An Expert System Architecture for Construction Planning

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C. Hendrickson, C. Zozaya-Gorostiza, D. Rehak, E. Baracco-Miller, P. Lim

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Abstract

Construction planning involves the choice of construction technologies, the definition of work tasks, the estimation of required resources and durations, the estimation of costs, and the preparation of project schedules. A knowledge-based expert system design to accomplish these tasks, CONSTRUCTION PLANEX, is described in this paper. This system synthesizes activity networks, diagnose resource needs and predicts durations and costs. The CONSTRUCTION PLANEX system could be useful as an intelligent assistant in routine planning, as a laboratory for the analysis and evaluation of planning strategies, and as a component of more extensive construction assistance systems involving design or project control. The operation of a prototype system to plan building excavation tasks is described and illustrated with an example.

Introduction

Construction planning is a fundamental and challenging activity in the management and execution of construction projects. It involves the choice of construction technologies, the definition of work tasks, the estimation of the required resources and durations for individual tasks, and the identification of any interactions or constraints among the different tasks. A good construction plan is the basis for developing the project budget and the schedule of work. Poor estimates or schedules can easily result in large construction cost increases or delays. Inappropriate or inconsistent decisions concerning the appropriate technologies to use can have similar effects. As a result, construction planning is crucial to the eventual success of a project.

Current construction planning relies upon manual formulation of plans and is usually performed in an intuitive and unstructured fashion with considerable reliance on engineering judgement. Few aids for activity scheduling exist other than general project templates or past project networks that can be adapted to the particulars of a new project. Descriptions of the characteristics of good project plans exist in the literature (see, for example, [Willis 86]), but little attention has been paid to analyzing the process by which plans are or should be formed.

In this paper, a knowledge-based expert system for construction project planning is described. The system is intended to synthesize activity networks, to recommend appropriate technologies, to estimate required resources, and to develop a project schedule. This system includes three major components:

1. a *hierarchical model* to record information about project activities and decisions made during the planning process;

2. a set of *operators* to perform specific planning tasks such as technology choice, activity duration estimation, or scheduling; and

3. a store of *knowledge sources* to provide relevant information to specific operators.

Experience with an initial prototype of the overall system is also described. This prototype plans activities associated with the excavation of building foundations.

The construction planning expert system described here, called CONSTRUCTION PLANEX, is proposed for several reasons. First, this system provides a means to formalize the planning process so as to permit analysis and evaluation of different strategies and tasks within the overall process. By formalizing the various decisions and planning strategies, existing knowledge can be examined and gaps in knowledge or procedures highlighted. Many expert system development projects have had secondary effects of this sort [Shortliffe 76].

Second, the system represents a framework for the development of automated planning assistants based on knowledge-based expert system and artificial intelligence programming techniques. These techniques promise to have a revolutionary impact on construction engineering and management since they greatly expand the capability to manipulate and utilize qualitative and experiential information so prevalent in the construction field. In the realm of construction planning, the expert system is likely to work as an assistant to a planner to handle details of planning or to suggest alternatives. With an automated assistant, more detailed and accurate activity networks should be feasible and cost effective.

Finally, the proposed system might provide a component for more extensive project control systems in which project monitoring or facility design are major goals. By facility design, we include the entire process of architecture and engineering design and facility fabrication. For project monitoring and adaptation of a plan over time, the expert system has the advantage of preserving a record of decision points and hierarchy among activities so that past decisions can be reviewed and modified in light of new events.

The next section briefly describes some background on the use of expert systems and artificial intelligence in planning. The following section describes a typical planning problem in the domain of building foundation excavation and the performance of a simple planning expert system. This system illustrates the functional requirements of an expert system in this area. Following this, a more general architecture for automated construction planning is described. A concluding section summarizes preliminary results in **the area.**

Background

Knowledge-based expert systems are computer programs based on artificial intelligence techniques and designed to reach the level of performance of a human expert in some specialized problem solving domain. Expert systems have considerable potential in ill-structured problem solving domains where explicit algorithms do not exist or where traditional computer programs provide only restricted problem solving capabilities.

A distinguishing characteristic of knowledge-based expert systems is the functional separation between three categories: the knowledge (called the *knowledge-base,* which includes inference rules and factual knowledge); a control mechanism (often called an *inference engine*); and information about a particular problem (called the problem *context*), as illustrated in Figure 1. Many existing expert systems store knowledge in the form *of production* rules or *if-then* statements. Other knowledge representation schemes are possible such as the use of *frames* which possess *slots* containing values, lists, text, procedural statements (such as calculation or manipulation instructions), pointers or other entities. In CONSTRUCTION PLANEX, the knowledge-base, control mechanism and the context are all organized in frames.

Numerous applications of expert systems in the realm of construction project management have been suggested; Levitt [Levitt 87] provides a general review. Systems for project monitoring [McGartland 85], schedule updating [Levitt 85], schedule criticism [O'Connor 86] and activity duration estimation [Hendrickson 86] have been described in the literature. Several expert systems for diagnosis of equipment and other purposes are in routine use [Kostem 86]. However, no system currently exists for the construction project planning problem.

In the literature of artificial intelligence, numerous papers have addressed the general problem of planning, although not specifically in the context of construction. The most common application area has been in the realm of planning movements of blocks to achieve desired goals. The system *NOAH* (for Network of Action Hierarchies) was an initial formalization of the problem in which declarative and procedural knowledge about activities were represented in a network. This system began with a system statement of desired goals represented as a node in a network, and this network was then expanded and modified by defined operators [Sacerdoti 74, Sacerdoti 77]. The system *NONLIN*

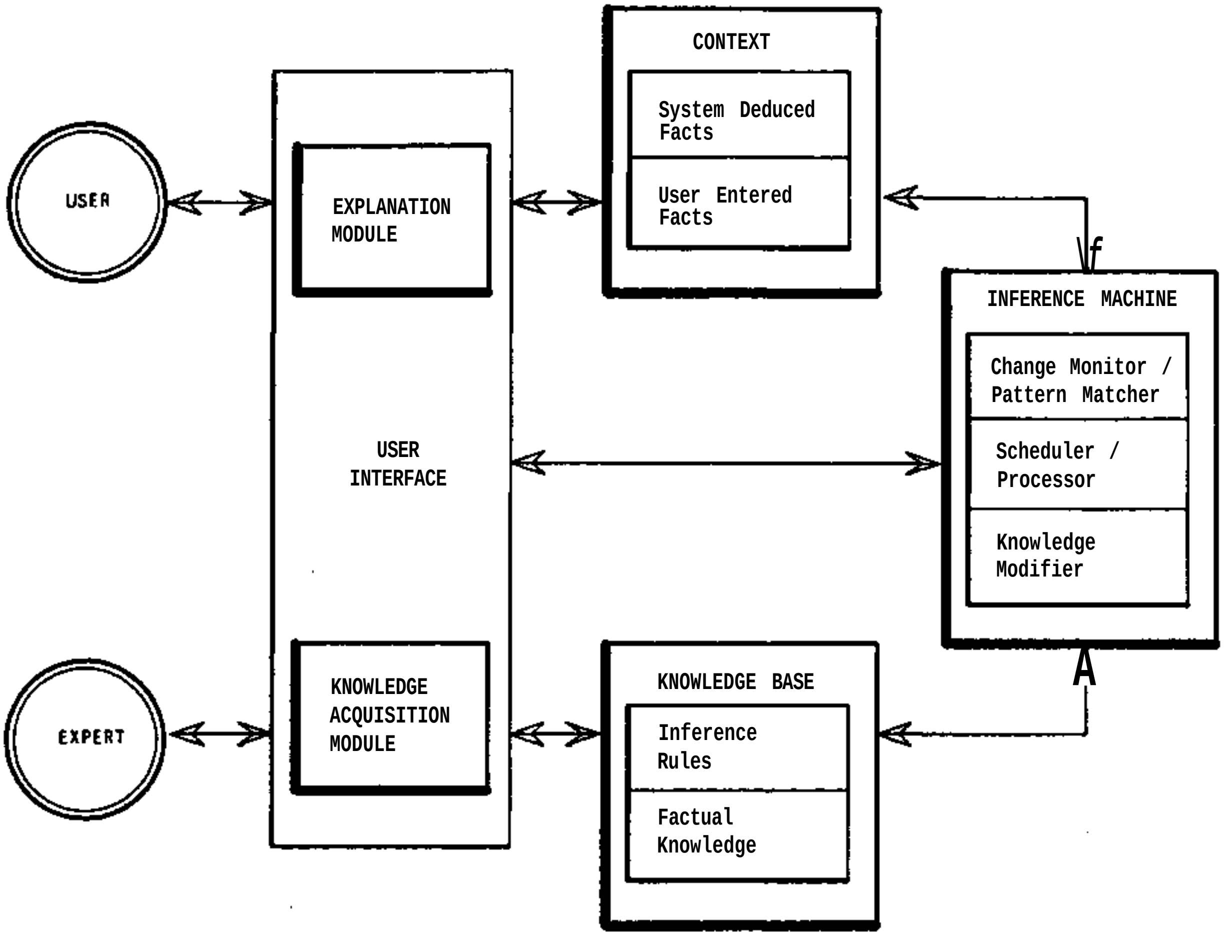

Figure 1: Schematic View of a Typical Rule-Based Expert System

was an extension of NOAH which included a decision graph to permit backtracking and alternative resource decisions [Tate 77]. The system *DEVISER* was intended to plan and schedule an autonomous unmanned spacecraft [Vere 83]; it contained explicit information on time constraints in the process. The system *MOLGEN* also used explicit operators in a hierarchical task space to perform planning of genetic experiments [Stefik 81a, Stefik 81b]. MOLGEN featured a flexible control structure and explicit formalisms for constraints on the activity plan. Finally, the scheduling system *ISIS* and its successor *CALUSTO* developed a general system of activity representation within the realm of job shop scheduling [Fox 83, Fox 84].

While these artificial intelligence based planning systems offer some extremely useful conceptual tools, each has significant limitations for construction planning. First, these systems generally incorporate only a relatively small number of well defined, repetitive tasks. In contrast, construction requires numerous distinct tasks for completion. Second, construction planning involves the selection of appropriate resources to apply, in contrast to blockworld or job shop scheduling problems in which resources are given. Third, construction has numerous important planning concerns with respect to time constraints, cost and resource trade offs, and spatial restrictions which are not explicitly considered by existing AI planning systems. In particular, the trade-offs between cost, technology and activity duration is important for construction planning but is not considered in existing AI planning models. Fourth, the large size of construction planning problems suggests that efficient, algorithmic scheduling tools may be required rather than relying entirely on heuristic allocations. Fifth, construction planning is highly knowledge intensive, so explicit use of expert knowledge is required in the planning process. Accordingly, a different system architecture is required in the construction domain than occurs in existing AI planning models.

Prototype Overview: Excavation Planning

To illustrate the problems of construction planning and a computer based architecture for automated planning, we consider the problem of planning the site excavation phase for a new building. A prototype excavation planner for this purpose has been developed; its functions are described in this section. The system was developed i Franz LISP [Foderaro 81] and calls functions of FRAMEKIT [Carbonell 85a] and RULEKIT [Carbonell 85b]. The system has also been written in the KNOWLEDGE CRAFT[1] expert system environment.

In this example, it is assumed that the elements of work have been quantified. Elements of work represent the different tasks to be performed for specific design elements. A design element is a facility component such as a footing, a column, etc. For example excavation and formwork are elements of work for each footing. Along with general project information such as soil conditions, the listing of the required elements of work for bulk, footing and trench excavations form the input or initial *context* for the planning process. Using this information, the planning problem is to generate the network of required excavation activities, to define the precedence relationships among these activities, to recommend a particular machine type for the excavation, and to estimate the duration of the entire excavation phase.

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[1] KNOWLEDGE CRAFT is a registered trademark of Carnegie Group, Inc.

In this prototype system, overall control of the planning process is provided by the user. Menus of planning activities are provided from which a user selects an option. For example, options available in the main menu include: (1) input or modify information; (2) display information; (3) define project and element activities; (4) perform resource and technology selection; (5) apply a critical path scheduling algorithm; and (6) output reports. After each planning activity, the user can review results and modify decisions as desired.

Figure 2 shows the plan of required footing and trench wall excavations for a sample excavation problem of this type. In this example, 66 different excavation elements are defined based on the foundation design, including 54 column footings, 11 wall footings and 1 elevator pit. Information about elements of work for each design element is stored in *frames* such as the example for a column footing shown in Figure 3. Each element of work is identified by a *narrowscope* code similar to that of the standard CSI MASTERFORMAT [CSI 83] system. Other slots in the element of work frame identify the specific design component (column 46 in this case), its location (including coordinates and block), and dimensions.

The prototype excavation planning expert system accepts the elements of work as input and initially identifies *general tasks* necessary to complete the excavation phase such as *excavation massive, haul excavation massive, excavation foundation, haul excavation foundation,* and *formwork foundation.* A general task defines a type of activity to be performed. However, general tasks cannot be used in activity networks, because they stand for one or more *project activities* to be executed independently. Frames representing *project activities* are created based on sets of rules relating general tasks with elements of work. For example, generic rules are:

If Element of Work Frame has Narrowscope Code <NC>
    Then Its general task is <GT>

If Element of Work Frame with Narrowscope Code <NC> exists
  And It is located in Block <BL>
  And It is located in Floor <FL>
  And There is no Project Activity <GT>Block<BL>Floor<FL> created
    Then Create a Project Activity <GT>Block<BL>Floor<FL>

Specific values in our example could be <NC> = 02220-21, <GT> = foundation excavation, <Block> = a, and <Floor> = none.

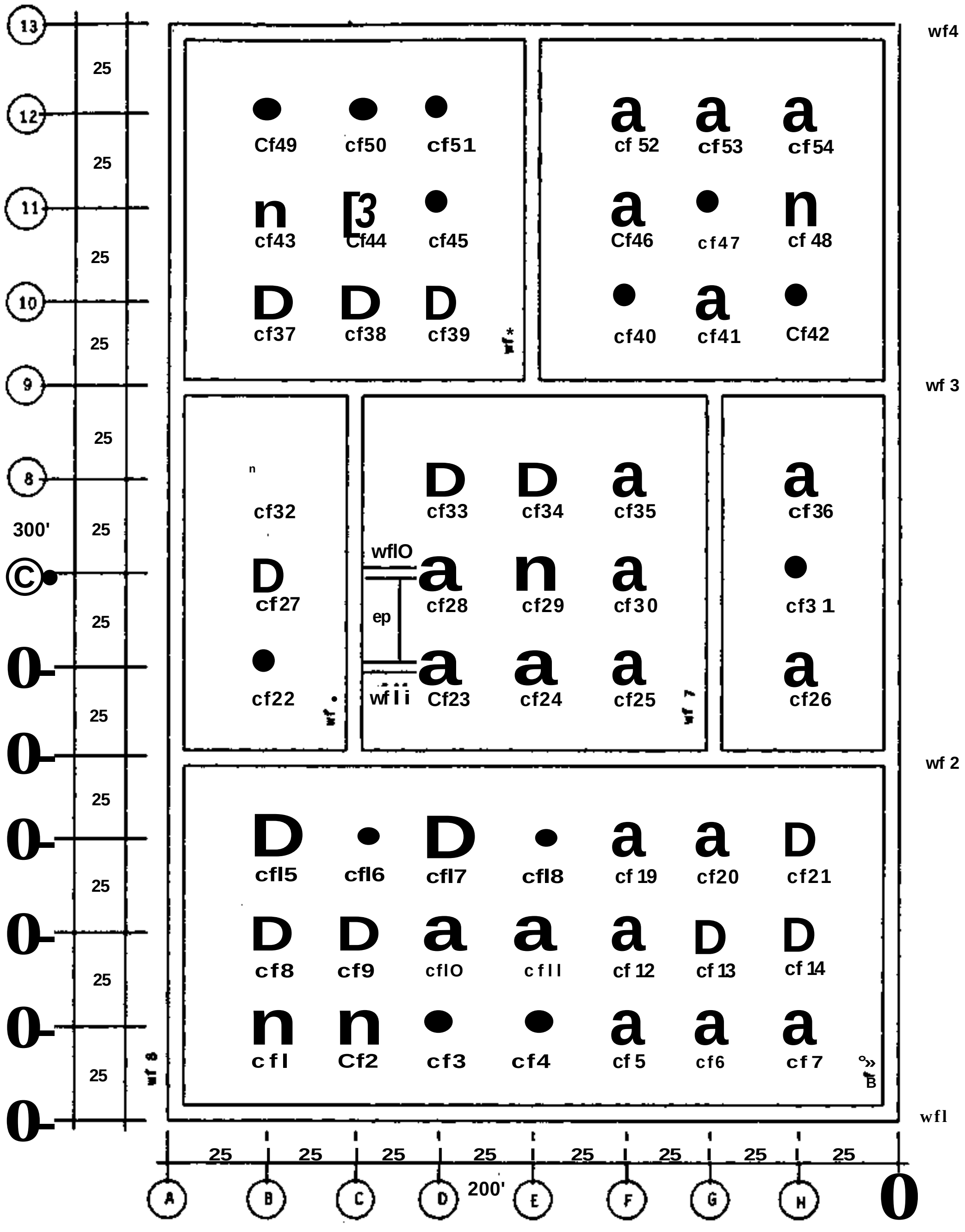

Figure 2: Example Plan of Required Foundation Excavation

```
--------------------------------------------------------
|                    ELEMENT OF WORK                    |
--------------------------------------------------------
|                                                       |
|    Element-id            CF-46                        |
|    Narrowscope-code      02220-21                     |
|    Element-unit-id       Column 46                    |
|    Xl-coord              125.0    ft                  |
|    Yl-coord              250.0    ft                  |
|    Block                 a                            |
|    Bulk                  bulk-1                       |
|    Width                 11.0     ft                  |
|    Length                11.0     ft                  |
|    Depth                 6.0      ft                  |
|    Volume                26.89    cy                  |
|                                                       |
--------------------------------------------------------
```

Figure 3: Example Element of Work Frame

Besides *general tasks* and *prqject activities,* the system creates a third level of activities called *element activities.* Each element activity is a portion of a project activity, thus *excavation column footing 46 in block* a is a portion of *excavation foundation in block* a. The system proceeds in a top down fashion to create project activities associated with each general task and then assigns element activities to particular project activities. The result is a tree structure of activities at different levels of aggregation and abstraction.

The prototype excavation system has no capability for defining new types of tasks. General tasks, project activities and element activities are chosen from a pre-defined set of possible activities. In effect, the activity creation portion of the prototype system is a *synthesizer* in which known components (in this case pre-specified possible activities) are combined to solve the problem at hand. New types of tasks can only be defined by extending the knowledge-base.

Once the different project tasks are created, a variety of subsidiary decision and estimation problems are addressed. These problems include determining the equipment to be used, the number of crews or pieces of equipment, inter-task precedences, and task durations. In contrast to the synthesis involved in activity definition, these tasks involve *diagnosis* and *prediction.*

For equipment choice, a set of decision tables are included to recommend a particular type of equipment based on characteristics of the site and the required elements of work. For example, bulk excavation might be performed by a power-shovel or a clamshell, and the decision between the two types of equipment may be based on soil type, water content and amount of excavation. Equipment recommendations made by the system can be reviewed and over-ridden by the user. Equipment choices are recorded in a slot in the *project activity* frames. In the prototype expert system, the number of pieces of equipment and crews is input by the user; in a more extensive system, recommendations on numbers of crews could be made by the system.

Task durations are estimated from decision tables and calculating rules in a manner similar to that used in the *MASON* system [Hendrickson 86]. In that system, a basic productivity is estimated and then modified in light of specific conditions of a job. In the excavation prototype, productivities are modified for different equipment types and other special problems. Recommendations for improving task productivity could also be provided as in the MASON system, but this capability is not provided in the excavation prototype.

Precedences among *element activities* are also determined and recorded in slots of the element activity frames. These precedences can be of two types: (1) physical or (2) resource related. Physical precedences are based on necessary sequences of activities for particular project activities and element of work. For example, completion of the excavation task must precede formwork activities on a design element. Narrowscope codes serve as basic information in such determinations. Resource related precedences are obtained by assigning the sequence in which a particular machine or crew would undertake different *element activities.* These resource allocation decisions are made by a set of rules based on an appropriate starting point and the spatial orientation of design elements. In a more extensive system, these resource allocations could be made by means of heuristic rules prior to scheduling or as part of the application of a resource constrained scheduling algorithm.

Application of a critical path scheduling algorithm is a final utility available in the prototype excavation system. Once element activities, precedences and durations are identified, this scheduling procedure is straightforward. With an initial schedule and plan, the user can then revise the allocation of machinery or the number of resources available to achieve desired goals.

For the example problem illustrated in figure 2, the resulting network of element activities is illustrated in Figure 4. In the figure, *puem* stands for *pile-up excavation massive, dmem* for *dispose-material excavation massive, excf* for *excavation column footing, exwf* for *excavation wall footing, fcf* for *formwork column footing,* and *fwf* for *formwork wall footing.* This project plan includes 136 element activities, 5 project activities and 5 general tasks. With 2 power shovels, 3 clamshells and 4 crews working on formwork, the overall duration of the excavation phase is 260 hours.

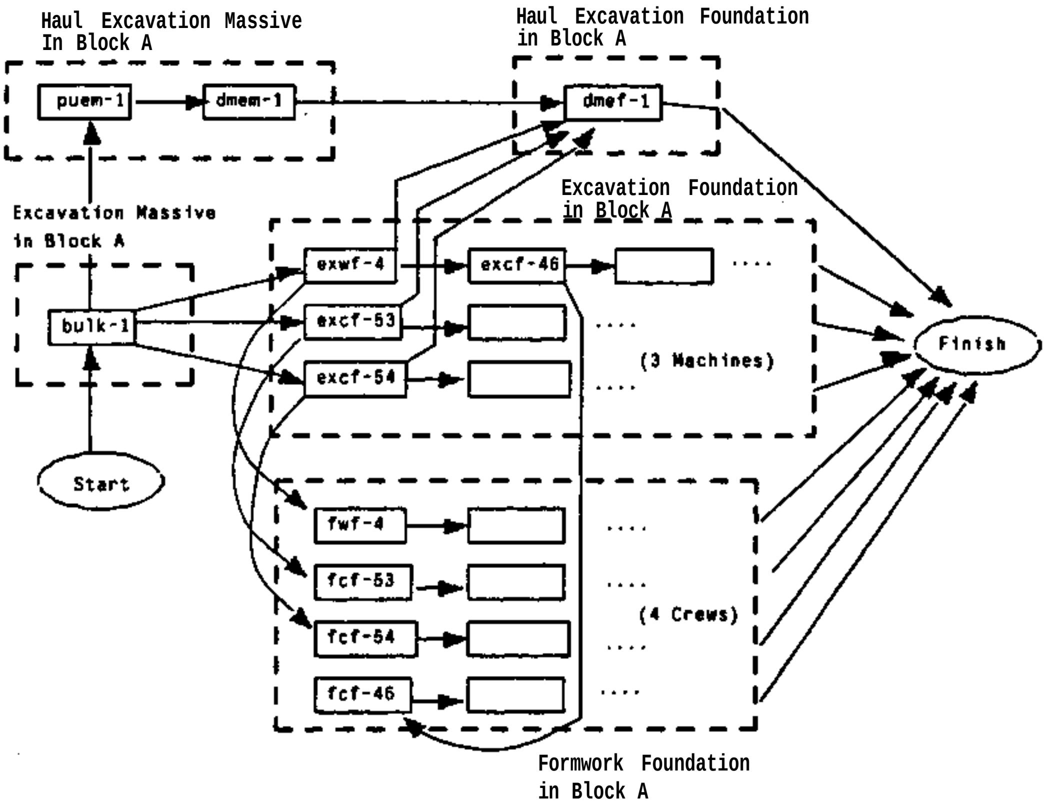

Figure 4: Detailed Network

This small excavation planning prototype illustrates many of the essential operations in a general planning system. Synthesis of project activities is accomplished by reference to design elements. In the excavation implementation, this synthesis is accomplished by creating frames with some pre-defined characteristics and some features relevant to specific design elements. Knowledge sources in the form of one or more decision tables are used to suggest appropriate technologies and to estimate required resources. A conventional scheduling algorithm can be used to develop the final project schedule. The prototype system has several limitations, such as the reliance on manual control of operators, a limited user interface, and pre-defined hierarchical relationships among activities. In the next section, a more general architecture for a construction planning system is presented.

CONSTRUCTION PLANEX Overview

In this section, we describe the overall architecture of the CONSTRUCTION PLANEX system. This architecture adds several features to the small excavation prototype described in the previous section such as cost estimation, automatic control and algorithmic resource allocation. It also represents a more comprehensive and flexible implementation scheme than the prototype.

Similar to other knowledge-based expert systems, CONSTRUCTION PLANEX has three essential parts as illustrated in Figure 5. The *Context* contains information on the particular project being considered, including the design, site characteristics, the planning decisions made, and the current project plan. The *Operator Module* contains operators that create, delete or modify the information stored in the context. Operators are of two types: (1) Specialized, and (2) Control. Specialized operators are used for different tasks such as technology choice, activity synthesis, duration estimation and others. Control operators decide on the order in which specialized operators are executed. Interaction between the two types of operators occurs by means of a message interface that plays the role of a blackboard. The *Knowledge-Base* contains distinct *knowledge sources* of tables and rules specific to particular technology choices, activity durations, or other considerations. Each knowledge source is used by a particular operator. In addition to these central components, a user interface including an explanation module is included.

In the *Context,* a variety of objects storing information are available, including:

- Design Element objects that store information about design components,
- Quantity-Take-Off objects that store information about elements of work,
- Site-Characteristics objects that store information about different conditions on the site,
- Activity objects that represent construction tasks at different levels of

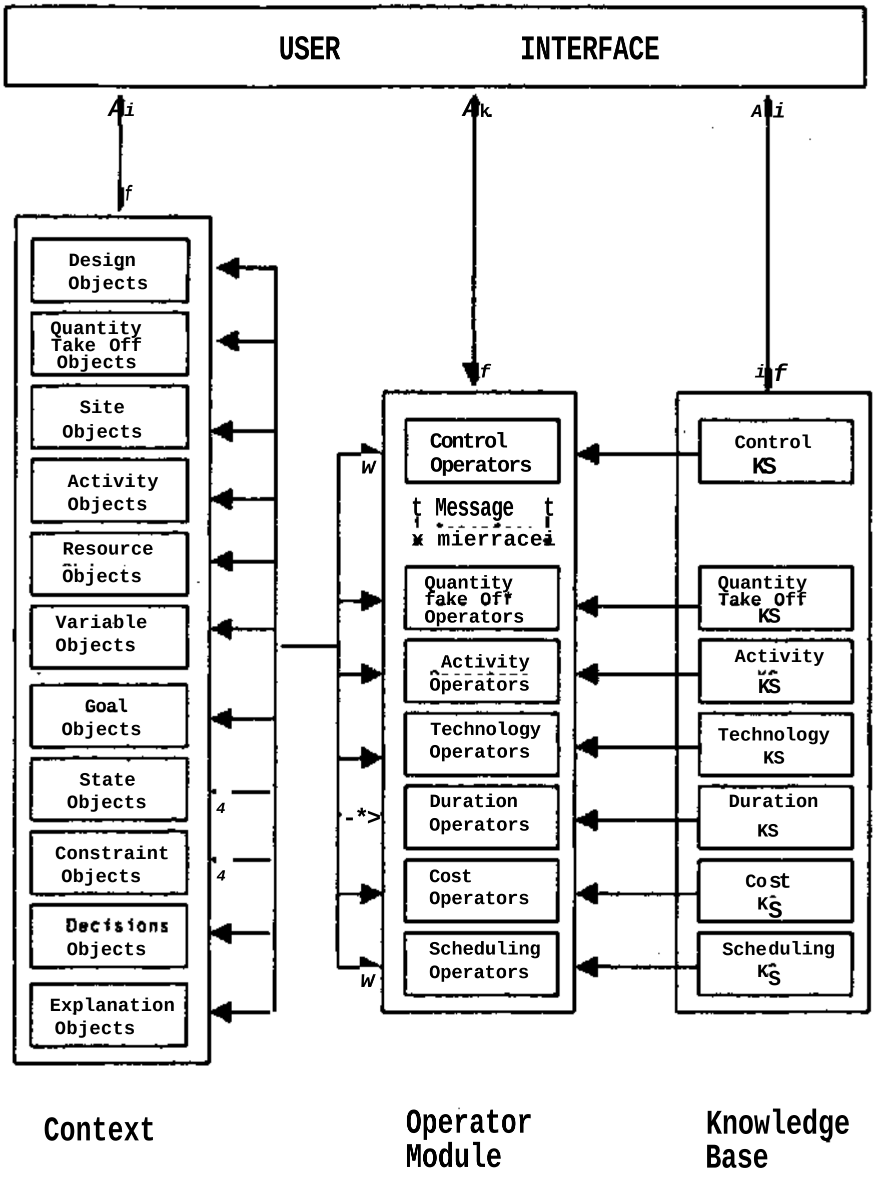

Figure 5: Overview of CONSTRUCTION PLANEX

aggregation,

- **Resource** objects indicating the characteristics of equipment, labor or materials,
- **Variable** objects storing information about input or calculated variables such as volumes or areas,
- **Goal** objects that define different stages in the planning process,
- State objects used dynamically to describe the characteristics of the planning process,
- **Constraint** objects to represent required relationships among states and variables,
- Decision objects for representing points in the planning process that are affected by technology choice, resource allocation or other decisions made by the user or CONSTRUCTION PLANEX, and
- Explanation objects to store information or pointers to information about the construction plan.

These different objects are related by a network of relations that represents the current project plan, decisions made during the planning process, and different aggregation schemes. Thus, the set of activities form a project network while the system context contains a more extensive network which also records the planning process and other information. The insertion of design element objects in the context provides the means to automate the generation of elements of work that in the prototype were defined by the user.

The **operator module** contains a number of modules similar to those described for the excavation prototype, such as:

- **QTO** operators to create elements of work based on design element information,
- **Activity** operators to create, elaborate, expand, link or aggregate activities,
- **Technology** operators to suggest appropriate equipment or technology,
- **Duration** operators to perform estimation, and
- **Scheduling** operators to provide a project schedule including critical path identification and any required resource allocation.

In addition to these basic operators used in the excavation prototype, cost estimation operators and control operators to influence the process of planning are also defined. All operators are generic, so that a single operator can be used for all activities. For example, the duration estimation operator would be called for each element activity and consult a knowledge source specific to each narrowscope activity to obtain a duration estimate.

By creating a flexible and generic framework, the CONSTRUCTION PLANEX system should be capable of application to different types of projects, although each type of project would require different knowledge sources. The system is now being implemented in the KNOWLEDGE CRAFT expert system environment for the application domain of office building construction.

Conclusion

We have described the architecture and function of a knowledge-based expert system for construction planning. A small excavation planning prototype demonstrated the feasibility of the system in that activity networks were developed automatically, durations estimated, and a project schedule obtained. The more general system CONSTRUCTION PLANEX should improve upon the performance of the excavation prototype.

While the feasibility of an automated planning system has been demonstrated, the desirability of an expert system of this sort is still an open question. Considerably more experience with the system will be required, especially field testing. However, the potential benefits Of the system should be substantial.

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