An Expert System for Construction Planning

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Abstract

Among other concerns, construction planning involves the choice of construction technology, the definition of work tasks, the estimation of required resources and durations, the estimation of costs, and the preparation of a project schedule. A prototype knowledge intensive expert system to accomplish these tasks, CONSTRUCTION PLANEX, is described in this paper. This system generates project activity networks, cost estimates and schedules, including the definition of activities, specification of precedences, selection of appropriate technologies and estimation of durations and costs. The CONSTRUCTION PLANEX system could be useful as an automated assistant in routine planning, as a laboratory for the analysis and evaluation of planning strategies, and as a component for more extensive construction assistance systems involving design, site layout or project control. The current application for CONSTRUCTION PLANEX is to plan modular high rise buildings, including excavation, foundation and structural construction.

Short Abstract

A prototype knowledge intensive expert system to accomplish construction planning for modular high rise buildings, CONSTRUCTION PLANEX, is described in this paper. This system generates project activity networks, cost estimates and schedules, including the definition of activities, specification of precedences, selection of appropriate technologies and estimation of durations and costs.

Key Words

Construction, Planning, Computer Applications, Expert Systems, Scheduling, Project Management

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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 judgment. Few computer based 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 Commercial scheduling systems require a complete construction plan as an input Descriptions of the characteristics of good project plans exist in the literature (see, for example, (Willis, 1986)), but little attention has been paid to analyzing the process by which plans are or should be formed (Baracco-Millcr, 1987).

In this paper, a knowledge intensive expert system for construction project planning is described. The system generates project activity networks, cost estimates and schedules, including the definition of activities, specification of precedences, selection of appropriate technologies and estimation of durations and costs. The system includes three major components:

1. *hierarchical representation structures* 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 for operations.

Experience with a prototype of the overall system is also described. This prototype plans activities associated with site preparation, excavation, foundation construction, and structural erection for high rise buildings.

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 strategics, 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, 1976).

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 the architecture of the CONSTRUCTION PLANEX system. Operation of the system is illustrated with a planning problem for a modular building. A concluding section summarizes preliminary results in the area.

Background

Numerous applications of expert systems in the realm of construction project management have been suggested; Levitt (Levitt, 1986) provides a general review. Systems for project monitoring (McGartland, 1985), schedule updating (Levitt, 1985), schedule criticism (O'Connor, 1986) and activity duration estimation (Hendrickson, 1987) have been described in the literature. Several expert systems for diagnosis of equipment and other purposes are in routine use (Kostem, 1986). However, no system currently exists for the construction project planning problem (O'Connor, 1987).

In the literature of artificial intelligence, numerous papers have addressed the general problem of planning, although not specifically in the context of constaiction. The most common application area has been in the realm of planning movements of blocks to achieve desired goals. *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, 1974, Sacerdoti, 1977). *NONLIN* was an extension of NOAH which included a decision graph to permit backtracking and alternative resource decisions (Tate, 1977). *DEVISER* was intended to plan and schedule an autonomous unmanned spacecraft (Vere, 1983); it contained explicit information on time constraints in the process. *MOLGEN* also used explicit operators in a hierarchical task space to perform planning of genetic experiments (Stefik, 1981a, Stefik, 1981b). MOLGEN featured a flexible control structure and explicit formalisms for constraints on the activity plan. Finally, the scheduling system *ISIS* and its successor *CALLISTO* developed a general system of activity representation within the realm of job shop scheduling (Fox, 1984, Sathi, 1986).

While these artificial intelligence based planning systems offer some 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 myopic, heuristic allocations. The computational burden of scheduling in construction is significant: construction schedules can include hundreds of activities. 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.

CONSTRUCTION PLANEX Overview

Similar to other knowledge-based expert systems, CONSTRUCTION PLANEX has three essential parts as illustrated in Figure 1. 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 used for different tasks such as technology choice, activity synthesis, duration estimation and others. Hie *Knowledge-Base*

contains distinct *knowledge sources* of tables and rules specific to particular technology choices, activity durations, or other considerations. In addition to these three components, CONSTRUCTION PLANEX contains a menu driven interface used to control the execution of the operators and a *Knowledge Source Acquisition Module* used to modify the contents of the Knowledge Base. The system is implemented in KNOWLEDGECRAFr™ on a Texas Instruments' EXPLORER™ computer.

In the *Context,* information is stored in a series of hierarchically organized *frames.* Each frame is linked to *parent* or *children* frames from which information can be inherited. Frames are named and contain various *slots* to record information. As an example, Figure 2 shows a frame for an individual design element consisting of a column footing. This frame is titled "p01-s00-b00-f00-de-60-01-0r and contains four types of slots:

- *Classification Slots* that identify the type of design element. CONSTRUCTION PLANEX uses a *design code* to identify design elements. In particular, *is-a* is used to indicate that this frame is a design element frame, the slot *name-code* with value 60 indicates that this design element frame corresponds to a column footing, the slot *type-element* with value 01 indicates that this is a concrete footing and the slot *number-element* indicates that this is the first of several concrete column footings.

- *Location Slots* that specify in what *project, sector, block* and *floor* is located the particular design element Also, there are slots such as *xg-coordinate, yg-coordinate* and *zg-coordinate* that specify the global coordinates of a point of the design element

- *Geometry Slots* that describe the geometric characteristics of the design element such as *xl-coordinate, yl-coordinate, zl-coordinate, x-angle, yangle* and *z-angle.* Geometry slots may be named differently (for example *yhcoordinate* could be named *width);* also, each type of design element has its own set of geometry slots.

- *Specifications Slots* that contain other information concerning the design element relevant to the planning process. For example, the *construction'type* and the *concrete-type* are useful specifications for determining appropriate construction technologies.

Design elements of this type would be basic inputs to the planning system.

During operation of the system, additional frames are created to represent activities and decisions. For example, Figure 3 illustrates a frame created to describe the excavation activity required for the column footing described in Figure 2. Attributes describing this activity include:

- *Classification Slots* that identify the type of clement activity. CONSTRUCTION PLANEX uses an extended MASTERFORMAT code (CSI, 1983) to identify element activities. For example, the *ea-code* of this activity indicates that it belongs to Division 2 (Sitework) of the MASTERFORMAT, to Broadscope 220 (Excavation, Backfilling & Compacting) and to Narrowscope 10 (Column Footing).

- *Hierarchy Slots* that specify the relationships between the element activity frame and other frames of the context. For example, the *ea-of-DE* slot is used to identify the design element for which this activity takes place, the *parent-EA* slot indicates a pointer to a parent frame common to several element activities of the same MASTERFORMAT code and the *parent-PA* slot indicates a pointer to a higher aggregation of construction activities.

- *Quantity Take-Off Slots* that contain information about the *amount of work* and the *unit-of measure* for the element activity.

- *Specification Slots* that describe other information relevant to the activity such as the type *of material-package* that has to be used. The information of these slots might be common to several element activities. If this is the case, the system stores this information in higher levels of the hierarchical frame structure.

- *Technology-Decision Slots* containing information about technology choices such as the type of *crew* to be used. In the general case, technology information is inherited from other frames in the context as described below. However, the user may override this values and specify technology choices at the level of element activities.

- *Technology Consequence Slots* that describe information dependent upon the technology choice affecting the element activity, such as the *duration* of the activity, its *successors* and its *cost.*

Element activities do not represent an appropriate level of detail for planning purposes. Construction planners work with more aggregated activities that involve several element activities of similar nature. These aggregated activities are used to create the *project* network that is used as the basis for technology choices and for scheduling purposes. Figure 4 illustrates a *project activity* frame. Slots in this frame include:

- *Classification Slots* that identify the type of project activity. CONSTRUCTION PLANEX uses an internal *pa-code* for classifying project activities.

- *Hierarchy Slots* that specify the relationships of the project activity frame in the context such as the *pa-has-eas* slot that contains pointers to all the element activities belonging to the project activity and the *parent-PA* slot that points to a group of project activities of similar characteristics.

- *Quantity Take-Off Slots* that contain information about the *amount of work* and the *unit-of measure* for the project activity. The amount of work of a project activity is obtained by aggregating the quantities-take-off of its element activities.

- *Specification Slots* that describe other aggregated information such as the quantity of materials required to perform the activity.

- *Technology Decision Slots* containing information about the type of *crew* and number of crews allocated to this project activity. The information in the slot *number-crews* is important because it affects the overall duration of the activity and the sequence in which its element activities are performed.

- *Technology Consequence Slots* that describe information such as *duration* cost, successors* and *successor lags.*

- *Scheduling Slots* that describe scheduling information such as the earliest and latest start time of the activity and the *milestones* imposed on the activity.

Project activity slots as well the various slot attributes are created by the CONSTRUCTION PLANEX system.

These different frames are organized to represent the current project plan, decisions made during the planning process, and different aggregation schemes. Figure 5 shows the general structure of the context. On top of the hierarchy there are frames used to store information at the *project, sector, block and floor* levels. Below them there are trees for *design elements, element activities* and *project activities*. Element activities are linked to design elements, to element activity groups and to project activities. Decisions and computations undertaken during the planning process can be stored in any of the frames of this hierarchy and inherited by element activities. Furthermore, inherited values can be overridden by local decisions for particular cases. Thus, the set of activities can form a conventional project network while the system context contains a more extensive network which also records the planning process and other information.

The operator modules alter the system context by creating frames or modifying attributes. The exact modifications made are found by evaluating relevant *knowledge sources* in the knowledge base. In the initial creation of a construction plan, the following sequence of operations might be followed:

- *Create Element Activities* for design elements". This operation only identifies the set of element activities required to accomplish each design element. Other information is added to element activity frames using other operators.

- *Group Element Activities* of common characteristics in order to have a hierarchy of element activities similar to that of the MASTERFORMAT.

- *Determine Amounts of Work* for element activities. Geometric information is inherited from design element frames.

- *Select Units of Measure* for element activities. Crew productivities or material quantities may be expressed in different units (eg. days instead of hours). In these cases, the system performs appropriate unit conversions.

- *Determine Material Packages* for element activities. Material Packages should satisfy design specifications.

- *Create Project Activities* that aggregate element activities.

- *Determine Precedences* for project activities. Project activities can be structured into a *project network*.

- *Compute Lags* for project activities. Element activities of several project activities are structured into an *element activity subnetwork*. A simple CPM algorithm is used

to determine scheduling information in this subnetwork. This information can be analyzed to compute lags between aggregated project activities.

- *Select Technologies* for project activities. For this operation the system uses heuristics related to soil and site information, resource productivity information and other factors (such as weather). Dependent choices are expressed by creating auxiliary frames pointing to several project activities.

- *Estimate Durations* for project and element activities. Standard productivities of selected resources are adjusted in order to estimate the duration of construction activities.

- *Schedule* project activities using CPM, resource allocation and constraint satisfaction algorithms.

- *Estimate Costs* by computing activity costs and project costs using unit costs and scheduling information.

The knowledge base is organized into a set of *knowledge sources* (KS) that represent rules, heuristics, and calculation functions. These knowledge sources can best be pictured as decision tables, although they are actually written as frames and production rules. An example of a knowledge source appears in Figure 6. This KS contains two conditions, 3 rules and 3 actions. The first rule indicates that if the *soil-type* is *hard and* the result of evaluating *KS-water-level* is not *wet,* then the appropriate technology is *power-shovel.* The second rule indicates that if the *soil-type* is not *hard* and the result of evaluating *KS-water-level* is *wet,* then the appropriate technology is *clamshell.* Finally, the third rule indicates that if none of the previous two rules were fired, the appropriate technology is *special-machine.*

When performing the operations described previously, the system evaluates numerous KS using two types of generic operators:

- *Knowledge Source Evaluator(KSE).* This operator is used to determine results of KS that affect leafs or subtrees of the context. For example, activity duration estimation is an operation that affects only single activities. For this operation, the KSE is used to consult a knowledge source specific to each narrowscope activity.

- *Knowledge Source Evaluator with Grouping (KSEG).* This operator is used to determine results of KS that affect frames of different subtrees of the context For example, selecting the type of equipment to be used *fox pouring concrete in columns* of a particular floor might constrain the type of equipment to be used in similar activities of other floors.

In designing the CONSTRUCTION PLANEX system, our goal was to create a flexible and generic framework for knowledge intensive activity planning. By substituting different knowledge sources, the system is capable of application to different types of projects.

Prototype Overview: Modular Buildings

The current version of CONSTRUCTION PLANEX does not interact with any computer aided design system. The system reads input files with information about individual design elements such as the one presented in Figure 2. However, providing the system with geometric information about every design element of a building is a cumbersome task, especially in high rise buildings. While the PLANEX system can handle an arbitrary design, we have created an input program that receives information about the design elements of a *module* of the building and uses this data to generate the project plan for the whole building. An example of such module is illustrated in Figure 7. This module contains 4 column footings, 4 columns, 4 beams and 1 slab. The input file of this module would have 13 design element frames. The current user interface is relatively crude, consisting of menus, text messages and a limited number of graphs.

Once the basic module of the building has been created, the user specifies the characteristics of the building in terms of this basic module. First, the user specifies the number of identical modules in the x, y and z directions. With this information, the system creates frames for each type of design element with information for the whole building. Then, the user may modify *instances of* the basic module in order to allow buildings with variable spacing between columns or floors. An example of a *modular building* is presented in Figure 8. This building is composed of 4 X 4 X n identical modules sharing some common design elements.

The second task is to create element activities for each design element The schema representation of a knowledge source that can be evaluated in this process, *ks-create-ea-60-1,* is displayed in Figure 9. Seven of the following eight element activities may be needed for a column footing: *excavation, dispose-off-excavation, formwork, reinforcing-steel, pour-concrete, remove-forms, borrowmaterial* and *pile-up.* The *pile-up* and *borrow-material* activities are exclusive. The latter is needed when the soil is inappropriate for backfilling.

The next task is to perform operations on the element activity frames. First, the system structures them hierarchically and then it computes the amount of work and the unit of measure for each element activity. The KS to obtain quantities return formulas that have to be evaluated subsequently. These formulas are written in non LISP code to make them more readable. For example, formula-03 is:

```
(xl-coordinate • yl-coordinate • (abs zl-coordinate) •
 ks-swell-factor))
```

During the evaluation of this formula, the system must evaluate *ks-swell-factor* to obtain the adjusted volume.

The third task is to aggregate element activities into project activities. The system performs this task by evaluating a KS for each narrowscope frame of the element activity tree. The output for some of the *remove-forrm* element activities is the following:

```
--> Analyzing Project Activity for  EA >
     P01-S00-B00-F00-EA-3-110-20-60-1-1
•••••• Evaluating KS > KS-PA-3-110-20
Result > (P01-S00-B00-F00-PA-30-60
           REMOVE-FORMS-FOUNDATION-P01-S00-B00-F00)
   ** Creating new project activity schema >
     P01-S00-B00-F00-PA-30-60

--> Analyzing Project Activity for  EA >
     P01-S00-B00-F00-EA-3-110-20-60-1-2
    EA is coupled below PA > P01-S00-B00-F00-PA-30-60

                      - - - - - - - - - -
```

At this point, the system generates project tasks for other floors, blocks, and sectors of the project. The number of project activities created depend on the initial specification of the modular building.

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 KS are included to recommend a particular type of equipment based on characteristics of the site and the required elements of work. Equipment recommendations made by the system can be reviewed and over-ridden by the user. For example, the PLANEX output for a technology choice might be:

```
****** Evaluating KS > KS-TECHNOLOGY-ROOT
****** Evaluating KS > KS-TECH-50-65

Grouping children > (P01-S00-B00-F00-PA-50-65
                     P01-S00-B00-F01-PA-50-65
                     P01-S00-B00-F02-PA-50-65
                                :
                     P01-S00-B00-F0n-PA-50-65)

under group object > GROUP-TECHNOLOGY-2
with result > CREW-CONCRETE-05
```

In this example, all the *pour-concrete-columns* activities were grouped according to the conditions of KS *ks-technology50-65,* under an auxiliary group object that is used to store the common technology choice.

Task durations are estimated from decision tables and calculating rules in a manner similar to

that used in the *MASON* system (Hendrickson, 1987). In that system, a basic productivity is estimated and then modified in light of specific conditions of a job. In the 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 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. 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. An example output for the precedence identification at the level of project activities is the following:

```
-> Determining successors of PA >
   POUR-CONCRETE-FOUNDATION-P01-S00-B00-F00

 ****** Evaluating KS > KS-SUCC-50-60
 Result>  (REMOVE-FORMS-FOUNDATION-P01-S00-B00-F00
          FORMWORK-COLUMNS-P01-S00-B00-F01)
```

The output of the prototype system during the computation of the appropriate number of crews and adjusted duration of project activities is the following (input from the user is underlined):

```
 --> Determining duration  of PA >
     EXCAVATION-FOUNDATION-P01-S00-B00-F00
 ****** Evaluating KS > KS-DURA-10-60

 No Knowledge has been given for computing the set of
 productivity factors

 The system assigns to activity
 EXCAVATION-FOUNDATION-P01-S00-B00-F00
 a default duration of 10 days.

 Number of crews needed to satisfy this duration are 1.04 crews
 of type CREW-EXCAVATION-05
```

```
••••• Duration Information  for PA
      EXCAVATION-FOUNDATION-P01-S00-B00-F00

   -   Crew                 CREW-EXCAVATION-05
   -   Components of Crew    ((1 BACKHOE-3/4)
                              (1 OPERATOR-BACKHOE-3/4))
   -   Number of Crews       1.04     .
   -   Number of days        10
```

Would you like to change any of these settings ? [n] > i

Type of change > change-crews

 -> Give me the number of crews LO

```
***** Duration Information  for PA
      EXCAVATION-FOUNDATION-P01-S00-B00-F00

   -   Crew                 CREW-EXCAVATION-05
   -   Components of Crew    ((1 BACKHOE-3/4)
                              (1 OPERATOR-BACKHOE-3/4))
   -   Number of Crews       1.0
   -   Number of days        10.42
```

 Would you like to change any.of these settings ? [n] > a

•*•• The duration of PA P01-S00-B00-F00-PA-10-60 is 83.33 hours
••*• or io.42 days

Would you like to use overtime in order to eliminate
day fractions? j

At this point, the system divides the total duration into 10 days of normal hours and 0.42 days of overtime hours.

Application of a critical path scheduling algorithm is a final utility available in the prototype PLANEX system.   Once project 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. Figure 10 shows a typical project activity network obtained with the prototype system.

Conclusion

We have described the architecture and function of a knowledge-based expert system for construction planning. Applications of the prototype to modular buildings demonstrated the feasibility of the system in that activity networks were developed automatically, durations estimated, and a project schedule obtained. A number of features of the system are notable. First, the development of the system led to a more formal description of the construction project planning process. CONSTRUCTION PLANEX is the first knowledge-based system that emulates the complete construction planning process. Second, the architecture of the system is modular, and this makes it flexible and easily applicable for other types of construction projects. The prototype system incorporated numerous *knowledge sources* to perform technology choice, duration estimation, precedence setting and activity identification in the domain of office building projects. Third, during the planning process, the system develops and maintains a *context* with an extended description of a construction plan including hierarchies of design elements and work activities, as well as constraints on items such as resources, technology choices and milestone completion dates. Decisions undertaken during the planning process are also represented in the context in a hierarchical manner. This provides the system with the capability of backtracking previous decisions and providing explanations to the user about outcomes of particular tasks. The hierarchy of project activities provides a detailed work breakdown but also represents appropriate aggregations of activities along with resource availability and technology choice at appropriate levels of aggregation. The design element hierarchy also provides a representation at different levels of abstraction that may be useful for integration with three dimensional computer aided design systems. This plan context provides a much richer description of the construction process and available options than does traditional activity networks.

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 could be substantial.

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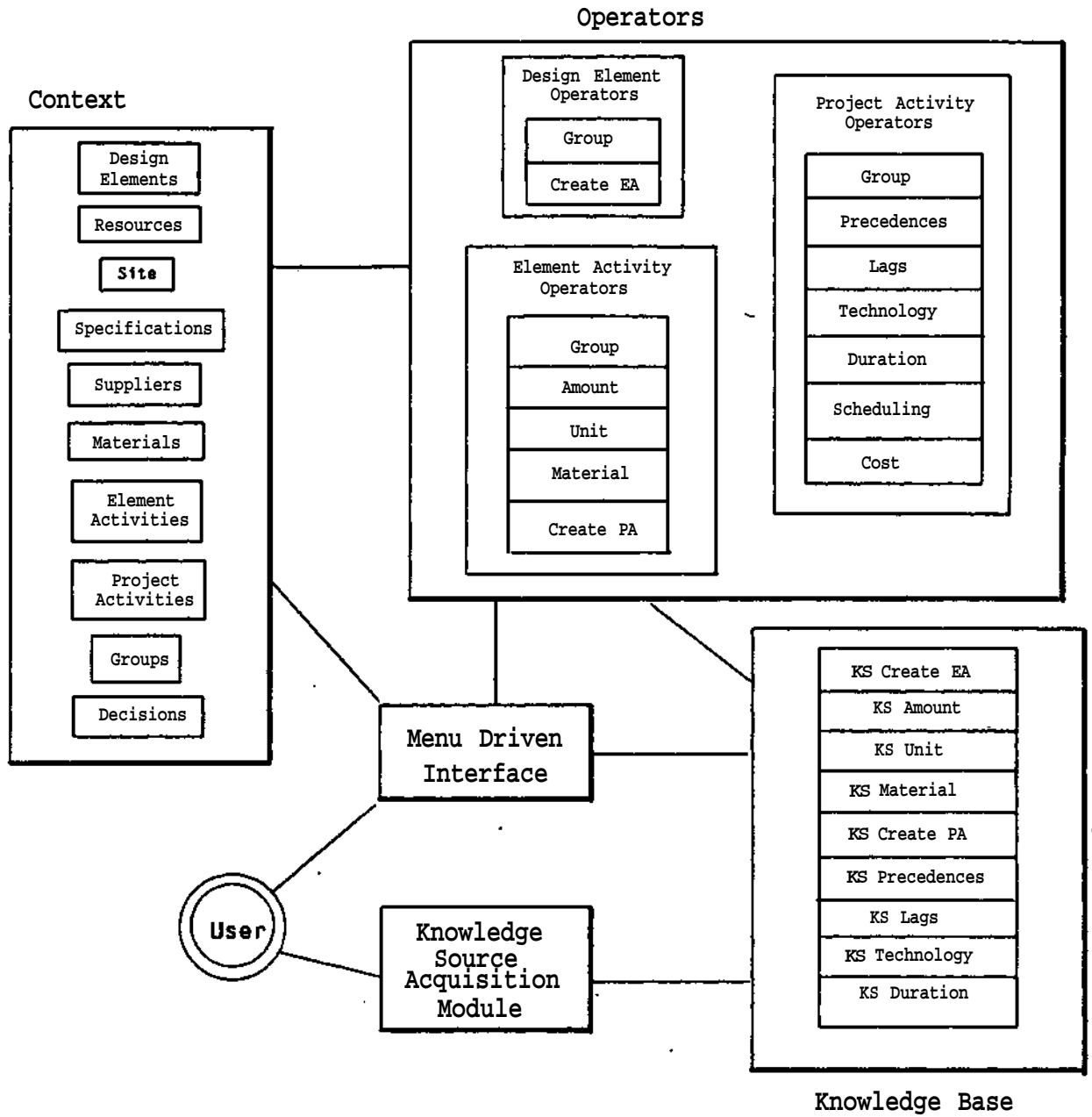Willis E.M. (1986). *Scheduling Construction Projects.* New York: John Wiley and Sons.

Context

Design Elements
Resources
Site
Specifications
Suppliers
Materials
Element Activities
Project Activities
Groups
Decisions

Operators

Design Element Operators

Group
Create EA

Element Activity Operators

Group
Amount
Unit
Material
Create PA

Project Activity Operators

Group
Precedences
Lags
Technology
Duration
Scheduling
Cost

Menu Driven Interface

User

Knowledge Source Acquisition Module

KS Create EA
KS Amount
KS Unit
KS Material
KS Create PA
KS Precedences
KS Lags
KS Technology
KS Duration

Knowledge Base

Figure 1: Overview of CONSTRUCTION PLANEX

DESIGN-ELEMENT pOl-sOO-bOO-fOO-de-60-Ol-Ol	
SLOT	**VALUE**
is-a	de
name	column-footing
name-code	60
type-element	01
number-element	01
project	pOl
sector	sOO
block	bOO
floor	fOO
construction-type	cast-in-place
concrete-type	normalweight-3000
re-steel-density	rsd-1
xg-coordinate	10
yg-coordinate	10
zg-coordinate	-4
xl-coordinate	10
yl-coordinate	8
zl-coordinate	-1.50
x-angle	0
y-angle	0
z-angle	0

Figure 2:   An Example Column Footing Design Element Frame

ELEMENT-ACTIVITY p01-s00-b00-f00-ea-02-220-10-01	
SLOT	**VALUE**
is-a	ea
ea-name	excavation-column-footing-01
ea-code	02-220-10-01
ea-of-DE	p01-s00-b00-fO0-de-60-01-01
parent-EA	p01-s00-b00-f00-ea-02-220-10
ea-of-PA	p01-s00-b00-fO0-pa-10-60
amount-of-work	24.0
unit-of-measure	cu-yd
crew	excavation-foundation-05
material-package	none
duration	16 hours
successors	p01-s00-b00-f00-ea-02-220-10-02

Figure 3: An Example Element Activity Frame

SLOT	VALUE
PROJECT-ACTIVITY p01-sOO-bOO-fOO-pa-10-60	
is-a	pa
pa-name	Excavation-Foundation-pOl-sOO-bOO-fOO
pa-code	10-60
parent-PA	pOl-sOO-bOO-fOO-pa-lO
pa-has-eas	p01-s00-b00-f00-ea-02-220-10
amount-of-work	720.0
unit-of-measure	cu-yd
crew	Excavation-Foundation-05
number-crews	1
material-list	none
duration	480.0
successors	p01-s00-f00-pa-20-60
succ-lags	16 hours
EST	day 15
LST	day 15
EFT	day 75
LFT	day 75

Figure 4:   An Example Project Activity Frame

Figure 5: Context Structure in CONSTRUCTION PLANEX

KS-Technology- Exam pie						
Object	Slot	Op	Value	RULES		
soil-characteristics	soil-type	is	hard	t	f	i
	KS-water-level	is	wet	f	t	i
	power - shovel			x		
	clamshell				x	
	special - machine					x

Figure 6:   Example of a Knowledge Source
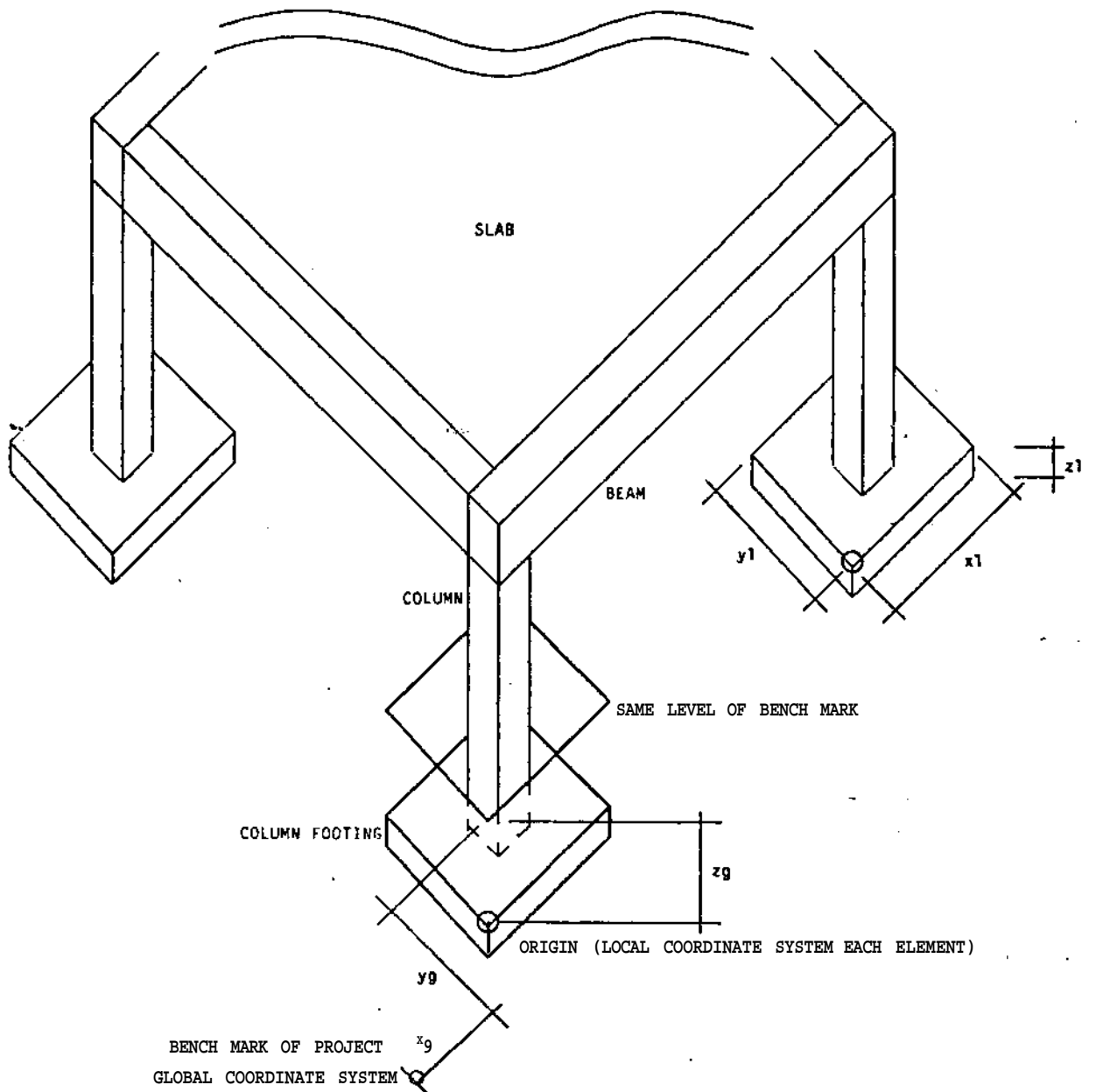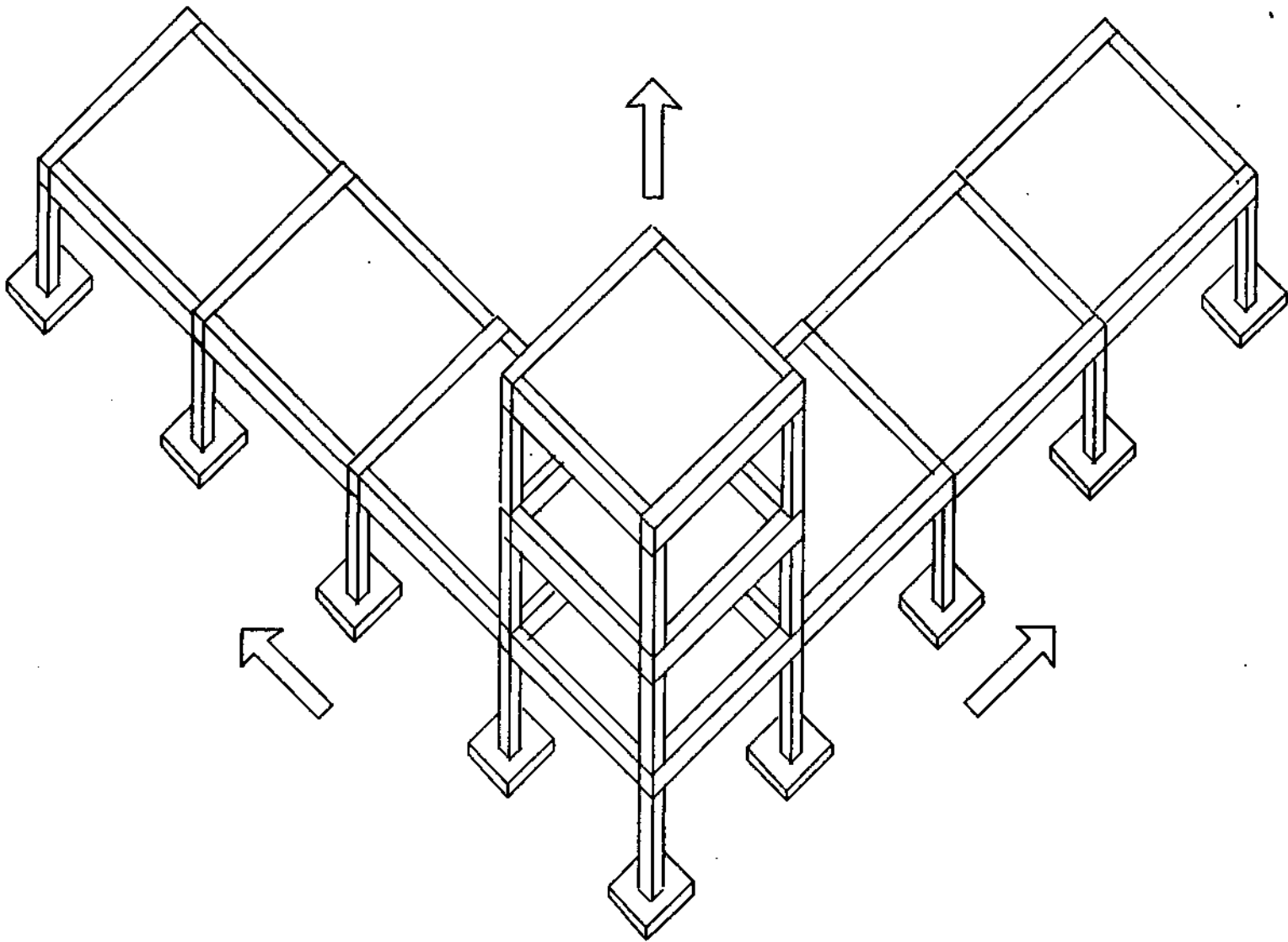
Figure 7: Example of a Basic Building Module

Figure 8: .Example of a Modular Building

```
(defschema ks-create-ea-60-1
;
;  This ks takes the current design element and returns
;  a list of actions of the form
;  (  (EA-schema  the-value-of-slot-"name")
;     (EA-schema  the-value-of-slot-"name"))
;
        (is-a ks)
        (ks-name ks-create-ea-60-1)
        (ks-type all)
        (cond-objects current-object current-object current-object
                    soil-info)
        (conditions (= root-code <root>)
                    (= name-code 60)
                    (= number-element <any>)
                    (= appropriate-for-backfill yes))
        (lhs-rules (t t t i) (t t t t) (t t t f))
        (rhs-rules  ( x x 1 1 x x x x )  ( 1 1 x 1 1 1 1 1 )
                    ( 1 1 1 x 1 1 1 1 ) )
        (actions
                (<root>-ea-2-220-10-60-1
                        excavation-column-footIng)
                (<root>-ea-2-225-10-60-1
                        dispose-off-excavation-column-footing)
                (<root>-ea-2-225-20-60-1
                pile-up-excavation-column-footing)
                (<root>-ea-2-220-40-60-1
                        borrow-material-column-footing)
                (<root>-ea-3-110-10-60-1
                        formwork-column-footing)
                (<root>-ea-3-210-00-60-1
                        reinforcing-steel-column-footing)
                (<root>-ea-3-310-10-60-1
                        pour-concrete-column-footing)
                (<root>-ea-3-110-20-60-1
                        remove-forms-column-footing))
)
```

Figure 9: Example of a Knowledge Source for Element Activity Creation

Figure 10: An Example Project Activity Network

List of Figures