples, these average scores were 15.00 and 34.14 respectively, an improvement of 128 percent. Thus, the use of the prototype knowledge-based system resulted in significant improvements in the quality of the schedule produced by both groups of subjects with greater improvement observed in this case for the subjects with non-civil engineering background.

Table II shows a summary of the test statistics for the difference in quality measurements between the manual and computer scheduling methods for the two samples. From the t-test on civil engineering sample, the null hypothesis was rejected at both the 0.05 and 0.01 significance levels. The alternative hypothesis was accepted, implying that a significant improvement in performance quality can be achieved with the use of computer system.

Table II. SUMMARY OF TEST STATISTICS FOR DIFFERENCE IN QUALITY

One-Tail Test at 1% and 5% Significance Levels

	Computed by SAS	Significance Levels	
		0.01	0.05
Testing population means for CE sample (t value)	3.68	2.681	1.782
Testing population means for EM sample (t value)	11.48	2.650	1.771
Comparing 2 sample variances between CE and EM samples (F value)	1.08	3.96	2.60

A similar result was achieved for for the t-test on engineering management sample. The null hypothesis was rejected while the alternative hypothesis was accepted at both the significance levels considered. At both the 0.05 and 0.01 significant levels, it can be concluded that computer scheduling yielded significant improvements over manual scheduling for both the civil engineering and engineering management samples. Therefore, based on the quality productivity measure, the knowledge-based system was found to be an effective productivity tool.

From the test on variances, the null hypothesis was failed to reject at both the 0.05 and 0.01 significance levels. This is because the difference between the variances of the two samples cannot be distinguished. Thus, at 0.05 and 0.01 significance levels, the subjects from civil engineering and engineering management samples can be taken as having come from the same population with regards to their variances.

This experiment has demonstrated that a knowledge-based system is capable of improving the quality of construction schedules produced by novice schedulers. The improvement is much more significant among users with some prior knowledge of scheduling but limited knowledge of construction.

b. Time Productivity Measure. A similar analysis was performed on the time taken by each subject to produce a construction schedule. The results provided by the SAS output are shown in Appendix K. The average time spent by the subjects with a civil engineering background was 52 minutes for manual scheduling and 37 minutes for computer scheduling. This represents an improvement of 29 percent. For subjects with engineering management background, this performance time was 42 minutes and 39 minutes respectively, an improvement of 7 percent.

It was conceived that a higher productivity would be achieved if the time spent to prepare a construction schedule could be reduced. Table III shows a summary of the test statistics for the difference in performance time measurements between manual and computer scheduling for the both the samples. For the civil engineering subjects, the null hypothesis was rejected at both the 0.05 and 0.01 significance levels. The alternative hypothesis was accepted because a significant difference in the mean between manual and computer scheduling methods was obtained. This implies that a significant improvement in performance time can be achieved with the use of a computer system.

While it was true that an improved productivity could be achieved for the subjects with a civil engineering background, it was not true for the subjects with an engineering management background. The null hypothesis was failed to reject at both the 0.05 and 0.01 significance levels. Therefore, we are unable to say that there is a significant difference in terms of the time productivity measure when using the manual or computer scheduling methods.

Table III. SUMMARY OF TEST STATISTICS FOR DIFFERENCE IN TIME

One-Tail Test at 1% and 5% Significance Levels

	Computed by SAS	Significance Levels	
		0.01	0.05
Testing population means for CE sample (t value)	6.59	2.681	1.782
Testing population means for EM sample (t value)	0.57	2.650	1.771
Comparing 2 sample variances between CE and EM samples (F value)	5.93	3.96	2.60

One interpretation could be that subjects without civil engineering background had less knowledge about construction scheduling. It is therefore conceivable that when scheduling manually, some engineering management subjects overlooked several civil engineering considerations and developed a poor quality construction schedule in a short time. However, when they scheduled by computer, the system guided them through the construction planning process and helped them to produce a better schedule. This improvement, however, required additional time from the scheduler. The ability of the system to explain, assist and educate the user has therefore been demonstrated. In fact the average performance time of the engineering management subjects using the computer system was comparable to that of the subjects with civil engineering background.

From the test on variances, the null hypothesis was rejected at both the 0.05 and 0.01 significance levels. The alternative hypothesis was accepted which implies that there is a variability between the two samples. Thus, the two samples of civil engineering and engineering management students cannot be taken as having come from the same population with regard to their variances on the time of performance.

3. Limitations. Since computer scheduling was performed after manual scheduling, learning effects might have contributed some biases towards the result. However, to reduce this bias, alternate designs were assigned for the two scheduling exercises and a time lapse of three weeks was interspersed.

Subjects participating in the experiment were required to identify themselves on the scheduling output. This could constitute an evaluator bias toward the subjects' scheduling outputs. Since two different formats of output were produced, one for the manual and the other for computer, the evaluator could contribute some biases toward either output.

The number of subjects participating in this experiment was 27. Since participation was voluntary and the subjects were selected based on the criteria set forth, it was difficult to recruit more subjects. Furthermore, this experiment required each subject to participate in both scheduling sessions which were timetabled at different times. At each scheduling session, the subjects were required to spend a considerable amount of time and mental energy. This limited the number of participants. If more subjects were available, then the subjects could have been grouped into more refined groupings based on their backgrounds. This could effectively identify which group of users mostly benefit from the system being evaluated.

The project designs selected for this experiment were small enough to allow the assignment to be completed in a reasonable amount of time. However, with more complex designs, a better measure could be achieved. This would however require more time on the part of the participants. Consequently, it would be more difficult to recruit targeted subjects.

E. IMPLICATIONS

1. Contribution. This experiment has contributed towards the formal evaluation of a knowledge-based system. The impact of a knowledge-based computer system in assisting inexperienced construction planners to produce a construction schedule has been examined. Subjects using the computer method performed better and reported better insight into producing construction schedules. The computer system seemed to produce some teaching and learning effects during the consultation. Besides targeting the system for industry use, it could therefore be designed and tailored for teaching purposes. The results achieved in this experiment thus support further development of knowledge-based systems in construction scheduling.

2. Future Evaluation. Future research in the system's evaluation should be directed towards evaluating all the characteristics as outlined in the introduction. In particular, this evaluation should examine the utility of the system in the user environment. However, before these characteristics could be evaluated, this construction schedule planning knowledge-based system should be developed to completion.

Future experiments should look into the possibilities of eliminating the learning effects and the evaluator's bias towards the scheduling output. To eliminate the evaluator's bias, the output from manual scheduling should be presented to the evaluator in the same format as the computer printout.

Future experiments would need bigger sample sizes so that these subjects could be grouped into more distinct backgrounds. The experimental design could then effectively identify the targeted group for the system being tested. The effects on quality and time performance should also be investigated for more complicated construction designs. Different kinds of construction projects could be tested as the prototype system matures and becomes robust enough for extensive evaluation.

VI. CONCLUSION

A. STATE-OF-THE-ART

This dissertation has attempted to formalize the various functional phases for planning and controlling construction operations, to identify the stages of construction planning most suited to the application of knowledge-based system's technique, to summarize some of the reported applications in construction engineering and management using knowledge-based system's methodology, and finally to develop and evaluate a prototype knowledge-based system for application in construction schedule planning.

The approach used in this research is quite different from the typical approaches used in developing a similar knowledge-based system. While in most cases knowledge-based system development starts with rapid prototyping, this research first develops a system model, then prototypes the system based on the model, and finally evaluates the effectiveness of the system by conducting a laboratory experiment. Although a significant number of prototype systems has been developed for construction planning and control purposes, very few prototypes emphasized applications in construction schedule planning areas.

This research effort can therefore be regarded as a small attempt to fill the need of schedulers and planners in the construction industry for a system that could improve their productivity. The approach used in this research is aimed at providing a general system's framework toward achieving this ultimate goal.

B. CONTRIBUTIONS

The overall contribution of this research has been in the development of a construction schedule planning system by incorporating the technique developed from artificial intelligence known as knowledge-based systems. Specifically, the research has extended the body of knowledge in the area of construction planning by:

(1) Development of a construction schedule planning model that mimics the actual process employed by practitioners in the industry.

(2) Development of a computerized system for automated generation of initial construction schedules using a knowledge-based system tool.

(3) Development of a methodology for evaluating the effectiveness of the system as a productivity enhancement tool.

This research has therefore demonstrated the feasibility of applying knowledge system technology to construction schedule planning area. Knowledge system tools such as M.1 have great potential in solving symbolic processing and ill-structured problems commonly encountered in construction. Since a construction schedule normally involves a large number of activities, a computerized system that generates this schedule is desirable. The knowledge-based system developed in this research has consequently suggested the possibility of designing such a system that would automatically generate an initial construction network.

The system development phase of this research has provided a better understanding of the construction schedule planning process. This is achieved through modeling the system. The model has identified the work breakdown process and establishing precedence relationships among tasks as the two major components of schedule planning. The database structure, heuristic formalism and algorithmic procedures identified during modeling have emulated a complete schedule planning process. The architecture of the system is designed to be modular, which makes the system rapid to prototype, adaptable to other domains and easy to update. Although the algorithms are applicable to all construction domains, the database and heuristic contents have to be coded with domain specific knowledge before application in a different problem domain.

From the laboratory experiment conducted, the prototype system developed helped in providing high quality construction schedules despite the limitations of the system. The design of the experiment has provided a methodology for evaluating a knowledge-based system. By conducting the experiment on potential users, a realistic evaluation on the applicability of the system and the targeted user group has been achieved.

The outcome of this research can provide the impetus for further system development and refinement in construction schedule planning areas. From the work being reported in current journals, two teams of researchers are currently active in developing similar systems. These researchers are at Carnegie-Mellon University and Massachusetts Institute of Technology. However, their development is still in its infancy and details of their work is not widely publicized. My research work should therefore be regarded as a contribution to a much wider ongoing effort to develop computer-based solutions for construction planning problems.

C. LIMITATIONS

The prototype system developed in this research lacks the completeness of knowledge. This knowledge is domain specific and covers the description of activities necessary to schedule a particular type of construction. Because of this limitation, the system is not able to produce desirable construction schedules for a wide class of construction projects. However, the system is intelligent enough to conduct a meaningful consultation and was also able to produce high quality schedules for the projects used in the experiment.

Even though the system is able to produce a construction schedule, further refinements are required to make the output more presentable. At present, the output consists of a listing of precedence relationships which may also include a number of redundant relationships. The process of cleaning up these redundancies is straight forward since a procedure is available from operations research to do this job. Some kinds of graphic capability will make the output more readable.

The expertise of a knowledge-based system is derived from the heuristics being acquired and formalized into its knowledge base. For this prototype system, the heuristics are related to the scheduling module breakdown, level of detail and the precedence condition. Since the process of acquiring these heuristics is time consuming, only pertinent rules are formalized in an effort to demonstrate the implementation of the system. This limitation by no means affects the feasibility of the system.

D. FUTURE RESEARCH

Future development should extend this demonstration prototype towards achieving a production standard system. This would require refinement and structuring the work breakdown structure to cover activities within a broader construction domain. An industry standard scheduling format similar to that of MASTERFORMAT and UNIFORMAT needs to be developed. The refinements to the scheduling ouput would require incorporating the algorithm to clean up task redundancies and the graphic capability to draw the output into a logical network.

While the feasibility of building a construction schedule planning system has been demonstrated, the utility of such system needs to be investigated. This would involve researching into users' acceptability of the system in terms of system's interactiveness, ease of use, graphics, output documentations and productivity. A similar laboratory approach that was used during system evaluation in this research could be adopted.

Enhanced system building tools could be used for further development. As new and better tools are available, this would make prototyping much easier in the development environment as well as in the user environment. Future research should investigate building the inference engine and prototyping the system in high level languages instead of using a shell. A knowledge acquisition subsystem could be developed to facilitate building the knowledge base.

Future development should be directed towards developing an integrated system that would interface the newly captured knowledge-base with the conventional database within the domain of construction cost, time and performance. This integration is required to automate planning, scheduling, costing, monitoring and control of the overall construction process.

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VITA

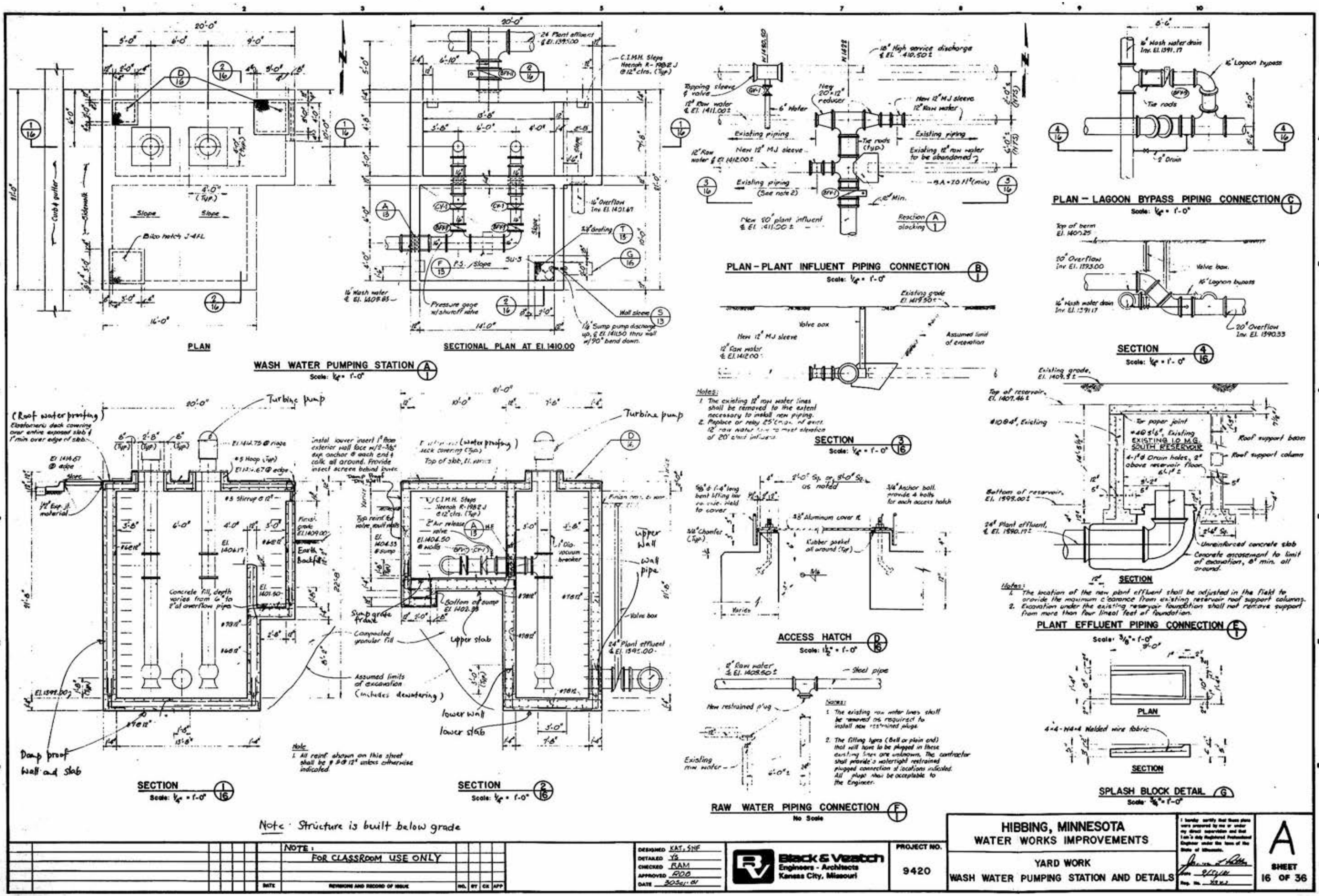
Nordin B. Yunus was born on April 11, 1953 in Kedah, Malaysia. He received a Bachelor of Science degree in Civil Engineering from the University of Manchester, England in July 1976, a Master of Science degree in Civil Engineering from Washington University, St. Louis, Missouri in August 1982 and an Engineer degree in Construction Engineering & Management from the University of Southern California, Los Angeles, California in May 1986.

He has worked with the Public Works Department, Government of Malaysia, as a Civil Engineer from August 1976 to January 1978, District Engineer from February 1978 to January 1980, and Resident Engineer from February 1980 to July 1980. From August 1982 to February 1983, he worked as a Senior Executive Engineer for Design & Research with the same department. On March 1983, he was seconded to the Treasury of Malaysia as a Technical Advisor in the Works & Procurement Division until August 1984. Currently, he is attending the University of Missouri-Rolla since August 1986.

He has attended courses at the University of Malaya, Malaysia, University of Sussex, England and University of Illinois, Urbana-Champaign. He also participated in conferences at Kuala Lumpur, Singapore, Bangkok and Manila. He is a registered professional engineer in Malaysia and a member of the American Society of Civil Engineers, the British Institute of Management and the Institution of Engineers Malaysia.

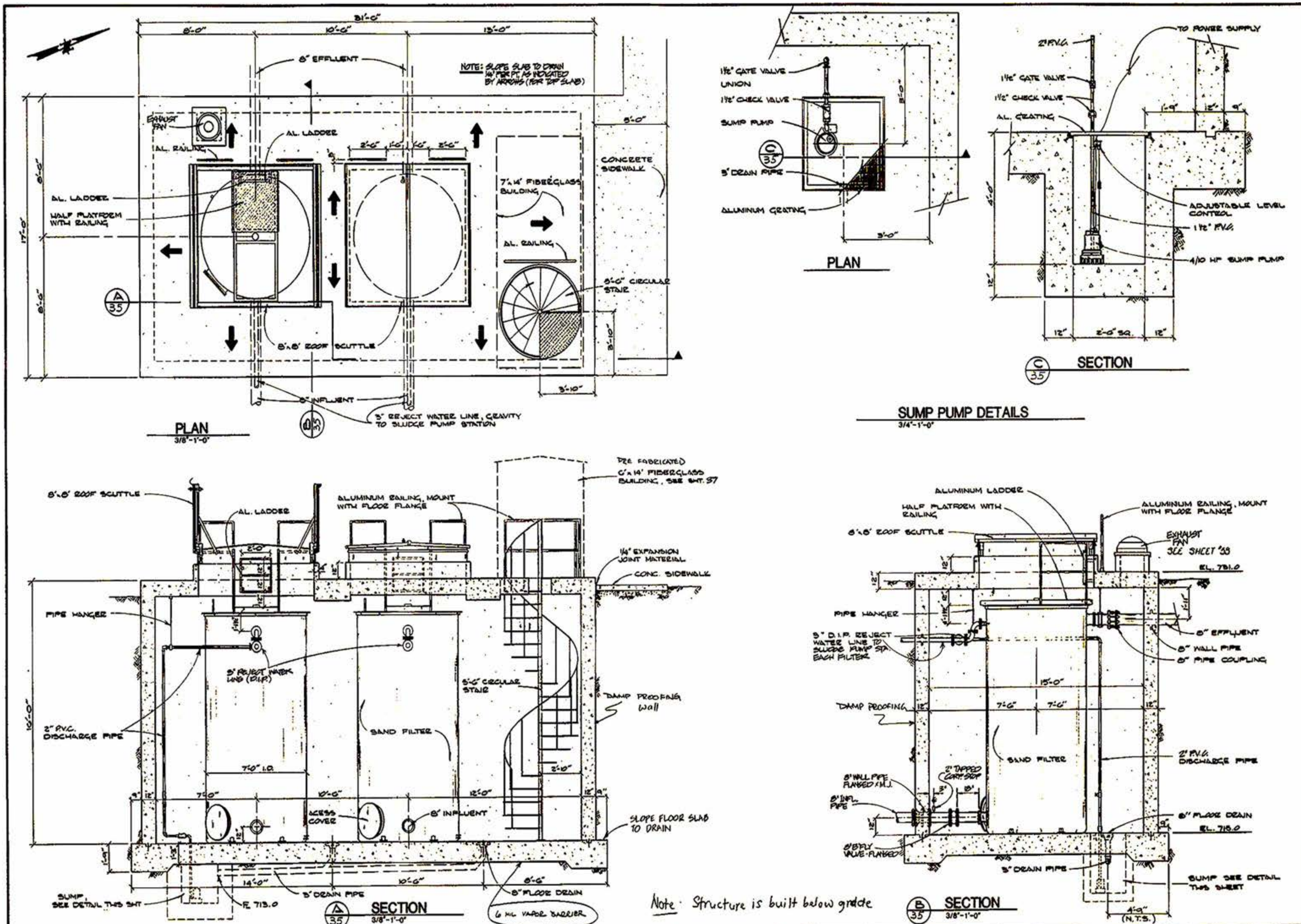
APPENDIX A

PROJECT A: WASH WATER PUMPING STATION


PLAN
SECTIONAL PLAN AT EL. 1410.00
WASH WATER PUMPING STATION (A/1)
Scale: 1/4" = 1'-0"
PLAN - PLANT INFLUENT PIPING CONNECTION (B/1)
Scale: 1/4" = 1'-0"
PLAN - LAGOON BYPASS PIPING CONNECTION (C/1)
Scale: 1/4" = 1'-0"
SECTION (3/16)
Scale: 1/4" = 1'-0"
SECTION (4/16)
Scale: 1/4" = 1'-0"
Notes:
1. The existing 12" raw water lines shall be removed to the extent necessary to install new piping.
Notes:
1. The location of the new plant effluent shall be adjusted in the field to provide the maximum clearance from existing reservoir roof support columns.
2. Excavation under the existing reservoir foundation shall not remove support from more than four lineal feet of foundation.
PLANT EFFLUENT PIPING CONNECTION (E/1)
Scale: 3/8" = 1'-0"
ACCESS HATCH (D/16)
Scale: 1 1/2" = 1'-0"
SPLASH BLOCK DETAIL (G)
SECTION (1/16)
Scale: 1/4" = 1'-0"
SECTION (2/16)
Scale: 1/4" = 1'-0"
Note
1. All reinf. shown on this sheet shall be #5 @ 12" unless otherwise indicated.
Notes:
1. The existing raw water lines shall be removed as required to install new restrained plugs.
2. The fitting types (Bell or plain end) that will have to be plugged in these existing lines are unknown. The contractor shall provide a watertight restrained plugged connection at locations indicated. All plugs shall be acceptable to the Engineer.
RAW WATER PIPING CONNECTION (F/1)
No Scale
Note · Structure is built below grade
Damp proof wall and slab
Turbine pump
NOTE: FOR CLASSROOM USE ONLY
DESIGNED KAT, SHF
DETAILED YS
CHECKED RAM
APPROVED RDD
Black & Veatch
Engineers - Architects
Kansas City, Missouri
PROJECT NO. 9420
HIBBING, MINNESOTA
WATER WORKS IMPROVEMENTS
YARD WORK
WASH WATER PUMPING STATION AND DETAILS
A
SHEET 16 OF 36

APPENDIX B

PROJECT B: SAND FILTER BUILDING



NO.	DATE	REVISION DESCRIPTION	BY	NO.	DATE	REVISION DESCRIPTION
	6-83	As Constructed	J. Cowden			NOTE: FOR CLASSROOM USE ONLY

CRANE & FLEMING
ENGINEERS • ARCHITECTS • SURVEYORS
4500 PARIS GRAVEL RD., HANNIBAL, MO 63401
P.O. BOX 917 TELEPHONE (314) 221-4046

WASTEWATER FACILITY IMPROVEMENTS
ALTON, MISSOURI

SAND FILTERS

B

SURVEYED	DESIGNED	DRAWN	CHECKED	APPROVED	RELEASED	SCALE	DRAWING NO.	PROJECT NO.	SHEET NO.
	M. PEARSON	G. SIX	D. YOHN	D. BOETTCHER		AS SHOWN		80-2099	35

APPENDIX C

KNOWLEDGE BASE LISTING

```
/*=========================================================*/
/*-PROTO.DOC--July 1988----------------------top of file-*/
/*=========================================================*/
/*-Nordin B Yunus -- Department of Engineering Management-*/
/*=========================================================*/

configuration(banner) = ['
                    +---------------------------------------+', '
                    +          WELCOME TO SCHEDULER         +', '
                    +   A CONSTRUCTION SCHEDULE PLANNING    +', '
                    +        KNOWLEDGE BASED SYSTEM         +', '
                    +---------------------------------------+', nl,
nl, '
     This Knowledge-Based System will assist Building Planners &
Schedulers plan and schedule their construction into appropriate
construction activities.  When consulting the system, it is assumed
that the user has prior knowledge about construction and building
technology.', '
     This system will ask simple questions about the project.  If you
do not know the answer to a question, please type <UNKNOWN> at the >>
prompt,  At the end of consultation, the system will recommend with a
list of construction activities and their immediate predecessors.', '
     Before you begin dialog with the system, please take some times
to examine the project drawing provided.  From this drawing you should
be able to identify what are the elements or components of your
project.  All information that are required during this session could
be inferred from the drawing.  Thank you for your participation.',
nl, nl].

configuration(prompt) = "SCH>".
configuration(startup) = go.
disable(list).
nolist(X).

initialdata = [proceed, done].

noautomaticquestion(ALL).
automaticmenu(ALL).
enumeratedanswers(ALL).

question(begin) = ['Would you like to begin now ?'].
legalvals(begin) = [yes, no].

if begin and
   display(['\f', nl, nl, '
                    +---------------------------------------+', '
                    +                                       +', '
                    +   A CONSTRUCTION SCHEDULE PLANNING    +', '
                    +        KNOWLEDGE BASED SYSTEM         +', '
                    +                                       +', '
                    +---------------------------------------+', nl,
nl])
then proceed.

if (begin = no or
   begin is unknown) and
   display(['\f', nl, nl, '
                    +---------------------------------------+', '
                    +                                       +', '
                    +   A CONSTRUCTION SCHEDULE PLANNING    +', '
                    +        KNOWLEDGE BASED SYSTEM         +', '
                    +                                       +', '
                    +---------------------------------------+', nl,
nl, '
                        You are now aborting the system.', nl, '
             To continue consultation, type <go> at the SCH> prompt.',
nl, '
                To return to DOS, type <exit> at the SCH> prompt.',
nl, nl, nl]) and
```

```
/*======================================================*/
/*-PROTO.DOC--July 1988----------------------top of file-*/
/*======================================================*/
/*-Nordin B Yunus -- Department of Engineering Management-*/
/*======================================================*/

configuration(banner) = ['
                    +--------------------------------------+', '
                    +          WELCOME TO SCHEDULER        +', '
                    +  A CONSTRUCTION SCHEDULE PLANNING    +', '
                    +        KNOWLEDGE BASED SYSTEM        +', '
                    +--------------------------------------+', nl,
nl, '
     This Knowledge-Based System will assist Building Planners &
Schedulers plan and schedule their construction into appropriate
construction activities.  When consulting the system, it is assumed
that the user has prior knowledge about construction and building
technology.', '
     This system will ask simple questions about the project.  If you
do not know the answer to a question, please type <UNKNOWN> at the >>
prompt,  At the end of consultation, the system will recommend with a
list of construction activities and their immediate predecessors.', '
     Before you begin dialog with the system, please take some times
to examine the project drawing provided.  From this drawing you should
be able to identify what are the elements or components of your
project.  All information that are required during this session could
be inferred from the drawing.  Thank you for your participation.',
nl, nl].

configuration(prompt) = "SCH>".
configuration(startup) = go.
disable(list).
nolist(X).

initialdata = [proceed, done].

noautomaticquestion(ALL).
automaticmenu(ALL).
enumeratedanswers(ALL).

question(begin) = ['Would you like to begin now ?'].
legalvals(begin) = [yes, no].

if begin and
   display(['\f', nl, nl, '
                    +--------------------------------------+', '
                    +                                      +', '
                    +  A CONSTRUCTION SCHEDULE PLANNING    +', '
                    +        KNOWLEDGE BASED SYSTEM        +', '
                    +                                      +', '
                    +--------------------------------------+', nl,
nl])
then proceed.

if (begin = no or
   begin is unknown) and
   display(['\f', nl, nl, '
                    +--------------------------------------+', '
                    +                                      +', '
                    +  A CONSTRUCTION SCHEDULE PLANNING    +', '
                    +        KNOWLEDGE BASED SYSTEM        +', '
                    +                                      +', '
                    +--------------------------------------+', nl,
nl, '
                        You are now aborting the system.', nl, '
          To continue consultation, type <go> at the SCH> prompt.',
nl, '
                To return to DOS, type <exit> at the SCH> prompt.',
nl, nl, nl]) and
```

```
   do(abort)
 then proceed.

 if do(log inf.doc) and
    wbs and
    display(['\f',
'knowledgebasedsystemknowledgebasedsystemknowledgebasedsystemknowledge
basedsystem', nl, nl, nl, nl, nl,
'                                    A', nl,
'                      Construction Schedule Planning', nl,
'                          KNOWLEDGE BASED SYSTEM', nl, nl, nl, nl,
nl,
'                          End of Consultation', nl, nl,
'                    Please Wait For Recommendations', nl, nl, nl,
nl, nl, nl,
'                          .....thinking!.....', nl,
'                                    ']) and
    (pre10 = yes or pre10 is unknown) and
    (pre21 = yes or pre21 is unknown) and
    (pre22 = yes or pre22 is unknown) and
    (pre23 = yes or pre23 is unknown) and
    (pre24 = yes or pre24 is unknown) and
    (pre25 = yes or pre25 is unknown) and
    (pre30 = yes or pre30 is unknown) and
    (pre99 = yes or pre99 is unknown) and
    do(reset activity-"00000A") and
    do(reset activity-"99999A") and
    do(reset "99999A"-"Finish"-"¬"-"00000A"-"Start") and
    do(reset ACTIV-PROC-"¬"-ACTIV-PROC) and
    do(log inf) and
    display(['\f', nl,
nl, 'RECOMMENDATIONS', nl]) and
    display([nl, nl, 'Activity Listing:', nl, nl]) and
    do(show activity-XXX) and
    display(['#', '\f', 'Precedence Relationship:', nl, nl,
'     12345A-Activity', nl,
'            67890A-Immediate predecessor', nl, nl]) and
    do(show ACTIV-PROC-"¬"-FIRST-PREC) and
    display(['\f', nl, nl, '
                    +--------------------------------------+', '
                    +                                      +', '
                    +   A CONSTRUCTION SCHEDULE PLANNING   +', '
                    +        KNOWLEDGE BASED SYSTEM        +', '
                    +                                      +', '
                    +--------------------------------------+', nl,
nl, '
                         PROGRAM EXECUTION COMPLETED', nl, '
          To get a hard copy of the RECOMMENDATION, press <F10>.',
nl, '
          To begin a new consultation, type <go> at the SCH>
prompt.',
nl, '
             To return to DOS, type <exit> at the SCH> prompt.',
nl,  nl, nl, nl]) and
   display([nl, nl])
then done.

/*--------------------------------------------------------*/
/* ACTIVITY BREAKDOWN  ALGORITHM */
/*--------------------------------------------------------*/
if (con = yes or
   con is unknown) and
   work00 = WBS and
   (breakdown-WBS or
   breakdown-WBS is unknown)
then wbs.

if WBS == [FIRST|REST] and
   (select-FIRST or
   select-FIRST is unknown) and
```

```
   breakdown-REST is unknown
then breakdown-WBS.

if act-CODE = yes and
   do(set pact-CODE = yes) and
   do(set schd-CODE = yes) and
   CODE = TASKLIST and
   display(['\f', 'Please Wait ...']) and
   (analyze-CODE-TASKLIST = yes or
   analyze-CODE-TASKLIST is unknown) and
   notdel-CODE is unknown and
   display(['\f', 'Please Wait ...']) and
   (substitute-CODE-TASKLIST = yes or
   substitute-CODE-TASKLIST is unknown)
then select-CODE.

if TASKLIST == [FIRST|REST] and
   act-FIRST = yes and
   do(set pact-FIRST = yes) and
   do(set schd-FIRST = yes) and
   activity-FIRST = TASK and
   do(reset activity-CODE) and
   do(reset schd-CODE) and
   do(set notdel-CODE = yes) and
   display(['\f', 'Please Wait ...']) and
   analyze-CODE-REST is unknown
then analyze-CODE-TASKLIST.

if TASKLIST == [FIRST|REST] and
   (act-FIRST = no or
   act-FIRST is unknown) and
   display(['\f', 'Please Wait ...']) and
   analyze-CODE-REST is unknown
then analyze-CODE-TASKLIST.

if TASKLIST == [FIRST|REST] and
   do(set schd-FIRST = schd-CODE) and
   display(['\f', 'Please Wait ...']) and
   (trace-CODE-FIRST = yes or
   trace-CODE-FIRST is unknown) and
   display(['\f', 'Please Wait ...']) and
   substitute-CODE-REST is unknown
then substitute-CODE-TASKLIST.

if CODE = TASKLIST and
   display(['\f', 'Please Wait ...']) and
   (substitute-PARENT-TASKLIST or
   substitute-PARENT-TASKLIST is unknown)
then trace-PARENT-CODE.

/*------------------------------------------------------*/
/* TASK SEQUENCING ALGORITHM */
/*------------------------------------------------------*/
if pact-"02000A" = yes and
   task10 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre10.

if pact-"21000A" = yes and
   task21 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre21.

if pact-"22000A" = yes and
   task22 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre22.
```

```
if pact-"23000A" = yes and
   task23 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre23.

if pact-"24000A" = yes and
   task24 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre24.

if pact-"25000A" = yes and
   task25 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre25.

if pact-"30000A" = yes and
   task30 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre30.

if pact-"99999A" = yes and
   task99 = ALL and
   (sequence-ALL = yes or
   sequence-ALL is unknown)
then pre99.

if WBS == [FIRST|REST] and
   ((pact-FIRST = no or
   pact-FIRST is unknown) and
   (schd-FIRST = no or
   schd-FIRST is unknown)) and
   sequence-REST is unknown
then sequence-WBS.

if WBS == [FIRST|REST] and
   pact-FIRST = yes and
   schd-FIRST = yes and
   stringjoin(['A', FIRST]) = AFIRST and
   (actv-FIRST-AFIRST = yes or
   actv-FIRST-AFIRST is unknown) and
   sequence-REST is unknown
then sequence-WBS.

if WBS == [FIRST|REST] and
   schd-FIRST = schd-PARENT and
   stringjoin(['A', FIRST]) = AFIRST and
   (actv-PARENT-AFIRST = yes or
   actv-PARENT-AFIRST is unknown) and
   sequence-REST is unknown
then sequence-WBS.

if AACT = LIST and
   (prec-ACT-LIST or
   prec-ACT-LIST is unknown)
then actv-ACT-AACT.

if LIST == [FIRST|REST] and
   schd-FIRST = yes and
   pact-FIRST = yes and
   activity-FIRST = PREC and
   activity-ACTIV = PROC and
   do(set ACTIV-PROC-"¬"-FIRST-PREC) and
   prec-ACTIV-REST is unknown
then prec-ACTIV-LIST.
```

```
if LIST == [FIRST|REST] and
   (schd-FIRST = no or
   schd-FIRST is unknown) and
   pact-FIRST = yes and
   (replace-ACTIV-FIRST = yes or
   replace-ACTIV-FIRST is unknown) and
   prec-ACTIV-REST is unknown
then prec-ACTIV-LIST.

if CHILD = TASKLIST and
   (prec-PARENT-TASKLIST = yes or
   prec-PARENT-TASKLIST is unknown)
then replace-PARENT-CHILD.

if LIST == [FIRST|REST] and
   (schd-FIRST = no or
   schd-FIRST is unknown) and
   (pact-FIRST = no or
   pact-FIRST is unknown) and
   (backtrack-ACTIV-FIRST = yes or
   backtrack-ACTIV-FIRST is unknown) and
   prec-ACTIV-REST is unknown
then prec-ACTIV-LIST.

if stringjoin(['A', PREC]) = APREC and
   APREC = TASKLIST and
   (prec-LEADER-TASKLIST or
   prec-LEADER-TASKLIST is unknown)
then backtrack-LEADER-PREC.

if stringjoin(['A', PREC]) = APREC and
   APREC is unknown and
   (replace-LEADER-PREC or
   replace-LEADER-PREC is unknown)
then backtrack-LEADER-PREC.

if LIST == [FIRST|REST] and
   schd-FIRST = schd-PARENT and
   activity-PARENT = PREC and
   activity-ACTIV = PROC and
   do(set ACTIV-PROC-"¬"-PARENT-PREC) and
   prec-ACTIV-REST is unknown
then prec-ACTIV-LIST.

/*-----------------------------------------------------*/
/* TASK REDUNDANCY ALGORITHM */
/*-----------------------------------------------------*/

/*-----------------------------------------------------*/
/* HEURISTICS */
/*-----------------------------------------------------*/
/* START/FINISH */
/*-----------------------------------------------------*/
act-"00000A" = yes.
pact-"000C0A" = yes.
schd-"00000A" = yes.

act-"99999A" = yes.
pact-"99999A" = yes.
schd-"99999A" = yes.

/*-----------------------------------------------------*/
/* CONSTRUCTION */
/*-----------------------------------------------------*/
act-"10000A" = yes.

if activity-"10000A" = Y and
   act-"10000A" = yes
then con.
```

```
multivalued(construction).
question(construction) = ['\f', "In construction, the project could be
broken down into site work, substructural work and superstructural
work.", nl, nl, "SITE WORKS are works related to site preparation,
demolition, paving and surfacing of sidewalk, curb, etc. and other
similar works that are external to the building.", nl, nl,
"SUBSTRUCTURAL WORKS are foundation, structural and architectural
works that are constructed below the grade or ground surface.", nl,
nl, "SUPERSTRUCTURAL WORKS are structural and architectural works that
are constructed above the grade or ground surface.", nl, nl, "Please
identify the major breakdowns for your building construction
project.", nl, "Select one or more from the list below:"].
legalvals(construction) = ["Site work", "Substructural work",
"Superstructural work"].

if construction = "Site work"
then act-"02000A".

if construction = "Substructural work"
then act-"20000A".

if construction = "Superstructural work"
then act-"30000A".

/*-------------------------------------------------------*/
/* SUBSTRUCTURAL WORK */
/*-------------------------------------------------------*/
presupposition(member-"20000A") = act-"20000A".
multivalued(member-"20000A").
question(member-"20000A") = ['\f', 'For the substructural work, please
identify the works associated with your construction.', nl, nl,
'FOUNDATION WORKS are works associated with earthwork, excavation,
backfill, compaction, dewatering, piling and others that prepare the
base for the building.', nl, nl, 'STRUCTURAL WORKS are works
associated with the construction of structural floors, walls, roofs
and stairs.', nl, nl, 'ARCHITECTURAL WORKS are works associated with
finishes, moisture protection and the installation of structural
accessories.', nl, nl, 'Select one or more from the list below:'].
legalvals(member-"20000A") = ["Foundation work", "Structural work",
"Architectural work"].

if member-"20000A" = "Foundation work"
then act-"21000A".

if member-"20000A" = "Structural work"
then act-"22000A".

if member-"20000A" = "Architectural work"
then act-"23000A".

presupposition(act-"24000A") = act-"20000A".
question(act-"24000A") = ['\f', 'Do you need to build and install
works related to MECHANICAL?', nl, 'Mechanical work includes the
installation of pumps, equipments, plumbing and pipings, etc.'].
legalvals(act-"24000A") = [yes,no].

presupposition(act-"25000A") = act-"20000A".
question(act-"25000A") = ['\f', 'Do you need to build and install
works related to ELECTRICAL?', nl, 'Electrical work includes the
installation of electrical wiring, lighting, communications, high
voltage distribution, etc.'].
legalvals(act-"25000A") = [yes,no].

/*-------------------------------------------------------*/
/* FOUNDATION WORK */
/*-------------------------------------------------------*/
presupposition(act-"02221A") = act-"21000A".
question(act-"02221A") = ['\f', 'For the SUBSTRUCTURAL work, do you
need to excavate the FOUNDATION?'].
legalvals(act-"02221A") = [yes, no].
```

```
multivalued(construction).
question(construction) = ['\f', "In construction, the project could be
broken down into site work, substructural work and superstructural
work.", nl, nl, "SITE WORKS are works related to site preparation,
demolition, paving and surfacing of sidewalk, curb, etc. and other
similar works that are external to the building.", nl, nl,
"SUBSTRUCTURAL WORKS are foundation, structural and architectural
works that are constructed below the grade or ground surface.", nl,
nl, "SUPERSTRUCTURAL WORKS are structural and architectural works that
are constructed above the grade or ground surface.", nl, nl, "Please
identify the major breakdowns for your building construction
project.", nl, "Select one or more from the list below:"].
legalvals(construction) = ["Site work", "Substructural work",
"Superstructural work"].

if construction = "Site work"
then act-"02000A".

if construction = "Substructural work"
then act-"20000A".

if construction = "Superstructural work"
then act-"30000A".

/*-------------------------------------------------------*/
/* SUBSTRUCTURAL WORK */
/*-------------------------------------------------------*/
presupposition(member-"20000A") = act-"20000A".
multivalued(member-"20000A").
question(member-"20000A") = ['\f', 'For the substructural work, please
identify the works associated with your construction.', nl, nl,
'FOUNDATION WORKS are works associated with earthwork, excavation,
backfill, compaction, dewatering, piling and others that prepare the
base for the building.', nl, nl, 'STRUCTURAL WORKS are works
associated with the construction of structural floors, walls, roofs
and stairs.', nl, nl, 'ARCHITECTURAL WORKS are works associated with
finishes, moisture protection and the installation of structural
accessories.', nl, nl, 'Select one or more from the list below:'].
legalvals(member-"20000A") = ["Foundation work", "Structural work",
"Architectural work"].

if member-"20000A" = "Foundation work"
then act-"21000A".

if member-"20000A" = "Structural work"
then act-"22000A".

if member-"20000A" = "Architectural work"
then act-"23000A".

presupposition(act-"24000A") = act-"20000A".
question(act-"24000A") = ['\f', 'Do you need to build and install
works related to MECHANICAL?', nl, 'Mechanical work includes the
installation of pumps, equipments, plumbing and pipings, etc.'].
legalvals(act-"24000A") = [yes,no].

presupposition(act-"25000A") = act-"20000A".
question(act-"25000A") = ['\f', 'Do you need to build and install
works related to ELECTRICAL?', nl, 'Electrical work includes the
installation of electrical wiring, lighting, communications, high
voltage distribution, etc.'].
legalvals(act-"25000A") = [yes,no].

/*-------------------------------------------------------*/
/* FOUNDATION WORK */
/*-------------------------------------------------------*/
presupposition(act-"02221A") = act-"21000A".
question(act-"02221A") = ['\f', 'For the SUBSTRUCTURAL work, do you
need to excavate the FOUNDATION?'].
legalvals(act-"02221A") = [yes, no].
```

```
presupposition(act-"02140A") = act-"02221A".
question(act-"02140A") = ['\f', 'During excavation, do you need to
DEWATER the foundation?'].
legalvals(act-"02140A") = [yes, no].

presupposition(act-"02222A") = act-"02221A".
question(act-"02222A") = ['\f', 'After excavation, do you need to
BACKFILL and compact the foundation?'].
legalvals(act-"02222A") = [yes, no].

/*-------------------------------------------------------*/
/* STRUCTURAL WORK */
/*-------------------------------------------------------*/
presupposition(member-"22000A") = act-"22000A".
multivalued(member-"22000A").
question(member-"22000A") = ['\f', 'STRUCTURAL elements of a building
SUBSTRUCTURE might consist of the frame, floor, wall and roof.', nl,
nl, 'FRAME is the skeleton structure that made up of columns, beams
and girders.', nl, nl, 'FLOOR is the horizontal structure that made up
of slabs and/or beams,', nl, nl, 'WALL is made of reinforced concrete
or masonry (such as the hollow blocks and the bricks).', nl, nl, 'ROOF
is made up of slabs and/or beams or other materials such as the steel
and wood frames and trusses.', nl, nl, 'For your project, please
identify these elements.', nl, 'Select one or more from the list
below:'].
legalvals(member-"22000A") = ["Frame", "Floor", "Wall", "Roof"].

if member-"22000A" = "Floor"
then act-"22000F".

if member-"22000A" = "Wall"
then act-"22000W".

if member-"22000A" = "Roof"
then act-"22000R".

presupposition(act-"22000S") = act-"22000A".
question(act-"22000S") = ['\f', 'Do you need to build some kinds of
STRUCTURAL stairs, ladders or steps?'].
legalvals(act-"22000S") = [yes,no].

presupposition(type-"22000F") = act-"22000F".
question(type-"22000F") = ['\f', 'What kind of STRUCTURAL floor is
it?', nl, 'Select ONE from the list below:'].
legalvals(type-"22000F") = ["Concrete slab on grade", "Precast
concrete slab", "Mass concrete"].

if type-"22000F" = "Concrete slab on grade"
then act-"22001F".

presupposition(act-"22010F") = act-"22000F".
question(act-"22010F") = ['\f', 'Do you need to build some kinds of
concrete SUMP within the floor slab?'].
legalvals(act-"22010F") = [yes,no].

presupposition(oper-"22001F") = act-"22001F".
question(oper-"22001F") = ['\f', 'Would you like to build the floor
slab into TWO or MORE operations depending on the different floor
levels?'].
legalvals(oper-"22001F") = [yes, no].

if oper-"22001F" = yes
then act-"22002F" = yes.

if oper-"22001F" = yes
then act-"22003F" = yes.

if oper-"22001F" = yes and
   act-"22010F" = yes and
```

```
   do(reset act-"22010F")
then act-"22011F" = yes.

presupposition(act-"02223W") = act-"02222A".
if oper-"22001F" = yes and
   do(reset act-"02222A")
then act-"02223W" = yes.

if oper-"22001F" = yes
then act-"02224W" = yes.

presupposition(bed-"22001F") = oper-"22001F" = no.
question(bed-"22001F") = ['\f', 'Would there be any pipes or conduits
embedded under the floor slab?'].
legalvals(bed-"22001F") = [yes, no].

if bed-"22001F" = yes
then act-"03100F" = yes.

if bed-"22001F" = yes
then act-"03300F" = yes.

presupposition(bed-"22002F") = act-"22002F".
question(bed-"22002F") = ['\f', 'Would there be any pipes or conduits
embedded under the lower floor slab?'].
legalvals(bed-"22002F") = [yes, no].

if bed-"22002F" = yes
then act-"03102F" = yes.

if bed-"22002F" = yes
then act-"03302F" = yes.

presupposition(bed-"22003F") = act-"22003F".
question(bed-"22003F") = ['\f', 'Would there be any pipes or conduits
embedded under the upper floor slab?'].
legalvals(bed-"22003F") = [yes, no].

if bed-"22003F" = yes
then act-"03103F" = yes.

if bed-"22003F" = yes
then act-"03303F" = yes.

presupposition(type-"22000W") = act-"22000W".
question(type-"22000W") = ['\f', 'What kind of STRUCTURAL wall is
it?', nl, 'Select ONE from the list below:'].
legalvals(type-"22000W") = ["Reinforced Concrete Wall", "Reinforced
Masonry Wall"].

if type-"22000W" = "Reinforced Concrete Wall"
then act-"22001W".

presupposition(oper-"22001W") = act-"22001W".
question(oper-"22001W") = ['\f', 'Would you like to build the wall
into TWO or MORE operations depending on the different floor
levels?'].
legalvals(oper-"22001W") = [yes, no].

if oper-"22001W" = yes
then act-"22002W" = yes.

if oper-"22001W" = yes
then act-"22003W" = yes.

presupposition(bed-"22001W") = oper-"22001W" = no.
question(bed-"22001W") = ['\f', 'Would there be any pipes or conduits
embedded in or projected through the wall?'].
legalvals(bed-"22001W") = [yes, no].
```

```
if bed-"22001W" = yes
then act-"03100W" = yes.

if bed-"22001W" = yes
then act-"03300W" = yes.

presupposition(bed-"22002W") = act-"22002W".
question(bed-"22002W") = ['\f', 'Would there be any pipes or conduits
embedded in or projected through the lower wall?'].
legalvals(bed-"22002W") = [yes, no].

if bed-"22002W" = yes
then act-"03102W" = yes.

if bed-"22002W" = yes
then act-"03302W" = yes.

presupposition(bed-"22003W") = act-"22003W".
question(bed-"22003W") = ['\f', 'Would there be any pipes or conduits
embedded in or projected through the upper wall?'].
legalvals(bed-"22003W") = [yes, no].

if bed-"22003W" = yes
then act-"03103W" = yes.

if bed-"22003W" = yes
then act-"03303W" = yes.

presupposition(type-"22000R") = act-"22000R".
question(type-"22000R") = ['\f', 'What kind of STRUCTURAL roof is
it?', nl, 'Select ONE from the list below:'].
legalvals(type-"22000R") = ["Reinforced concrete roof deck",
"Composite steel-concrete roof deck", "Steel joist/truss roof
framing", "Wood joist/truss roof framing"].

if type-"22000R" = "Reinforced concrete roof deck"
then act-"22001R".

presupposition(bed-"22001R") = act-"22001R".
question(bed-"22001R") = ['\f', 'Would there be any openings or roof
accessories to be installed on the roof?'].
legalvals(bed-"22001R") = [yes, no].

if bed-"22001R" = yes
then act-"03100R" = yes.

if bed-"22001R" = yes
then act-"03300R" = yes.

presupposition(type-"22000S") = act-"22000S".
multivalued(type-"22000S").
question(type-"22000S") = ['\f', 'What types of STAIRS are needed to
be built or installed?', nl, 'Select one or more from the list
below:'].
legalvals(type-"22000S") = ["Reinforced concrete stair", "Spiral steel
stair", "Grouted M.H. steel steps", "Roof access alluminium ladder"].

if type-"22000S" = "Spiral steel stair"
then act-"05715S".

if type-"22000S" = "Grouted M.H. steel steps"
then act-"05525S".

if type-"22000S" = "Roof access alluminium ladder"
then act-"05515S".

/*---------------------------------------------------------*/
/* ARCHITECTURAL WORK */
/*---------------------------------------------------------*/
```

```
if act-"22000F" = yes
then act-"23000F" = yes.

if act-"22000W" = yes
then act-"23000W" = yes.

if act-"22000R" = yes
then act-"23000R" = yes.

if act-"22000F" = yes and
   act-"22000W" = yes and
   act-"22000R" = yes
then act-"23000G" = yes.

presupposition(type-"23000F") = act-"23000F".
multivalued(type-"23000F").
question(type-"23000F") = ['\f', 'Moisture protections are materials
applied to walls, slabs and decks.  They are classified into water
proofing, damp proofing and vapor retarder/barrier.', nl, 'What kinds
of moisture protections are required for the FLOOR?', nl, 'Select one
or more from the list below:'].
legalvals(type-"23000F") = ["Waterproofing", "Damp proofing", "Vapor
retarder/barrier"].

if type-"23000F" = "Damp proofing"
then act-"07150F".

if type-"23000F" = "Vapor retarder/barrier"
then act-"07192F".

if act-"22010F" = yes
then act-"05530F" = yes.

presupposition(type-"23000W") = act-"23000W".
multivalued(type-"23000W").
question(type-"23000W") = ['\f', 'Moisture protections are materials
applied to walls, slabs and decks.  They are classified into water
proofing, damp proofing and vapor retarder/barrier.', nl, 'What kinds
of moisture protections are required for the WALL?', nl, 'Select one
or more from the list below:'].
legalvals(type-"23000W") = ["Waterproofing", "Damp proofing", "Vapor
retarder/barrier"].

if type-"23000W" = "Damp proofing"
then act-"07150W".

presupposition(type-"23001W") = act-"23000W".
multivalued(type-"23001W").
question(type-"23001W") = ['\f', 'What kinds of accessories and
specialties are required for the wall?', nl, 'Select one or more from
the list below:'].
legalvals(type-"23001W") = ["Louvers and vents", "Grilles and
screens", "Windows", "Doors"].

if type-"23001W" = "Louvers and vents"
then act-"10200W".

if type-"23001W" = "Grilles and screens"
then act-"10240W".

presupposition(type-"23000R") = act-"23000R".
multivalued(type-"23000R").
question(type-"23000R") = ['\f', 'Moisture protections are materials
applied to walls, slabs and decks.  They are classified into water
proofing, damp proofing and vapor retarder/barrier.', nl, 'What kinds
of moisture protections are required for the ROOF?', nl, 'Select one
or more from the list below:'].
legalvals(type-"23000R") = ["Waterproofing", "Damp proofing", "Vapor
retarder/barrier"].
```

```
if type-"23000R" = "Waterproofing"
then act-"07100R".

presupposition(act-"07720R") = act-"23000R".
question(act-"07720R") = ['\f', 'Do you need to build and install some
kinds of ROOF ACCESSORIES like hatches, scuttle, railings etc?'].
legalvals(act-"07720R") = [yes,no].

presupposition(type-"07720R") = act-"07720R".
multivalued(type-"07720R").
question(type-"07720R") = ['\f', 'What types of accessories are
required for the roof?', nl, 'Select one or more from the list
below:'].
legalvals(type-"07720R") = ["Prefabricated hatches", "Bilco hatches",
"Scuttle", "Railing", "Prefabricated building"].

if type-"07720R" = "Prefabricated hatches"
then act-"07721R".

if type-"07720R" = "Bilco hatches"
then act-"07722R".

if type-"07720R" = "Scuttle"
then act-"07723R".

if type-"07720R" = "Railing"
then act-"05520R".

if type-"07720R" = "Prefabricated building"
then act-"10280R".

/*-------------------------------------------------------*/
/* MECHANICAL WORK */
/*-------------------------------------------------------*/
presupposition(type-"24000A") = act-"24000A".
multivalued(type-"24000A").
question(type-"24000A") = ['\f', 'What types of plumbing and pipings
are required for the MECHANICAL work?', nl, 'Select one or more from
the list below:'].
legalvals(type-"24000A") = ["Water distribution piping", "Floor drain
pipes", "Wall pipes - pipes that project through the wall", "HVAC
piping"].

if type-"24000A" = "Water distribution piping"
then act-"15400A".

if type-"24000A" = "Floor drain pipes"
then act-"02721F".

if type-"24000A" = "Wall pipes - pipes that project through the wall"
then act-"15410W".

if oper-"22001W" = yes
then act-"15412W" = yes.

if oper-"22001W" = yes
then act-"15413W" = yes.

presupposition(act-"15865R") = act-"24000A".
question(act-"15865R") = ['\f', 'Would you need to install some kinds
of ROOF EXHAUST FAN for ventilation purposes?'].
legalvals(act-"15865R") = [yes, no].

presupposition(type-"24001A") = act-"24000A".
multivalued(type-"24001A").
question(type-"24001A") = ['\f', 'What types of water supply and
treatment EQUIPMENT are required to be installed?', nl, 'Select one or
more from the list below:'].
legalvals(type-"24001A") = ["Turbine pump", "Clarifiers", "Sand
filters", "Sump pump", "Flouridation equipment"].
```

```
if type-"24001A" = "Sump pump"
then act-"11210F".

if type-"24001A" = "Turbine pump"
then act-"11211A".

if type-"24001A" = "Sand filters"
then act-"11201A".

/*--------------------------------------------------------*/
/* SITE WORK */
/*--------------------------------------------------------*/
presupposition(type-"02000A") = act-"02000A".
multivalued(type-"02000A").
question(type-"02000A") = ['\f', 'What types of exterior pavings and
surfacings are included as part of the SITE WORK?', nl, 'Select one or
more from the list below:'].
legalvals(type-"02000A") = ["Concrete sidewalk", "Sidewalk curbs and
gutters", "Brick pavers", "Bituminous surfacing"].

if type-"02000A" = "Concrete sidewalk"
then act-"02510A".

if type-"02000A" = "Sidewalk curbs and gutters"
then act-"02525A".

/*--------------------------------------------------------*/
/* HIERARCHY OF ACTIVITIES DATABASE */
/*--------------------------------------------------------*/
"10000A" = ["02000A", "20000A", "30000A"].
"20000A" = ["21000A", "22000A", "23000A", "24000A", "25000A"].
"21000A" = ["02221A", "02140A", "02222A"].
"22000A" = ["22000F", "22000W", "22000R", "22000S"].
"22000F" = ["22001F", "22010F"].
"22001F" = ["22002F", "22003F", "22011F", "02223W", "02224W",
"03100F", "03300F"].
"22002F" = ["03102F", "03302F"].
"22003F" = ["03103F", "03303F"].
"22000W" = ["22001W"].
"22001W" = ["22002W", "22003W", "03100W", "03300W"].
"22002W" = ["03102W", "03302W"].
"22003W" = ["03103W", "03303W"].
"22000R" = ["22001R"].
"22001R" = ["03100R", "03300R"].
"22000S" = ["05715S", "05525W", "05515R"].
"23000A" = ["23000F", "23000W", "23000R", "23000G"].
"23000F" = ["07150F", "07192F", "05530F"].
"23000W" = ["07150W", "10200W", "10240W"].
"23000R" = ["07100R", "07720R"].
"07720R" = ["07721R", "07722R", "07723R", "05520R", "10280R"].
"24000A" = ["15400A", "02721F", "15410W", "15865R", "11210F",
"11211A", "11201A"].
"15410W" = ["15412W", "15413W"].
"02000A" = ["02510A", "02525A"].

/*--------------------------------------------------------*/
/* TASKS PRECEDENT RELATIONSHIP DATABASE */
/*--------------------------------------------------------*/
"A02510A" = ["02525A", "11211A", "11201A"].
"A02525A" = ["07721R"].

"A02221A" = ["00000A"].
"A02222A" = ["22001W"].
"A02140A" = ["02221A"].
"A02223W" = ["22002W"].
"A02224W" = ["07150W"].

"A22010F" = ["02221A", "02140A"].
"A22011F" = ["02223W"].
```

```
"A03100F" = ["22010F", "07192F"].
"A03300F" = ["03100F"].
"A03102F" = ["07192F"].
"A03302F" = ["03102F"].
"A03103F" = ["22010F", "07192F"].
"A03303F" = ["03103F"].
"A03100W" = ["22001F"].
"A03300W" = ["03100W"].
"A03102W" = ["03302F"].
"A03302W" = ["03102W", "15412W"].
"A03103W" = ["03303F"].
"A03303W" = ["03103W", "15413W"].
"A03100R" = ["03303W"].
"A03300R" = ["03100R", "07722R"].
"A05715S" = ["03300R"].
"A05525W" = ["03302W", "03303W"].
"A05515R" = ["22001R"].
"A23000G" = ["03300R"].

"A07150F" = ["22001F"].
"A07192F" = ["02140A"].
"A05530F" = ["02223W"].
"A07150W" = ["03300W"].
"A10200W" = ["03300W"].
"A10240W" = ["10200W"].
"A07100R" = ["03300R"].
"A07721R" = ["07100R"].
"A07722R" = ["03100R"].
"A07723R" = ["22001R"].
"A05520R" = ["22001R"].
"A10280R" = ["05715S"].

"A15400A" = ["11211A"].
"A02721F" = ["03102F"].
"A15865R" = ["03300R"].
"A11210F" = ["03300R"].
"A11211A" = ["03300R"].
"A11201A" = ["03300R"].
"A15412W" = ["03302W"].
"A15413W" = ["03303W"].

"A99999A" = ["02525A", "02510A", "23000G"].
"A30000A" = ["20000A"].
"A25000A" = ["22000A"].

/*------------------------------------------------------*/
/* PROJECT ACTIVITIES DATABASE */
/*------------------------------------------------------*/
activity-"00000A" = "Start".

activity-"99999A" = "Finish".

activity-"10000A" = "Build all construction work".

activity-"02000A" = "Build all site work".
activity-"20000A" = "Build all substructural work".
activity-"30000A" = "Build all superstructural work".

activity-"21000A" = "Build all foundation work".
activity-"22000A" = "Build all structural work".
activity-"23000A" = "Build all architectural work".
activity-"24000A" = "Build all mechanical work".
activity-"25000A" = "Build all electrical work".

activity-"02221A" = "Excavate building foundation".
activity-"02222A" = "Backfill and compact foundation".
activity-"02140A" = "Dewatering the foundation".

activity-"02223W" = "Granular backfill and compact for lower wall".
activity-"02224W" = "Earth backfill and compact for upper wall".
```

```
activity-"22000F" = "Build structural floor".
activity-"22000W" = "Build structural wall".
activity-"22000R" = "Build structural roof".
activity-"22000S" = "Build structural stair".

activity-"22001F" = "Form, pour, cure and strip reinforced concrete
slab on grade".
activity-"22010F" = "Build concrete sump".
activity-"22011F" = "Build concrete sump in upper slab".

activity-"22002F" = "Form, pour, cure and strip lower slab on grade".
activity-"22003F" = "Form, pour, cure and strip upper slab on grade".

activity-"03100F" = "Place formwork and reinforcement for slab on
grade".
activity-"03300F" = "Pour, cure and strip formwork for slab on grade".

activity-"03102F" = "Place formwork and reinforcement for lower slab
on grade".
activity-"03302F" = "Pour, cure and strip formwork for lower slab on
grade".

activity-"03103F" = "Place formwork and reinforcement for upper slab
on grade".
activity-"03303F" = "Pour, cure and strip formwork for upper slab on
grade".

activity-"22001W" = "Form, pour, cure and strip foundation wall".

activity-"22002W" = "Form, pour, cure and strip lower wall".
activity-"22003W" = "Form, pour, cure and strip upper wall".

activity-"03100W" = "Place formwork and reinforcement for foundation
wall".
activity-"03300W" = "Pour, cure and strip formwork for foundation
wall".

activity-"03102W" = "Place formwork and reinforcement for lower wall".
activity-"03302W" = "Pour, cure and strip formwork for lower wall".

activity-"03103W" = "Place formwork and reinforcement for upper wall".
activity-"03303W" = "Pour, cure and strip formwork for upper wall".

activity-"22001R" = "Form, pour, cure and strip reinforced concrete
roof deck".

activity-"03100R" = "Place formwork and reinforcement for roof slab".
activity-"03300R" = "Pour, cure and strip formwork for roof slab".

activity-"05715S" = "Install spiral steel stair".
activity-"05525W" = "Grout M.H. steps into the wall".
activity-"05515R" = "Install roof access alluminium ladder".

activity-"23000F" = "Build and install architectural floor work".
activity-"23000W" = "Build and install architectural wall work".
activity-"23000R" = "Build and install architectural roof work".
activity-"23000G" = "Grind and patch finishes".

activity-"07150F" = "Install slab on grade damp proofing".
activity-"07192F" = "Install slab on grade vapor retarder/barrier".
activity-"05530F" = "Set floor sump grate frame".

activity-"07150W" = "Install wall damp proofing".
activity-"10200W" = "Install wall louvers".
activity-"10240W" = "Install wall grilles and screens".

activity-"07100R" = "Install roof deck waterproofing".
activity-"07720R" = "Install roof top accessories".
```

```
activity-"07721R" = "Install roof hatches"
activity-"07722R" = "Install Bilco hatches".
activity-"07723R" = "Install roof scuttle"
activity-"05520R" = "Install roof access railing".
activity-"10280R" = "Install roof top prefabricated building".

activity-"15400A" = "Install all pipings".
activity-"02721F" = "Install floor drain pipes".
activity-"15410W" = "Install and set wall pipes".
activity-"15865R" = "Install roof exhaust fan".
activity-"11210F" = "Install sump pump".
activity-"11211A" = "Install and set turbine pump".
activity-"11201A" = "Install sand filters".

activity-"15412W" = "Install and set lower wall pipes".
activity-"15413W" = "Install and set upper wall pipes".

activity-"02510A" = "Build concrete sidewalk".
activity-"02525A" = "Install sidewalk curbs and gutters".

/*------------------------------------------------------*/
/* GENERAL DATABASE */
/*------------------------------------------------------*/
work00 = ["10000A", "20000A", "21000A", "22000A", "23000A", "02222A",
"22000F", "22000W", "22000R", "22000S", "22001F", "22002F", "22003F",
"22001W", "22002W", "22003W", "22001R", "23000F", "23000W", "23000R",
"07720R", "15410W", "02000A", "24000A"].

task10 = ["02510A", "02525A"].

task21 = ["02221A", "02222A", "02140A", "02223W", "02224W"].

task22 = ["22010F", "22011F", "03100F", "03300F", "03102F", "03302F",
"03103F", "03303F", "03100W", "03300W", "03102W", "03302W", "03103W",
"03303W", "03100R", "03300R", "05715S", "05525W", "05515R"].

task23 = ["07150F", "07192F", "05530F", "07150W", "10200W", "10240W",
"07100R", "07721R", "07722R", "07723R", "05520R", "10280R"].

task24 = ["15400A", "02721F", "15865R", "11210F", "11211A", "11201A",
"15412W", "15413W"].

task25 = ["25000A"].

task30 = ["30000A"].

task99 = ["99999A"].

/*------------------------------------------------------*/
/*                     END OF FILE                      */
/*------------------------------------------------------*/
```

APPENDIX D

TYPICAL CONSULTATION SESSION

```
Project A - Wash Water Pumping Station

Please Wait ...
In construction, the project could be broken down into site work,
substructural work and superstructural work.

SITE WORKS are works related to site preparation, demolition, paving
and surfacing of sidewalk, curb, etc. and other similar works that are
external to the building.

SUBSTRUCTURAL WORKS are foundation, structural and architectural works
that are constructed below the grade or ground surface.

SUPERSTRUCTURAL WORKS are structural and architectural works that are
constructed above the grade or ground surface.

Please identify the major breakdowns for your building construction
project.
Select one or more from the list below:
     1.  Site work
     2.  Substructural work
     3.  Superstructural work
>> 1,2
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
For the substructural work, please identify the works associated with
your construction.

FOUNDATION WORKS are works associated with earthwork, excavation,
backfill, compaction, dewatering, piling and others that prepare the
base for the building.

STRUCTURAL WORKS are works associated with the construction of
structural floors, walls, roofs and stairs.

ARCHITECTURAL WORKS are works associated with finishes, moisture
protection and the installation of structural accessories.

Select one or more from the list below:
     1.  Foundation work
     2.  Structural work
     3.  Architectural work
>> 1,2,3
Please Wait ...
Please Wait ...
Please Wait ...
Do you need to build and install works related to MECHANICAL?
Mechanical work includes the installation of pumps, equipments,
plumbing and pipings, etc.
     1.  yes
     2.  no
>> y
Please Wait ...
Do you need to build and install works related to ELECTRICAL?
Electrical work includes the installation of electrical wiring,
lighting, communications, high voltage distribution, etc.
     1.  yes
     2.  no
>> n
Please Wait ...
Please Wait ...
For the SUBSTRUCTURAL work, do you need to excavate the FOUNDATION?
     1.  yes
     2.  no
>> y
Please Wait ...
During excavation, do you need to DEWATER the foundation?
     1.  yes
```

```
    2.  no
>> y
Please Wait ...
After excavation, do you need to BACKFILL and compact the foundation?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
STRUCTURAL elements of a building SUBSTRUCTURE might consist of the
frame, floor, wall and roof.

FRAME is the skeleton structure that made up of columns, beams and
girders.

FLOOR is the horizontal structure that made up of slabs and/or beams,

WALL is made of reinforced concrete or masonry (such as the hollow
blocks and the bricks).

ROOF is made up of slabs and/or beams or other materials such as the
steel and wood frames and trusses.

For your project, please identify these elements.
Select one or more from the list below:
    1.  Frame
    2.  Floor
    3.  Wall
    4.  Roof
>> 2,3,4
Please Wait ...
Please Wait ...
Please Wait ...
Do you need to build some kinds of STRUCTURAL stairs, ladders or
steps?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
What kind of STRUCTURAL floor is it?
Select ONE from the list below:
    1.  Concrete slab on grade
    2.  Precast concrete slab
    3.  Mass concrete
>> 1
Please Wait ...
Do you need to build some kinds of concrete SUMP within the floor
slab?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
What kind of STRUCTURAL wall is it?
Select ONE from the list below:
    1.  Reinforced Concrete Wall
    2.  Reinforced Masonry Wall
>> 1
Please Wait ...
Please Wait ...
What kind of STRUCTURAL roof is it?
Select ONE from the list below:
    1.  Reinforced concrete roof deck
    2.  Composite steel-concrete roof deck
```

```
    3.  Steel joist/truss roof framing
    4.  Wood joist/truss roof framing
>> 1
Please Wait ...
Please Wait ...
What types of STAIRS are needed to be built or installed?
Select one or more from the list below:
    1.  Reinforced concrete stair
    2.  Spiral steel stair
    3.  Grouted M.H. steel steps
    4.  Roof access alluminium ladder
>> 3
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would you like to build the floor slab into TWO or MORE operations
depending on the different floor levels?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would there be any pipes or conduits embedded under the lower floor
slab?
    1.  yes
    2.  no
>> n
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would there be any pipes or conduits embedded under the upper floor
slab?
    1.  yes
    2.  no
>> n
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would you like to build the wall into TWO or MORE operations depending
on the different floor levels?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
```

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Please Wait ...
Please Wait ...
Would there be any pipes or conduits embedded in or projected through
the lower wall?
     1.  yes
     2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Would there be any pipes or conduits embedded in or projected through
the upper wall?
     1.  yes
     2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Would there be any openings or roof accessories to be installed on the
roof?
     1.  yes
     2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Moisture protections are materials applied to walls, slabs and decks.
They are classified into water proofing, damp proofing and vapor
retarder/barrier.
What kinds of moisture protections are required for the FLOOR?
Select one or more from the list below:
     1.  Waterproofing
     2.  Damp proofing
     3.  Vapor retarder/barrier
>> 2
Please Wait ...
Please Wait ...
Do you need to build some kinds of concrete SUMP within the floor
slab?
     1.  yes
     2.  no
>> y
Please Wait ...
Please Wait ...
Moisture protections are materials applied to walls, slabs and decks.
They are classified into water proofing, damp proofing and vapor
retarder/barrier.
What kinds of moisture protections are required for the WALL?
Select one or more from the list below:
     1.  Waterproofing
     2.  Damp proofing
     3.  Vapor retarder/barrier
>> 2
Please Wait ...
What kinds of accessories and specialties are required for the wall?
Select one or more from the list below:
     1.  Louvers and vents
     2.  Grilles and screens
     3.  Windows
     4.  Doors
>> 1
Please Wait ...
Please Wait ...
Please Wait ...
Moisture protections are materials applied to walls, slabs and decks.
They are classified into water proofing, damp proofing and vapor
retarder/barrier.
What kinds of moisture protections are required for the ROOF?
Select one or more from the list below:
     1.  Waterproofing
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    2.  Damp proofing
    3.  Vapor retarder/barrier
>> 1
Please Wait ...
Do you need to build and install some kinds of ROOF ACCESSORIES like
hatches, scuttle, railings etc?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
What types of accessories are required for the roof?
Select one or more from the list below:
    1.  Prefabricated hatches
    2.  Bilco hatches
    3.  Scuttle
    4.  Railing
    5.  Prefabricated building
>> 1,2
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
What types of plumbing and pipings are required for the MECHANICAL
work?
Select one or more from the list below:
    1.  Water distribution piping
    2.  Floor drain pipes
    3.  Wall pipes - pipes that project through the wall
    4.  HVAC piping
>> 1,3
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
What types of exterior pavings and surfacings are included as part of
the SITE WORK?
Select one or more from the list below:
    1.  Concrete sidewalk
    2.  Sidewalk curbs and gutters
    3.  Brick pavers
    4.  Bituminous surfacing
>> 1,2
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would you need to install some kinds of ROOF EXHAUST FAN for
ventilation purposes?
    1.  yes
    2.  no
>> n
Please Wait ...
What types of water supply and treatment EQUIPMENT are required to be
installed?
Select one or more from the list below:
    1.  Turbine pump
    2.  Clarifiers
    3.  Sand filters
    4.  Sump pump
    5.  Flouridation equipment
>> 1,4
Please Wait ...
Please Wait ...
Please Wait ...
knowledgebasedsystemknowledgebasedsystemknowledgebasedsystemknowledgeb
asedsystem
```

A
Construction Schedule Planning
KNOWLEDGE BASED SYSTEM

End of Consultation

Please Wait For Recommendations

.....thinking!.....

RECOMMENDATIONS

Activity Listing:

activity-02221A = Excavate building foundation (100%) because kb-49.
activity-02140A = Dewatering the foundation (100%) because kb-51.
activity-02222A = Backfill and compact foundation (100%) because kb-50.
activity-22000S = Build structural stair (100%) because kb-57.
activity-23000G = Grind and patch finishes (100%) because kb-87.
activity-22010F = Build concrete sump (100%) because kb-59.
activity-22002F = Form, pour, cure and strip lower slab on grade (100%) because kb-61.
activity-22003F = Form, pour, cure and strip upper slab on grade (100%) because kb-62.
activity-22011F = Build concrete sump in upper slab (100%) because kb-60.
activity-02223W = Granular backfill and compact for lower wall (100%) because kb-52.
activity-02224W = Earth backfill and compact for upper wall (100%) because kb-53.
activity-03102W = Place formwork and reinforcement for lower wall (100%) because kb-74.
activity-03302W = Pour, cure and strip formwork for lower wall (100%) because kb-75.
activity-03103W = Place formwork and reinforcement for upper wall (100%) because kb-76.
activity-03303W = Pour, cure and strip formwork for upper wall (100%) because kb-77.
activity-03100R = Place formwork and reinforcement for roof slab (100%) because kb-79.
activity-03300R = Pour, cure and strip formwork for roof slab (100%) because kb-80.
activity-07150F = Install slab on grade damp proofing (100%) because kb-88.
activity-05530F = Set floor sump grate frame (100%) because kb-90.
activity-07150W = Install wall damp proofing (100%) because kb-91.
activity-10200W = Install wall louvers (100%) because kb-92.
activity-07100R = Install roof deck waterproofing (100%) because kb-94.
activity-07721R = Install roof hatches (100%) because kb-96.
activity-07722R = Install Bilco hatches (100%) because kb-97.
activity-15412W = Install and set lower wall pipes (100%) because kb-108.

activity-15413W = Install and set upper wall pipes (100%) because kb-109.

activity-02510A = Build concrete sidewalk (100%) because kb-110.

activity-02525A = Install sidewalk curbs and gutters (100%) because kb-111.

activity-15400A = Install all pipings (100%) because kb-101.

activity-15410W = Install and set wall pipes (100%) because kb-103.

activity-11210F = Install sump pump (100%) because kb-105.

activity-11211A = Install and set turbine pump (100%) because kb-106.

#

Precedence Relationship:

12345A-Activity

67890A-Immediate predecessor

02510A-Build concrete sidewalk- ¬ -02525A-Install sidewalk curbs and gutters = yes (100%) because set by user.

02510A-Build concrete sidewalk- ¬ -11211A-Install and set turbine pump = yes (100%) because set by user.

02510A-Build concrete sidewalk- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.

02525A-Install sidewalk curbs and gutters- ¬ -07721R-Install roof hatches = yes (100%) because set by user.

02221A-Excavate building foundation- ¬ -00000A-Start = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -03102W-Place formwork and reinforcement for lower wall = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -03302W-Pour, cure and strip formwork for lower wall = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -03103W-Place formwork and reinforcement for upper wall = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -03303W-Pour, cure and strip formwork for upper wall = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -22002F-Form, pour, cure and strip lower slab on grade = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -22003F-Form, pour, cure and strip upper slab on grade = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -22011F-Build concrete sump in upper slab = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -02223W-Granular backfill and compact for lower wall = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -02224W-Earth backfill and compact for upper wall = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -22010F-Build concrete sump = yes (100%) because set by user.

02222A-Backfill and compact foundation- ¬ -02140A-Dewatering the foundation = yes (100%) because set by user.

02140A-Dewatering the foundation- ¬ -02221A-Excavate building foundation = yes (100%) because set by user.

02223W-Granular backfill and compact for lower wall- ¬ -03102W-Place formwork and reinforcement for lower wall = yes (100%) because set by user.

02223W-Granular backfill and compact for lower wall- ¬ -03302W-Pour, cure and strip formwork for lower wall = yes (100%) because set by user.

02224W-Earth backfill and compact for upper wall- ¬ -07150W-Install wall damp proofing = yes (100%) because set by user.

22010F-Build concrete sump- ¬ -02221A-Excavate building foundation = yes (100%) because set by user.

22010F-Build concrete sump- ¬ -02140A-Dewatering the foundation = yes (100%) because set by user.

22011F-Build concrete sump in upper slab- ¬ -02223W-Granular backfill and compact for lower wall = yes (100%) because set by user.

22002F-Form, pour, cure and strip lower slab on grade- ¬ -02140A-Dewatering the foundation = yes (100%) because set by user.

22003F-Form, pour, cure and strip upper slab on grade- ¬ -22010F-Build concrete sump = yes (100%) because set by user.

22003F-Form, pour, cure and strip upper slab on grade- ¬ -02140A-Dewatering the foundation = yes (100%) because set by user.
03102W-Place formwork and reinforcement for lower wall- ¬ -22002F-Form, pour, cure and strip lower slab on grade = yes (100%) because set by user.
03302W-Pour, cure and strip formwork for lower wall- ¬ -03102W-Place formwork and reinforcement for lower wall = yes (100%) because set by user.
03302W-Pour, cure and strip formwork for lower wall- ¬ -15412W-Install and set lower wall pipes = yes (100%) because set by user.
03103W-Place formwork and reinforcement for upper wall- ¬ -22003F-Form, pour, cure and strip upper slab on grade = yes (100%) because set by user.
03303W-Pour, cure and strip formwork for upper wall- ¬ -03103W-Place formwork and reinforcement for upper wall = yes (100%) because set by user.
03303W-Pour, cure and strip formwork for upper wall- ¬ -15413W-Install and set upper wall pipes = yes (100%) because set by user.
03100R-Place formwork and reinforcement for roof slab- ¬ -03303W-Pour, cure and strip formwork for upper wall = yes (100%) because set by user.
03300R-Pour, cure and strip formwork for roof slab- ¬ -03100R-Place formwork and reinforcement for roof slab = yes (100%) because set by user.
03300R-Pour, cure and strip formwork for roof slab- ¬ -07722R-Install Bilco hatches = yes (100%) because set by user.
22000S-Build structural stair- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.
22000S-Build structural stair- ¬ -03302W-Pour, cure and strip formwork for lower wall = yes (100%) because set by user.
22000S-Build structural stair- ¬ -03303W-Pour, cure and strip formwork for upper wall = yes (100%) because set by user.
22000S-Build structural stair- ¬ -03100R-Place formwork and reinforcement for roof slab = yes (100%) because set by user.
07150F-Install slab on grade damp proofing- ¬ -22002F-Form, pour, cure and strip lower slab on grade = yes (100%) because set by user.
07150F-Install slab on grade damp proofing- ¬ -22003F-Form, pour, cure and strip upper slab on grade = yes (100%) because set by user.
07150F-Install slab on grade damp proofing- ¬ -22011F-Build concrete sump in upper slab = yes (100%) because set by user.
07150F-Install slab on grade damp proofing- ¬ -02223W-Granular backfill and compact for lower wall = yes (100%) because set by user.
07150F-Install slab on grade damp proofing- ¬ -02224W-Earth backfill and compact for upper wall = yes (100%) because set by user.
07150F-Install slab on grade damp proofing- ¬ -22010F-Build concrete sump = yes (100%) because set by user.
07150F-Install slab on grade damp proofing- ¬ -02140A-Dewatering the foundation = yes (100%) because set by user.
05530F-Set floor sump grate frame- ¬ -02223W-Granular backfill and compact for lower wall = yes (100%) because set by user.
07150W-Install wall damp proofing- ¬ -22002F-Form, pour, cure and strip lower slab on grade = yes (100%) because set by user.
07150W-Install wall damp proofing- ¬ -22003F-Form, pour, cure and strip upper slab on grade = yes (100%) because set by user.
07150W-Install wall damp proofing- ¬ -22011F-Build concrete sump in upper slab = yes (100%) because set by user.
07150W-Install wall damp proofing- ¬ -02223W-Granular backfill and compact for lower wall = yes (100%) because set by user.
07150W-Install wall damp proofing- ¬ -02224W-Earth backfill and compact for upper wall = yes (100%) because set by user.
07150W-Install wall damp proofing- ¬ -22010F-Build concrete sump = yes (100%) because set by user.
07150W-Install wall damp proofing- ¬ -02140A-Dewatering the foundation = yes (100%) because set by user.
10200W-Install wall louvers- ¬ -22002F-Form, pour, cure and strip lower slab on grade = yes (100%) because set by user.
10200W-Install wall louvers- ¬ -22003F-Form, pour, cure and strip upper slab on grade = yes (100%) because set by user.
10200W-Install wall louvers- ¬ -22011F-Build concrete sump in upper slab = yes (100%) because set by user.

10200W-Install wall louvers- ¬ -02223W-Granular backfill and compact for lower wall = yes (100%) because set by user.
10200W-Install wall louvers- ¬ -02224W-Earth backfill and compact for upper wall = yes (100%) because set by user.
10200W-Install wall louvers- ¬ -22010F-Build concrete sump = yes (100%) because set by user.
10200W-Install wall louvers- ¬ -02140A-Dewatering the foundation = yes (100%) because set by user.
07100R-Install roof deck waterproofing- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.
07721R-Install roof hatches- ¬ -07100R-Install roof deck waterproofing = yes (100%) because set by user.
07722R-Install Bilco hatches- ¬ -03100R-Place formwork and reinforcement for roof slab = yes (100%) because set by user.
15400A-Install all pipings- ¬ -11211A-Install and set turbine pump = yes (100%) because set by user.
11210F-Install sump pump- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.
11211A-Install and set turbine pump- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.
15412W-Install and set lower wall pipes- ¬ -03302W-Pour, cure and strip formwork for lower wall = yes (100%) because set by user.
15413W-Install and set upper wall pipes- ¬ -03303W-Pour, cure and strip formwork for upper wall = yes (100%) because set by user.
99999A-Finish- ¬ -02525A-Install sidewalk curbs and gutters = yes (100%) because set by user.
99999A-Finish- ¬ -02510A-Build concrete sidewalk = yes (100%) because set by user.
99999A-Finish- ¬ -23000G-Grind and patch finishes = yes (100%) because set by user.

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+----------------------------------------+
+                                        +
+   A CONSTRUCTION SCHEDULE PLANNING     +
+         KNOWLEDGE BASED SYSTEM         +
+                                        +
+----------------------------------------+
```

PROGRAM EXECUTION COMPLETED

To get a hard copy of the RECOMMENDATION, press <F10>.

To begin a new consultation, type <go> at the SCH> prompt.

To return to DOS, type <exit> at the SCH> prompt.

SCH>exit

RECOMMENDATIONS

Activity Listing:

activity-02221A = Excavate building foundation
activity-02140A = Dewatering the foundation
activity-02222A = Backfill and compact foundation
activity-22000S = Build structural stair
activity-23000G = Grind and patch finishes
activity-22010F = Build concrete sump
activity-22002F = Form, pour, cure and strip lower slab on grade
activity-22003F = Form, pour, cure and strip upper slab on grade
activity-22011F = Build concrete sump in upper slab

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     activity-02223W = Granular backfill and compact for lower wall
     activity-02224W = Earth backfill and compact for upper wall
     activity-03102W = Place formwork and reinforcement for lower wall
     activity-03302W = Pour, cure and strip formwork for lower wall
     activity-03103W = Place formwork and reinforcement for upper wall
     activity-03303W = Pour, cure and strip formwork for upper wall
     activity-03100R = Place formwork and reinforcement for roof slab
     activity-03300R = Pour, cure and strip formwork for roof slab
     activity-07150F = Install slab on grade damp proofing
     activity-05530F = Set floor sump grate frame
     activity-07150W = Install wall damp proofing
     activity-10200W = Install wall louvers
     activity-07100R = Install roof deck waterproofing
     activity-07721R = Install roof hatches
     activity-07722R = Install Bilco hatches
     activity-15412W = Install and set lower wall pipes
     activity-15413W = Install and set upper wall pipes
     activity-02510A = Build concrete sidewalk
     activity-02525A = Install sidewalk curbs and gutters
     activity-15400A = Install all pipings
     activity-15410W = Install and set wall pipes
     activity-11210F = Install sump pump
     activity-11211A = Install and set turbine pump
Precedence Relationship:

     12345A-Activity
            67890A-Immediate predecessor

     02510A-Build concrete sidewalk-
            02525A-Install sidewalk curbs and gutters
     02510A-Build concrete sidewalk-
            11211A-Install and set turbine pump
     02510A-Build concrete sidewalk-
            03300R-Pour, cure and strip formwork for roof slab
     02525A-Install sidewalk curbs and gutters-
            07721R-Install roof hatches
     02221A-Excavate building foundation-
            00000A-Start
     02222A-Backfill and compact foundation-
            03102W-Place formwork and reinforcement for lower wall
     02222A-Backfill and compact foundation-
            03302W-Pour, cure and strip formwork for lower wall
     02222A-Backfill and compact foundation-
            03103W-Place formwork and reinforcement for upper wall
     02222A-Backfill and compact foundation-
            03303W-Pour, cure and strip formwork for upper wall
     02222A-Backfill and compact foundation-
            22002F-Form, pour, cure and strip lower slab on grade
     02222A-Backfill and compact foundation-
            22003F-Form, pour, cure and strip upper slab on grade
     02222A-Backfill and compact foundation-
            22011F-Build concrete sump in upper slab
     02222A-Backfill and compact foundation-
            02223W-Granular backfill and compact for lower wall
     02222A-Backfill and compact foundation-
            02224W-Earth backfill and compact for upper wall
     02222A-Backfill and compact foundation-
            22010F-Build concrete sump
     02222A-Backfill and compact foundation-
            02140A-Dewatering the foundation
     02140A-Dewatering the foundation-
            02221A-Excavate building foundation
     02223W-Granular backfill and compact for lower wall-
            03102W-Place formwork and reinforcement for lower wall
     02223W-Granular backfill and compact for lower wall-
            03302W-Pour, cure and strip formwork for lower wall
     02224W-Earth backfill and compact for upper wall-
            07150W-Install wall damp proofing
     22010F-Build concrete sump-
            02221A-Excavate building foundation
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22010F-Build concrete sump-
    02140A-Dewatering the foundation
22011F-Build concrete sump in upper slab-
    02223W-Granular backfill and compact for lower wall
22002F-Form, pour, cure and strip lower slab on grade-
    02140A-Dewatering the foundation
22003F-Form, pour, cure and strip upper slab on grade-
    22010F-Build concrete sump
22003F-Form, pour, cure and strip upper slab on grade-
    02140A-Dewatering the foundation
03102W-Place formwork and reinforcement for lower wall-
    22002F-Form, pour, cure and strip lower slab on grade
03302W-Pour, cure and strip formwork for lower wall-
    03102W-Place formwork and reinforcement for lower wall
03302W-Pour, cure and strip formwork for lower wall-
    15412W-Install and set lower wall pipes
03103W-Place formwork and reinforcement for upper wall-
    22003F-Form, pour, cure and strip upper slab on grade
03303W-Pour, cure and strip formwork for upper wall-
    03103W-Place formwork and reinforcement for upper wall
03303W-Pour, cure and strip formwork for upper wall-
    15413W-Install and set upper wall pipes
03100R-Place formwork and reinforcement for roof slab-
    03303W-Pour, cure and strip formwork for upper wall
03300R-Pour, cure and strip formwork for roof slab-
    03100R-Place formwork and reinforcement for roof slab
03300R-Pour, cure and strip formwork for roof slab-
    07722R-Install Bilco hatches
22000S-Build structural stair-
    03300R-Pour, cure and strip formwork for roof slab
22000S-Build structural stair-
    03302W-Pour, cure and strip formwork for lower wall
22000S-Build structural stair-
    03303W-Pour, cure and strip formwork for upper wall
22000S-Build structural stair-
    03100R-Place formwork and reinforcement for roof slab
07150F-Install slab on grade damp proofing-
    22002F-Form, pour, cure and strip lower slab on grade
07150F-Install slab on grade damp proofing-
    22003F-Form, pour, cure and strip upper slab on grade
07150F-Install slab on grade damp proofing-
    22011F-Build concrete sump in upper slab
07150F-Install slab on grade damp proofing-
    02223W-Granular backfill and compact for lower wall
07150F-Install slab on grade damp proofing-
    02224W-Earth backfill and compact for upper wall
07150F-Install slab on grade damp proofing-
    22010F-Build concrete sump
07150F-Install slab on grade damp proofing-
    02140A-Dewatering the foundation
05530F-Set floor sump grate frame-
    02223W-Granular backfill and compact for lower wall
07150W-Install wall damp proofing-
    22002F-Form, pour, cure and strip lower slab on grade
07150W-Install wall damp proofing-
    22003F-Form, pour, cure and strip upper slab on grade
07150W-Install wall damp proofing-
    22011F-Build concrete sump in upper slab
07150W-Install wall damp proofing-
    02223W-Granular backfill and compact for lower wall
07150W-Install wall damp proofing-
    02224W-Earth backfill and compact for upper wall
07150W-Install wall damp proofing-
    22010F-Build concrete sump
07150W-Install wall damp proofing-
    02140A-Dewatering the foundation
10200W-Install wall louvers-
    22002F-Form, pour, cure and strip lower slab on grade
10200W-Install wall louvers-
    22003F-Form, pour, cure and strip upper slab on grade

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10200W-Install wall louvers-
        22011F-Build concrete sump in upper slab
10200W-Install wall louvers-
        02223W-Granular backfill and compact for lower wall
10200W-Install wall louvers-
        02224W-Earth backfill and compact for upper wall
10200W-Install wall louvers-
        22010F-Build concrete sump
10200W-Install wall louvers-
        02140A-Dewatering the foundation
07100R-Install roof deck waterproofing-
        03300R-Pour, cure and strip formwork for roof slab
07721R-Install roof hatches-
        07100R-Install roof deck waterproofing
07722R-Install Bilco hatches-
        03100R-Place formwork and reinforcement for roof slab
15400A-Install all pipings-
        11211A-Install and set turbine pump
11210F-Install sump pump-
        03300R-Pour, cure and strip formwork for roof slab
11211A-Install and set turbine pump-
        03300R-Pour, cure and strip formwork for roof slab
15412W-Install and set lower wall pipes-
        03302W-Pour, cure and strip formwork for lower wall
15413W-Install and set upper wall pipes-
        03303W-Pour, cure and strip formwork for upper wall
99999A-Finish-
        02525A-Install sidewalk curbs and gutters
99999A-Finish-
        02510A-Build concrete sidewalk
99999A-Finish-
        23000G-Grind and patch finishes


                +---------------------------------------+
                +                                       +
                +   A CONSTRUCTION SCHEDULE PLANNING    +
                +        KNOWLEDGE BASED SYSTEM         +
                +                                       +
                +---------------------------------------+

                      PROGRAM EXECUTION COMPLETED

         To get a hard copy of the RECOMMENDATION, press <F10>.

        To begin a new consultation, type <go> at the SCH> prompt.

            To return to DOS, type <exit> at the SCH> prompt.


SCH>exit
```

```
Project B - Sand Filter Building

Please Wait ...
In construction, the project could be broken down into site work,
substructural work and superstructural work.

SITE WORKS are works related to site preparation, demolition, paving
and surfacing of sidewalk, curb, etc. and other similar works that are
external to the building.

SUBSTRUCTURAL WORKS are foundation, structural and architectural works
that are constructed below the grade or ground surface.

SUPERSTRUCTURAL WORKS are structural and architectural works that are
constructed above the grade or ground surface.

Please identify the major breakdowns for your building construction
project.
Select one or more from the list below:
     1.  Site work
     2.  Substructural work
     3.  Superstructural work
>> 1,2
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
For the substructural work, please identify the works associated with
your construction.

FOUNDATION WORKS are works associated with earthwork, excavation,
backfill, compaction, dewatering, piling and others that prepare the
base for the building.

STRUCTURAL WORKS are works associated with the construction of
structural floors, walls, roofs and stairs.

ARCHITECTURAL WORKS are works associated with finishes, moisture
protection and the installation of structural accessories.

Select one or more from the list below:
     1.  Foundation work
     2.  Structural work
     3.  Architectural work
>> 1,2,3
Please Wait ...
Please Wait ...
Please Wait ...
Do you need to build and install works related to MECHANICAL?
Mechanical work includes the installation of pumps, equipments,
plumbing and pipings, etc.
     1.  yes
     2.  no
>> y
Please Wait ...
Do you need to build and install works related to ELECTRICAL?
Electrical work includes the installation of electrical wiring,
lighting, communications, high voltage distribution, etc.
     1.  yes
     2.  no
>> n
Please Wait ...
Please Wait ...
For the SUBSTRUCTURAL work, do you need to excavate the FOUNDATION?
     1.  yes
     2.  no
>> y
Please Wait ...
During excavation, do you need to DEWATER the foundation?
     1.  yes
```

```
    2.  no
>> n
Please Wait ...
After excavation, do you need to BACKFILL and compact the foundation?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
STRUCTURAL elements of a building SUBSTRUCTURE might consist of the
frame, floor, wall and roof.

FRAME is the skeleton structure that made up of columns, beams and
girders.

FLOOR is the horizontal structure that made up of slabs and/or beams,

WALL is made of reinforced concrete or masonry (such as the hollow
blocks and the bricks).

ROOF is made up of slabs and/or beams or other materials such as the
steel and wood frames and trusses.

For your project, please identify these elements.
Select one or more from the list below:
    1.  Frame
    2.  Floor
    3.  Wall
    4.  Roof
>> 2,3,4
Please Wait ...
Please Wait ...
Please Wait ...
Do you need to build some kinds of STRUCTURAL stairs, ladders or
steps?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
What kind of STRUCTURAL floor is it?
Select ONE from the list below:
    1.  Concrete slab on grade
    2.  Precast concrete slab
    3.  Mass concrete
>> 1
Please Wait ...
Do you need to build some kinds of concrete SUMP within the floor
slab?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
What kind of STRUCTURAL wall is it?
Select ONE from the list below:
    1.  Reinforced Concrete Wall
    2.  Reinforced Masonry Wall
>> 1
Please Wait ...
Please Wait ...
What kind of STRUCTURAL roof is it?
Select ONE from the list below:
    1.  Reinforced concrete roof deck
    2.  Composite steel-concrete roof deck
```

```
    3.  Steel joist/truss roof framing
    4.  Wood joist/truss roof framing
>> 1
Please Wait ...
Please Wait ...
What types of STAIRS are needed to be built or installed?
Select one or more from the list below:
    1.  Reinforced concrete stair
    2.  Spiral steel stair
    3.  Grouted M.H. steel steps
    4.  Roof access alluminium ladder
>> 2,4
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would you like to build the floor slab into TWO or MORE operations
depending on the different floor levels?
    1.  yes
    2.  no
>> n
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would there be any pipes or conduits embedded under the floor slab?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Would you like to build the wall into TWO or MORE operations depending
on the different floor levels?
    1.  yes
    2.  no
>> n
Please Wait ...
Please Wait ...
Would there be any pipes or conduits embedded in or projected through
the wall?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Would there be any openings or roof accessories to be installed on the
roof?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
Please Wait ...
Moisture protections are materials applied to walls, slabs and decks.
They are classified into water proofing, damp proofing and vapor
retarder/barrier.
What kinds of moisture protections are required for the FLOOR?
Select one or more from the list below:
    1.  Waterproofing
    2.  Damp proofing
    3.  Vapor retarder/barrier
>> 3
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Moisture protections are materials applied to walls, slabs and decks.
```

```
They are classified into water proofing, damp proofing and vapor
retarder/barrier.
What kinds of moisture protections are required for the WALL?
Select one or more from the list below:
    1.  Waterproofing
    2.  Damp proofing
    3.  Vapor retarder/barrier
>> 2
Please Wait ...
What kinds of accessories and specialties are required for the wall?
Select one or more from the list below:
    1.  Louvers and vents
    2.  Grilles and screens
    3.  Windows
    4.  Doors
>> u
Please Wait ...
Please Wait ...
Please Wait ...
Moisture protections are materials applied to walls, slabs and decks.
They are classified into water proofing, damp proofing and vapor
retarder/barrier.
What kinds of moisture protections are required for the ROOF?
Select one or more from the list below:
    1.  Waterproofing
    2.  Damp proofing
    3.  Vapor retarder/barrier
>> u
Please Wait ...
Do you need to build and install some kinds of ROOF ACCESSORIES like
hatches, scuttle, railings etc?
    1.  yes
    2.  no
>> y
Please Wait ...
Please Wait ...
What types of accessories are required for the roof?
Select one or more from the list below:
    1.  Prefabricated hatches
    2.  Bilco hatches
    3.  Scuttle
    4.  Railing
    5.  Prefabricated building
>> 3,4,5
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
What types of plumbing and pipings are required for the MECHANICAL
work?
Select one or more from the list below:
    1.  Water distribution piping
    2.  Floor drain pipes
    3.  Wall pipes - pipes that project through the wall
    4.  HVAC piping
>> 2,3
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
What types of exterior pavings and surfacings are included as part of
the SITE WORK?
Select one or more from the list below:
    1.  Concrete sidewalk
```

```
    2.  Sidewalk curbs and gutters
    3.  Brick pavers
    4.  Bituminous surfacing
>> 1
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Please Wait ...
Would you need to install some kinds of ROOF EXHAUST FAN for
ventilation purposes?
    1.  yes
    2.  no
>> y
Please Wait ...
What types of water supply and treatment EQUIPMENT are required to be
installed?
Select one or more from the list below:
    1.  Turbine pump
    2.  Clarifiers
    3.  Sand filters
    4.  Sump pump
    5.  Flouridation equipment
>> 3,4
Please Wait ...
Please Wait ...
Please Wait ...
knowledgebasedsystemknowledgebasedsystemknowledgebasedsystemknowledgeb
asedsystem


                                   A
                    Construction Schedule Planning
                        KNOWLEDGE BASED SYSTEM


                          End of Consultation

                    Please Wait For Recommendations


                          .....thinking!.....


RECOMMENDATIONS


Activity Listing:

    activity-02221A = Excavate building foundation (100%) because kb-
49.
    activity-02222A = Backfill and compact foundation (100%) because
kb-50.
    activity-23000G = Grind and patch finishes (100%) because kb-87.
    activity-22010F = Build concrete sump (100%) because kb-59.
    activity-05715S = Install spiral steel stair (100%) because kb-81.
    activity-03100F = Place formwork and reinforcement for slab on
grade (100%) because kb-63.
    activity-03300F = Pour, cure and strip formwork for slab on grade
(100%) because kb-64.
```

activity-03100W = Place formwork and reinforcement for foundation wall (100%) because kb-72.
activity-03300W = Pour, cure and strip formwork for foundation wall (100%) because kb-73.
activity-03100R = Place formwork and reinforcement for roof slab (100%) because kb-79.
activity-03300R = Pour, cure and strip formwork for roof slab (100%) because kb-80.
activity-07192F = Install slab on grade vapor retarder/barrier (100%) because kb-89.
activity-05530F = Set floor sump grate frame (100%) because kb-90.
activity-07150W = Install wall damp proofing (100%) because kb-91.
activity-07723R = Install roof scuttle (100%) because kb-98.
activity-05520R = Install roof access railing (100%) because kb-99.
activity-10280R = Install roof top prefabricated building (100%) because kb-100.
activity-02510A = Build concrete sidewalk (100%) because kb-110.
activity-02721F = Install floor drain pipes (100%) because kb-102.
activity-15410W = Install and set wall pipes (100%) because kb-103.
activity-15865R = Install roof exhaust fan (100%) because kb-104.
activity-11210F = Install sump pump (100%) because kb-105.
#
Precedence Relationship:

12345A-Activity
67890A-Immediate predecessor

02510A-Build concrete sidewalk- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.
02221A-Excavate building foundation- ¬ -00000A-Start = yes (100%) because set by user.
02222A-Backfill and compact foundation- ¬ -07192F-Install slab on grade vapor retarder/barrier = yes (100%) because set by user.
02222A-Backfill and compact foundation- ¬ -22010F-Build concrete sump = yes (100%) because set by user.
02222A-Backfill and compact foundation- ¬ -15410W-Install and set wall pipes = yes (100%) because set by user.
02222A-Backfill and compact foundation- ¬ -03100W-Place formwork and reinforcement for foundation wall = yes (100%) because set by user.
02222A-Backfill and compact foundation- ¬ -03300W-Pour, cure and strip formwork for foundation wall = yes (100%) because set by user.
22010F-Build concrete sump- ¬ -02221A-Excavate building foundation = yes (100%) because set by user.
03100F-Place formwork and reinforcement for slab on grade- ¬ -22010F-Build concrete sump = yes (100%) because set by user.
03100F-Place formwork and reinforcement for slab on grade- ¬ -07192F-Install slab on grade vapor retarder/barrier = yes (100%) because set by user.
03300F-Pour, cure and strip formwork for slab on grade- ¬ -03100F-Place formwork and reinforcement for slab on grade = yes (100%) because set by user.
03100W-Place formwork and reinforcement for foundation wall- ¬ -07192F-Install slab on grade vapor retarder/barrier = yes (100%) because set by user.
03100W-Place formwork and reinforcement for foundation wall- ¬ -22010F-Build concrete sump = yes (100%) because set by user.
03100W-Place formwork and reinforcement for foundation wall- ¬ -15410W-Install and set wall pipes = yes (100%) because set by user.
03100W-Place formwork and reinforcement for foundation wall- ¬ -07150W-Install wall damp proofing = yes (100%) because set by user.
03100W-Place formwork and reinforcement for foundation wall- ¬ -03100F-Place formwork and reinforcement for slab on grade = yes (100%) because set by user.
03100W-Place formwork and reinforcement for foundation wall- ¬ -03300F-Pour, cure and strip formwork for slab on grade = yes (100%) because set by user.

03300W-Pour, cure and strip formwork for foundation wall- ¬ -03100W-Place formwork and reinforcement for foundation wall = yes (100%) because set by user.

03100R-Place formwork and reinforcement for roof slab- ¬ -22010F-Build concrete sump = yes (100%) because set by user.

03100R-Place formwork and reinforcement for roof slab- ¬ -07192F-Install slab on grade vapor retarder/barrier = yes (100%) because set by user.

03100R-Place formwork and reinforcement for roof slab- ¬ -15410W-Install and set wall pipes = yes (100%) because set by user.

03300R-Pour, cure and strip formwork for roof slab- ¬ -03100R-Place formwork and reinforcement for roof slab = yes (100%) because set by user.

05715S-Install spiral steel stair- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.

07192F-Install slab on grade vapor retarder/barrier- ¬ -02221A-Excavate building foundation = yes (100%) because set by user.

05530F-Set floor sump grate frame- ¬ -07192F-Install slab on grade vapor retarder/barrier = yes (100%) because set by user.

05530F-Set floor sump grate frame- ¬ -15410W-Install and set wall pipes = yes (100%) because set by user.

07150W-Install wall damp proofing- ¬ -03300W-Pour, cure and strip formwork for foundation wall = yes (100%) because set by user.

07723R-Install roof scuttle- ¬ -03100R-Place formwork and reinforcement for roof slab = yes (100%) because set by user.

07723R-Install roof scuttle- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.

05520R-Install roof access railing- ¬ -03100R-Place formwork and reinforcement for roof slab = yes (100%) because set by user.

05520R-Install roof access railing- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.

10280R-Install roof top prefabricated building- ¬ -05715S-Install spiral steel stair = yes (100%) because set by user.

02721F-Install floor drain pipes- ¬ -07192F-Install slab on grade vapor retarder/barrier = yes (100%) because set by user.

15865R-Install roof exhaust fan- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.

11210F-Install sump pump- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.

15410W-Install and set wall pipes- ¬ -07192F-Install slab on grade vapor retarder/barrier = yes (100%) because set by user.

15410W-Install and set wall pipes- ¬ -22010F-Build concrete sump = yes (100%) because set by user.

99999A-Finish- ¬ -03300R-Pour, cure and strip formwork for roof slab = yes (100%) because set by user.

99999A-Finish- ¬ -02510A-Build concrete sidewalk = yes (100%) because set by user.

99999A-Finish- ¬ -23000G-Grind and patch finishes = yes (100%) because set by user.

```
+---------------------------------------+
+                                       +
+   A CONSTRUCTION SCHEDULE PLANNING    +
+        KNOWLEDGE BASED SYSTEM         +
+                                       +
+---------------------------------------+
```

PROGRAM EXECUTION COMPLETED

To get a hard copy of the RECOMMENDATION, press <F10>.

To begin a new consultation, type <go> at the SCH> prompt.

To return to DOS, type <exit> at the SCH> prompt.

```
SCH>exit

RECOMMENDATIONS

Activity Listing:

     activity-02221A = Excavate building foundation
     activity-02222A = Backfill and compact foundation
     activity-23000G = Grind and patch finishes
     activity-22010F = Build concrete sump
     activity-05715S = Install spiral steel stair
     activity-03100F = Place formwork and reinforcement for slab on
grade
     activity-03300F = Pour, cure and strip formwork for slab on grade
     activity-03100W = Place formwork and reinforcement for foundation
wall
     activity-03300W = Pour, cure and strip formwork for foundation
wall
     activity-03100R = Place formwork and reinforcement for roof slab
     activity-03300R = Pour, cure and strip formwork for roof slab
     activity-07192F = Install slab on grade vapor retarder/barrier
     activity-05530F = Set floor sump grate frame
     activity-07150W = Install wall damp proofing
     activity-07723R = Install roof scuttle
     activity-05520R = Install roof access railing
     activity-10280R = Install roof top prefabricated building
     activity-02510A = Build concrete sidewalk
     activity-02721F = Install floor drain pipes
     activity-15410W = Install and set wall pipes
     activity-15865R = Install roof exhaust fan
     activity-11210F = Install sump pump
Precedence Relationship:

     12345A-Activity
          67890A-Immediate predecessor

     02510A-Build concrete sidewalk-
          03300R-Pour, cure and strip formwork for roof slab
     02221A-Excavate building foundation-
          00000A-Start
     02222A-Backfill and compact foundation-
          07192F-Install slab on grade vapor retarder/barrier
     02222A-Backfill and compact foundation-
          22010F-Build concrete sump
     02222A-Backfill and compact foundation-
          15410W-Install and set wall pipes
     02222A-Backfill and compact foundation-
          03100W-Place formwork and reinforcement for foundation wall
     02222A-Backfill and compact foundation-
          03300W-Pour, cure and strip formwork for foundation wall
     22010F-Build concrete sump-
          02221A-Excavate building foundation
     03100F-Place formwork and reinforcement for slab on grade-
          22010F-Build concrete sump
     03100F-Place formwork and reinforcement for slab on grade-
          07192F-Install slab on grade vapor retarder/barrier
     03300F-Pour, cure and strip formwork for slab on grade-
          03100F-Place formwork and reinforcement for slab on grade
     03100W-Place formwork and reinforcement for foundation wall-
          07192F-Install slab on grade vapor retarder/barrier
     03100W-Place formwork and reinforcement for foundation wall-
          22010F-Build concrete sump
     03100W-Place formwork and reinforcement for foundation wall-
          15410W-Install and set wall pipes
     03100W-Place formwork and reinforcement for foundation wall-
          07150W-Install wall damp proofing
```

```
03100W-Place formwork and reinforcement for foundation wall-
        03100F-Place formwork and reinforcement for slab on grade
03100W-Place formwork and reinforcement for foundation wall-
        03300F-Pour, cure and strip formwork for slab on grade
03300W-Pour, cure and strip formwork for foundation wall-
        03100W-Place formwork and reinforcement for foundation wall
03100R-Place formwork and reinforcement for roof slab-
        22010F-Build concrete sump
03100R-Place formwork and reinforcement for roof slab-
        07192F-Install slab on grade vapor retarder/barrier
03100R-Place formwork and reinforcement for roof slab-
        15410W-Install and set wall pipes
03300R-Pour, cure and strip formwork for roof slab-
        03100R-Place formwork and reinforcement for roof slab
05715S-Install spiral steel stair-
        03300R-Pour, cure and strip formwork for roof slab
07192F-Install slab on grade vapor retarder/barrier-
        02221A-Excavate building foundation
05530F-Set floor sump grate frame-
        07192F-Install slab on grade vapor retarder/barrier
05530F-Set floor sump grate frame-
        15410W-Install and set wall pipes
07150W-Install wall damp proofing-
        03300W-Pour, cure and strip formwork for foundation wall
07723R-Install roof scuttle-
        03100R-Place formwork and reinforcement for roof slab
07723R-Install roof scuttle-
        03300R-Pour, cure and strip formwork for roof slab
05520R-Install roof access railing-
        03100R-Place formwork and reinforcement for roof slab
05520R-Install roof access railing-
        03300R-Pour, cure and strip formwork for roof slab
10280R-Install roof top prefabricated building-
        05715S-Install spiral steel stair
02721F-Install floor drain pipes-
        07192F-Install slab on grade vapor retarder/barrier
15865R-Install roof exhaust fan-
        03300R-Pour, cure and strip formwork for roof slab
11210F-Install sump pump-
        03300R-Pour, cure and strip formwork for roof slab
15410W-Install and set wall pipes-
        07192F-Install slab on grade vapor retarder/barrier
15410W-Install and set wall pipes-
        22010F-Build concrete sump
99999A-Finish-
        03300R-Pour, cure and strip formwork for roof slab
99999A-Finish-
        02510A-Build concrete sidewalk
99999A-Finish-
        23000G-Grind and patch finishes


                  +--------------------------------------+
                  +                                      +
                  +   A CONSTRUCTION SCHEDULE PLANNING   +
                  +        KNOWLEDGE BASED SYSTEM        +
                  +                                      +
                  +--------------------------------------+

                          PROGRAM EXECUTION COMPLETED

             To get a hard copy of the RECOMMENDATION, press <F10>.

           To begin a new consultation, type <go> at the SCH> prompt.

                To return to DOS, type <exit> at the SCH> prompt.

SCH>exit
```

APPENDIX E

MANUAL SCHEDULING INSTRUCTIONS

CONSTRUCTION SCHEDULING ASSIGNMENT
MANUAL SCHEDULING
==================================

Instructions:
----

1. You are provided with one sheet of engineering drawing that describes the project. Please study the drawing carefully. All the information you need about the project can be inferred from the drawing.

2. Using the drawing, you are requested to schedule the project into appropriate construction activities. This scheduling assignment will require you to:

i. Work Breakdown

Break the work into appropriate construction activities For each activity, provide an activity number (Job Label) and a descriptive title (Job Description). Please use your judgement as to the description and the level of detail. However, it is envisaged that this project will consist of about 20 construction activities.

ii. Precedence Relationship

After the project has been broken down into appropriate activities, you are required to sequence them into a precedence format. This is done by listing the activities and their immediate predecessors. A blank format is provided for your convenience.

A precedence diagramming (activity on node) format will be required as the output of your assignment. This format will show the activities and their immediate predecessors. You are expected to assume that all the resources of labor, equipment and material required to perform the construction activities are available and unlimited. You are to conside only the finish/start relationship among the activities (that is zero lag), the physical constraints and the logic as to sequence these construction activities.

3. This assignment will take 1 hour and 15 minutes. You are advised to work within this time limit. This period includes the time to study the drawing and to produce the list of activities and their immediate predecessors on the forms provided.

4. This assignment further requires that you identify yourself by providing your name on the scheduling format sheet. Your work will be kept confidential.

Your participation is highly appreciated. Thank you and good luck.

Name:..........................
Tel.:....................(Home)
..................(Office)
Project: [A] or [B]

Date:...............

Time Start:.........
Time Finish:........

SCHEDULING FORMAT

Job Label	Job Description	Immediate Predecessors

APPENDIX F

PARTICIPANTS DATA QUESTIONNAIRE

CONSTRUCTION SCHEDULING EXPERIMENT
PARTICIPANT'S DATA
================================

Name:.........................   Date:...............

Time Start:.........
Project: [A] or [B]   Time Finish:........

Academic Background:

Please cross (X) appropriate boxes.

	Degrees Earned	Degree in Progress	Major Course of Study
BS			1.
			2.
			3.
MS			1.
			2.
PHD			1.

Work Experience:

Please cross (X) appropriate boxes.

	None	Less than 1 year	More than 1 year
Experience related to BS Major			
Experience NOT related to BS Major			

Have you ever prepared a construction schedule similar to this exercise before?	YES	NO
In class work		
In real work		

APPENDIX G

SCHEDULING EVALUATION FORMAT

SCHEDULING EVALUATION FORMAT

Name:...

MANUAL SCHEDULING

Project: [A] or [B]

Evaluation Criteria	Weight W	Rating R	System Utility U = R x W
Level of Detail (2.5)	1		
Completeness (2.5)	1		
Network Logic (5.0)	2		
Total Value			

COMPUTER SCHEDULING

Project: [A] or [B]

Evaluation Criteria	Weight W	Rating R	System Utility U = R x W
Level of Detail (2.5)	1		
Completeness (2.5)	1		
Network Logic (5.0)	2		
Total Value			

APPENDIX H

STATISTICAL ANALYSIS

RANDOMIZED PAIRED COMPARISON DESIGN

Variable: Quality of Performance
Population: Civil Engineering Background
No. of Subjects: 13

Student No.	Manual M	Computer C	d = C - M	d^2
1	30	39	9	81
2	31	35	4	16
3	27	36	9	81
4	33	34	1	1
5	32	33	1	1
6	27	34	7	49
7	25	24	-1	1
8	36	31	-5	25
9	21	34	13	169
10	28	39	11	121
11	30	36	6	36
12	20	33	13	169
13	15	33	18	324
SUM	355	441	86	1074
MEAN	27.31	33.92	6.62	
STD DEVIATION			6.49	
STD ERROR			1.80	
t-STATISTICS			3.68	
SIGNIFICANCE			0.0018	

RANDOMIZED PAIRED COMPARISON DESIGN

Variable: Quality of Performance
Population: Engineering Management Background
No. of Subjects: 14

Student No.	Manual M	Computer C	d = C - M	d^2
1	18	34	16	256
2	11	35	24	576
3	10	32	22	484
4	11	36	25	625
5	24	34	10	100
6	8	30	22	484
7	21	34	13	169
8	27	34	7	49
9	8	29	21	441
10	12	35	23	529
11	8	33	25	625
12	22	39	17	289
13	21	36	15	225
14	9	37	28	784
SUM	210	478	268	5636
MEAN	15.00	34.14	19.14	
STD DEVIATION			6.23	
STD ERROR			1.67	
t-STATISTICS			11.48	
SIGNIFICANCE			0.0005	

RANDOMIZED PAIRED COMPARISON DESIGN
QUALITY PRODUCTIVITY MEASURE
SUMMARY

	Group 1 Civil Engineering Background	Group 2 Engineering Management Background	All Subjects with Engineering Background
Number of Subjects	13	14	27
Mean Manual Solution	27.31	15.00	20.93
Mean Computer Solution	33.92	34.10	34.04
Mean of Difference: Manual verses Computer	6.61	19.14	13.11
Standard Deviation	6.49	6.24	8.92
Standard Error	1.80	1.67	1.72
t-Statistic	3.677	11.484	7.622
Significant Value	0.0018	< 0.0005	< 0.0005

RANDOMIZED PAIRED COMPARISON DESIGN

Variable: Time of Performance
Population: Civil Engineering Background
No. of Subjects: 13

Student No.	Manual M	Computer C	d = M - C	d^2
1	55	40	15	225
2	75	50	25	625
3	50	30	20	400
4	50	30	20	400
5	45	35	10	100
6	65	30	35	1225
7	40	30	10	100
8	50	40	10	100
9	35	30	5	25
10	50	40	10	100
11	60	40	20	400
12	55	50	5	25
13	50	30	20	400
SUM	680	475	205	4125
MEAN	52.31	36.54	15.77	
STD DEVIATION			8.62	
STD ERROR			2.39	
t-STATISTICS			6.59	
SIGNIFICANCE			0.0005	

RANDOMIZED PAIRED COMPARISON DESIGN

Variable: Time of Performance
Population: Engineering Management Background
No. of Subjects: 14

Student No.	Manual M	Computer C	d = M - C	d^2
1	30	35	-5	25
2	35	50	-15	225
3	20	45	-25	625
4	20	35	-15	225
5	45	30	15	225
6	75	30	45	2025
7	25	40	-15	225
8	35	30	5	25
9	25	45	-20	400
10	45	50	-5	25
11	45	35	10	100
12	60	35	25	625
13	50	35	15	225
14	75	45	30	900
SUM	585	540	45	5875
MEAN	41.79	38.57	3.21	
STD DEVIATION			21.00	
STD ERROR			5.61	
t-STATISTICS			0.57	
SIGNIFICANCE			0.2918	

RANDOMIZED PAIRED COMPARISON DESIGN
TIME PRODUCTIVITY MEASURE
SUMMARY

	Group 1 Civil Engineering Background	Group 2 Engineering Management Background	All Subjects with Engineering Background
Number of Subjects	13	14	27
Mean Manual Solution	52.31	41.79	46.85
Mean Computer Solution	36.54	38.57	37.59
Mean of Difference: Manual verses Computer	15.77	3.21	9.26
Standard Deviation	8.62	21.00	17.19
Standard Error	2.39	5.61	3.31
t-Statistic	6.593	0.573	2.799
Significant Value	< 0.0005	0.2918	0.0048

APPENDIX I

SAS DATA INPUT

```
DATA CE;
 INPUT ID MANUAL COMPUTER;
 DIFF=MANUAL-COMPUTER;
 CARDS;
 1  55  40
 2  75  50
 3  50  30
 4  50  30
 5  45  35
 6  65  30
 7  40  30
 8  50  40
 9  35  30
10  50  40
11  60  40
12  55  50
13  50  30
;
DATA EM;
 INPUT ID MANUAL COMPUTER;
 DIFF=MANUAL-COMPUTER;
 CARDS;
 1  30  35
 2  35  50
 3  20  45
 4  20  35
 5  45  30
 6  75  30
 7  25  40
 8  35  30
 9  25  45
10  45  50
11  45  35
12  60  35
13  50  35
14  75  45
;
DATA TD;
 INPUT SUBJECT $ DIFF @@;
 CARDS;
CE  15  CE  25  CE  20  CE  20  CE  10  CE  35  CE  10
CE  10  CE   5  CE  10  CE  20  CE   5  CE  20
EM  -5  EM -15  EM -25  EM -15  EM  15  EM  45  EM -15
EM   5  EM -20  EM  -5  EM  10  EM  25  EM  15  EM  30
;
PROC MEANS DATA=CE N MEAN STD SUM VAR STDERR T PRT;
 VAR MANUAL COMPUTER DIFF;
 TITLE PAIRED-COMPARISONS T TEST FOR CIVIL ENGINEERING;
PROC MEANS DATA=EM N MEAN STD SUM VAR STDERR T PRT;
 VAR MANUAL COMPUTER DIFF;
 TITLE PAIRED-COMPARISONS T TEST FOR ENGINEERING MANAGEMENT;
PROC TTEST DATA=TD;
 CLASS SUBJECT;
 VAR DIFF;
 TITLE TIME SCORES FOR DIFFERENCE: MANUAL VS. COMPUTER;
```

```
DATA CE;
 INPUT ID MANUAL COMPUTER;
 DIFF=COMPUTER-MANUAL;
 CARDS;
 1  30  39
 2  31  35
 3  27  36
 4  33  34
 5  32  33
 6  27  34
 7  25  24
 8  36  31
 9  21  34
10  28  39
11  30  36
12  20  33
13  15  33
;
DATA EM;
 INPUT ID MANUAL COMPUTER;
 DIFF=COMPUTER-MANUAL;
 CARDS;
 1  18  34
 2  11  35
 3  10  32
 4  11  36
 5  24  34
 6   8  30
 7  21  34
 8  27  34
 9   8  29
10  12  35
11   8  33
12  22  39
13  21  36
14   9  37
;
DATA QD;
 INPUT SUBJECT $ DIFF @@;
 CARDS;
CE   9  CE   4  CE   9  CE   1  CE   1  CE   7  CE  -1
CE  -5  CE  13  CE  11  CE   6  CE  13  CE  18
EM  16  EM  24  EM  22  EM  25  EM  10  EM  22  EM  13
EM   7  EM  21  EM  23  EM  25  EM  17  EM  15  EM  28
;
PROC MEANS DATA=CE N MEAN STD SUM VAR STDERR T PRT;
 VAR MANUAL COMPUTER DIFF;
 TITLE PAIRED-COMPARISONS T TEST FOR CIVIL ENGINEERING;
PROC MEANS DATA=EM N MEAN STD SUM VAR STDERR T PRT;
 VAR MANUAL COMPUTER DIFF;
 TITLE PAIRED-COMPARISONS T TEST FOR ENGINEERING MANAGEMENT;
PROC TTEST DATA=QD;
 CLASS SUBJECT;
 VAR DIFF;
 TITLE QUALITY SCORES FOR DIFFERENCE: MANUAL VS. COMPUTER;
```

APPENDIX J

SAS OUTPUT FOR QUALITY MEASURE

1
1

PAIRED-COMPARISONS T TEST FOR CIVIL ENGINEERING 11:46 THURSDAY, AUGUST 18, 1988

VARIABLE	N	MEAN	STANDARD DEVIATION	SUM	VARIANCE	STD ERROR OF MEAN	T	PR>|T|
MANUAL	13	27.30769231	5.83644606	355.00000000	34.06410256	1.61873889	16.87	0.0001
COMPUTER	13	33.92307692	3.77406806	441.00000000	14.24358974	1.04673815	32.41	0.0001
DIFF	13	6.61538462	6.48766087	86.00000000	42.08974359	1.79935338	3.68	0.0032

1
2

PAIRED-COMPARISONS T TEST FOR ENGINEERING MANAGEMENT 11:46 THURSDAY, AUGUST 18, 1988

VARIABLE	N	MEAN	STANDARD DEVIATION	SUM	VARIANCE	STD ERROR OF MEAN	T	PR>|T|
MANUAL	14	15.00000000	6.81627013	210.00000000	46.46153846	1.82172482	8.23	0.0001
COMPUTER	14	34.14285714	2.62699427	478.00000000	6.90109890	0.70209375	48.63	0.0001
DIFF	14	19.14285714	6.23707455	268.00000000	38.90109890	1.66692829	11.48	0.0001

1
3

QUALITY SCORES FOR DIFFERENCE: MANUAL VS. COMPUTER 11:46 THURSDAY, AUGUST 18, 1988

TTEST PROCEDURE

VARIABLE: DIFF

SUBJECT	N	MEAN	STD DEV	STD ERROR	MINIMUM	MAXIMUM	VARIANCES	T	DF	PROB > |T|
CE	13	6.61538462	6.48766087	1.79935338	-5.00000000	18.00000000	UNEQUAL	-5.1074	24.7	0.0001
EM	14	19.14285714	6.23707455	1.66692829	7.00000000	28.00000000	EQUAL	-5.1151	25.0	0.0001

FOR H0: VARIANCES ARE EQUAL, F'= 1.08 WITH 12 AND 13 DF PROB > F'= 0.8854

APPENDIX K

SAS OUTPUT FOR TIME MEASURE

1 1

PAIRED-COMPARISONS T TEST FOR CIVIL ENGINEERING 11:46 THURSDAY, AUGUST 18, 1988

VARIABLE	N	MEAN	STANDARD DEVIATION	SUM	VARIANCE	STD ERROR OF MEAN	T	PR>|T|
MANUAL	13	52.30769231	10.33105848	680.00000000	106.73076923	2.86532008	18.26	0.0001
COMPUTER	13	36.53846154	7.46787994	475.00000000	55.76923077	2.07121723	17.64	0.0001
DIFF	13	15.76923077	8.62316499	205.00000000	74.35897436	2.39163565	6.59	0.0001

1 2

PAIRED-COMPARISONS T TEST FOR ENGINEERING MANAGEMENT 11:46 THURSDAY, AUGUST 18, 1988

VARIABLE	N	MEAN	STANDARD DEVIATION	SUM	VARIANCE	STD ERROR OF MEAN	T	PR>|T|
MANUAL	14	41.78571429	18.35621283	585.00000000	336.95054945	4.90590424	8.52	0.0001
COMPUTER	14	38.57142857	7.18667876	540.00000000	51.64835165	1.92072069	20.08	0.0001
DIFF	14	3.21428571	20.99515904	45.00000000	440.79670330	5.61119228	0.57	0.5765

1 3

TIME SCORES FOR DIFFERENCE: MANUAL VS. COMPUTER 11:46 THURSDAY, AUGUST 18, 1988

TTEST PROCEDURE

VARIABLE: DIFF

SUBJECT	N	MEAN	STD DEV	STD ERROR	MINIMUM	MAXIMUM	VARIANCES	T	DF	PROB > |T|
CE	13	15.76923077	8.62316499	2.39163565	5.00000000	35.00000000	UNEQUAL	2.0583	17.5	0.0548
EM	14	3.21428571	20.99515904	5.61119228	-25.00000000	45.00000000	EQUAL	2.0027	25.0	0.0562

FOR H0: VARIANCES ARE EQUAL, F'= 5.93 WITH 13 AND 12 DF PROB > F'= 0.0040