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Factors for Generating Initial Construction Schedules

by
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This report outlines a Knowledge-Based Systems (KBS) approach to acquiring, formalizing, and representing construction scheduling knowledge. This process formalizes key factors that experienced schedulers use to develop initial construction schedules.

This study focused on identifying the factors used to logically sequence construction activities. Four such major factors are: (1) physical relationships among building components (e.g., supported-by, embedded-in, etc.); (2) interaction among crews, equipment, materials, etc.; (3) requirement of an interference-free path for components and their installation; and (4) code regulations that ensure the safety of construction operations and the ability to supervise and inspect installed components.

These factors were used to develop a KBS prototype, CASCH, (Computer-assisted Scheduling) computer program that helps formalize and represent the acquired knowledge. This prototype demonstrates the feasibility of delivering scheduling knowledge in a way that enables user interaction. CASCH uses object-oriented and rule-based knowledge representation tools to state typical sequencing rules that help to generate macro-level schedules for typical mid-rise commercial building construction.

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These factors were used to develop a KBS prototype, CASCH, (Computer-assisted Scheduling) computer program that helps formalize and represent the acquired knowledge. This prototype demonstrates the feasibility of delivering scheduling knowledge in a way that enables user interaction. CASCH uses object-oriented and rule-based knowledge representation tools to state typical sequencing rules that help to generate macro-level schedules for typical mid-rise commercial building construction.

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FACTORS FOR GENERATING
INITIAL CONSTRUCTION SCHEDULES

1   INTRODUCTION

1.1   Objective

The objective of this dissertation is to identify and formalize key factors for generating construction schedules. As such it is an attempt to contribute to the understanding of the knowledge used by experienced schedulers.

Schedule generation is a vital construction planning tool founded on experiential knowledge and on engineering and management procedures. Primary tasks associated with construction scheduling and studied here include: (1) identifying project activities, (2) logically sequencing the identified activities, and (3) determining activity and project durations.

A Knowledge Based Systems (KBS) approach is used as a means to acquire and represent the knowledge. Furthermore, the development of a KBS prototype requires the explicit definition of the formalized knowledge in a very clear way. As a consequence, the prototype implementation enriches the understanding of the scheduling process and the application of the formalized knowledge. The prototype does not address the knowledge of precise detail about components, nor detailed task ordering. It focuses on the typical sequencing rules to aid in the generation of macro-level schedules. These rules should not interfere but rather support the innovation in the planning of building construction.

1.2   Motivation

Successful construction of a facility is largely dependent on adequate planning and control of the construction process. The construction schedule is a cornerstone of the planning and control phases.

Generating schedules requires considerable time and effort of experienced and skilled construction planners. An important motivation of this dissertation is to contribute to an improved support for the construction scheduler. Enhanced tools are needed that increase his productivity. A crucial step in providing improved support is to reach a deeper understanding of the scheduling task.

Another motivating issue is to capture construction scheduling expertise in a form that is accessible to nonexperts. This reduces the loss of scheduling knowledge when an experienced scheduler retires. This accessibility may also benefit construction project participants whose decisions affect the project schedule, but do not have the knowledge to assess their schedule impact. The present effort is a small step toward contributing to this knowledge accessibility.

1.3   Scope of Work

This work is centered on mid-rise building construction scheduling. This focus was chosen for

several reasons: (1) construction planners/managers tend to specialize in particular facility types (power plant construction, building construction, for instance); (2) mid-rise building construction is common in the major urban areas close to Champaign-Urbana and therefore the required source of expertise is available; and (3) a good proportion of the construction projects managed by the Corps of Engineers, major sponsor of this work, consists of building projects [MCA 90].

The scope is further focused on the development of initial schedules for typical mid-rise commercial building construction. Typical mid-rise commercial building construction is defined here as the construction of building features that are common to most residential and office buildings. These are the two most frequent building types in the major urban areas addressed in this work. These common building features include the building systems described in Appendix D. Also, the major knowledge acquisition emphasis is on activity definition and sequencing.

Although the Corps of Engineers has an owner perspective for construction projects, this work concentrates on the contractor's scheduling perspective. This responds to the expertise available for this research effort, which is on the contractor side. In addition, because it is the contractor's responsibility to carry out the construction project, owner schedules are at least in part based on contractor schedules. It is therefore a more natural approach to focus first on the contractor's perspective.

There are different contractor managerial levels with accordingly different schedule level of detail needs [Levitt 87]. This work addresses the project manager's needs which consist of a balance between an overall job perspective and sufficient information to monitor and control construction progress.

1.4   Overview of Research Methodology and Dissertation Approach

The applied research methodology includes as a first step a review of relevant research efforts performed elsewhere. Then, a formalized body of scheduling knowledge is produced, founded on a program of structured interviews with experienced construction schedulers and on a state-of-the-art survey. A KBS prototype is later used as a means to incorporate a subset of the formalized knowledge.

The organization of this thesis follows the major steps accomplished to reach the stated objectives. Initially, in Chapter 2, the functions of a construction schedule are analyzed. This is used as an aid for establishing the strengths and limitations of related research efforts, together with an assessment of their contribution towards a deeper understanding of construction scheduling knowledge.

The knowledge elicitation method is defined in Chapter 3. Chapters 4 and 5 provide a description of the knowledge acquired and formalized. Chapter 6 presents the prototype implementation efforts and shows a demonstration run. Chapter 7 contains concluding remarks and suggests future developments of this work.

2 BACKGROUND

This chapter describes the nature of construction schedules from the perspective of the functions that they provide. This is intended as a reference to better assess the different contributions to the state-of-the-art by this and other research efforts.

This chapter also provides an overview of key research efforts, performed elsewhere, in construction scheduling KBS applications. This overview is relevant to identify their cumulative contribution to the understanding of the scheduling process, and to the advancement of scheduling support. Appendix A summarizes the nature of KBS's and introduces related terminology.

2.1 Construction Schedules: Their Nature and Functions

A construction schedule is a plan of action that specifies what is to be constructed, how, when, and by whom. To better understand its nature it is important to examine in more depth the management functions it supports. The material included in the paragraphs below originates in a number of references: [Antill 82], [Barrie 84], [Birrell 80, 89], [Clough 79], [O'Brien 69], and others. It also reflects a number of discussions with several thesis committee members and industry representatives.

2.1.1 Modeling Function

A construction schedule is a model of the installation approach for all required components and assemblies. It is therefore a tool that describes the construction process. As a consequence it provides an organized plan including activities or tasks required, their sequence, durations and required resources. This modeling function can be especially relevant for evaluating different building system alternatives in terms of their schedule impact ("what if" tool). This evaluation is critically important at early design stages, when decisions have the larger impact. It is also very useful to the project manager for initial work planning, and to replan when changes are being considered.

2.1.2 Communication and Trade Activity Coordination Function

Another crucial requirement of any good schedule is to provide a means of communication among the different project participants. The schedule has to communicate their roles to each of the participants. This is done by specifying what, when, where, and, to some extent, how and why each participant is expected to perform. Due to the nature of the construction process, a schedule is a vital communicating device for the installers (construction manager, contractor, subcontractors). It is also a valuable tool to inform the designers, the owner and even material and equipment suppliers of their expected participation. For instance, designers and owner have to be informed of what approvals are required and when they will be needed (shop drawings, for instance). Similarly, the owner is interested in the progress of the different construction phases that are relevant to the delivery of the finished product. A schedule should assist in providing this information.

2.1.3 Procurement and Financial Management Support Function

The schedule is an invaluable tool for determining when to perform activity resource procurement, especially long lead delivery or scarce resources. Resource procurement almost always requires the

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expenditure of money. In an increasingly competitive environment, it is important to have a careful financial management. Through the schedule, different project participants can anticipate cash flow information to support their financial management.

2.1.4 Progress Control Function

Another objective of any good plan is for it to be used as a control tool of the plan execution. A good schedule will support performance monitoring of the different project participants. The objective here is not only to assess the progress up to date, but also to make reasonable modifications of future activities to incorporate additional information produced by the monitoring of previous work.

2.1.5 Recording Function

This function entails the ability to use the experience gained from one project, to schedule future projects. This function also involves the recording and compilation of construction activity progress to support claims analysis and resolution situations. It is also tied to the progress control function presented above.

2.2 KBS Construction Scheduling Research: Project Survey

The schedule nature and functions introduced in the previous section serve as a basis to understand the contribution of a number of previous research projects. Other issues addressed include: (1) formalization of scheduling knowledge; (2) enhancement of user's schedule production efficiency, and (3) fostering integration of design and construction support tools.

From the description below it should be apparent that up to now the research emphasis in this area has been to study implementation tools. Most of the efforts concentrate on experimentation of the capabilities of KBS techniques and computer related features. The objective of the present work contributes to refocus the attention to the domain of construction scheduling.

2.2.1 The Platform Experiments

The Platform Experiments are work performed by Levitt and his colleagues in the early 1980's, at Stanford University [Levitt 85]. This work did not address the generation of construction schedules. It focused on the development of a proof of concept computer prototype based on a very limited set of top level activities. It addressed the computer assisted updating of design/construction schedules of offshore oil well drilling platforms.

The overall approach consisted of experimenting with KBS techniques for schedule updating: (1) use of an object-oriented representation of activities and other items, (2) implementation of a problem solving control structure via rules; and (3) a contingency handling mechanism supported by an Assumption-Based Truth Maintenance System (ATMS). ATMS's are tools that keep track of the dependencies of facts in a Knowledge Base.

The Platform prototype system was implemented in KEE™. It dealt with a simplified schedule for the design and construction phases of an offshore platform in the North Sea. Activities were represented symbolically and pointed to risk factors that could affect their durations positively ("knights") or

negatively ("villains"). Some schedule uncertainties (site geology, weather) were handled by providing contingent plans. A PERT approach was used to establish activity and project durations. Graphics were extensively used to produce a user-friendly interface.

As mentioned above, this work focused on monitoring and updating a given schedule and therefore did not deal with activity determination and sequencing. However, it opened the door to the application of KBS tools for the support of construction scheduling.

2.2.2 The TIME System

The TIME system was developed by Gray and his colleagues at Reading University, U.K. [Gray 86]. This was a rule-based KBS built in Prolog on a microcomputer. The main objective of the research effort behind this system was to provide the designer with some building construction knowledge. In this way, constructability of the resulting design would be increased.

The conceptual work performed by Gray and his colleagues was an important contribution to the understanding of the manner in which an experienced scheduler produces a construction schedule. Their work was important because they studied an expert's approach for identifying and sequencing the construction activities of a specific building project. On the basis of schedules produced by different contractors for the same building facility, Gray synthesized and formalized knowledge used by construction schedulers to breakdown a construction project into activities. Three main factors were considered for performing this breakdown:

- Type of work: if work differs in terms of (1) material put in place, (2) trade performing the work, or (3) equipment used, then the schedule should break down this work into separate activities.

- Operationally significant function: if the components installed perform a distinctive horizontal or vertical function (columns vs. slabs is an example) separate activities are required.

- Operationally significant location: building construction is divided into work areas dictated by the size and shape of the facility. The activity breakdown should reflect this decomposition into work areas.

Gray identified some of the reasons for sequencing construction activities. All of his identified reasons can be traced to physical relationships among the components that compose a building. Examples of activity sequence include the activity of installing drywall preceded by the enclosure installation, or the activity of painting a masonry wall preceded by the activity of erecting the wall. In these two cases, the enclosure provides a protected environment for the drywall and the paint covers the masonry wall, respectively.

2.2.3 Construction PLANEX

This work was performed by Zozaya-Gorostiza, Hendrickson and others, at Carnegie Mellon University [Zozaya 88]. Construction PLANEX is limited to the scheduling of only the foundation and frame construction of a modular building.

Construction PLANEX is a KBS that consists of a Context (working memory to store the known information describing the current problem), knowledge sources and operators that apply the knowledge sources as necessary. Activity sequencing in PLANEX is specified through the use of codes (which are tied to a Masterformat (CSI) classification of the elements to be installed). For instance, if an activity is related to an element which has a code of "steel column," then it should be followed by an activity related to a "steel beam."

Construction PLANEX requires as input a detailed description of all the building components (design elements) including exact dimensions and positions in a cartesian coordinate system. This detailed project design input requirement is a limiting factor for Construction PLANEX. Efforts are under way to address this shortcoming.

Relevant data and knowledge representation contributions were made by the research work behind Construction PLANEX. An important contribution consists of differentiating building components (design elements) from their installation tasks (element activities). The foundation and frame of a building are described in terms of design elements. For each design element there are corresponding installation element activities. Element activities are aggregated in a bottom-up manner to create higher level activities (project activities). This aggregate is based on the floor location of the design elements.

2.2.4 GHOST

GHOST is a prototype system [Navinchandra 88] that does not address activity generation but, given activities, has a limited ability to produce activity sequences.

The contribution of this work is not the identification of sequencing constraints, but rather the ways to represent them. Constraints are stored in different knowledge modules labeled Critics, that interact using a blackboard architecture. The prototype has Critics that incorporate: (1) basic sequencing knowledge derived from general principles (mainly gravity support). (2) explicit precedence links (rebar installation precedes casting concrete); and (3) procedures to handle redundancy and activity hierarchical decomposition.

GHOST operates by receiving construction activities as input. If no sequencing is provided, it initially assumes a totally parallel network of activities. Then the different Critics propagate their constraints until they are satisfied. This results in an activity sequence that complies with the constraints represented by the Critics.

2.2.5 BUILDER

This work was performed at MIT by Chemeff, Logcher and Sriram [Chemeff 88], who also developed BUILDER. This prototype system is limited to the creation of a two-dimensional drawing of architectural finishes from a few given primitives, such as generic walls, doors, etc. By performing simple geometric analyses, BUILDER is able to describe some of the spatial relationships among designed objects (objects tied or adjacent to other objects). These relationships are used by BUILDER to generate a sequence of detailed-level tasks associated with the installation of the different objects.

BUILDER is limited to dealing with simplified situations (a room with few objects and boundaries, and only planar dimensions). Its main contribution is that it demonstrates that it is possible to reason about objects in order to develop a detailed task sequence to install them.

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2.2.6 Construction Schedule Critic

This work was performed by De La Garza, Ibbs and O'Connor at the University of Illinois and the US Army Construction Engineering Research Laboratory (USACERL) [De La Garza 88]. The objective of this project was to develop an analysis and criticism system for mid-rise building construction schedules. Automated generation of construction schedules was not directly studied in this work, but the findings on good construction scheduling practice are relevant for the present project.

The different provisions identified for good scheduling were classified under four major areas: (1) general requirements, dealing with activity number, separation of the activities, incorporation of milestones, etc., (2) time, dealing with the satisfaction of time requirements, criticality of the activities, etc., (3) cost, focusing on front-end loading avoidance and other cost related issues, and (4) logic, centering on the verification of proper consideration of weather sensitivity, procurement and other factors in the sequencing of the activities.

Most of the efforts in this project were channeled towards the method to acquire and validate expert knowledge and towards the conceptual study of its formalization and representation. A proof of concept prototype system was also developed that dealt with a subset of the formalized knowledge.

2.2.7 The SUPR Model

The SUPR model is an environment for an integrated construction data representation. An object-oriented approach is used here to represent the information. An initial version of this representation model was proposed by Grobler and Boyer in 1988 at the University of Illinois [Grobler 88]. More work has been performed recently, in collaboration with S. Kim, at USACERL [Grobler 89].

Although this does not address activity generation or sequencing, the model is relevant for the present project because of its proposed object-oriented approach for construction data representation, and scheduling data in particular. Grobler proposed a hierarchical representation of construction activities based on the concept of PEC's (Primitive Elements of Construction). PEC's are tasks associated with a single activity and performed by a single crew.

2.2.8 Approach at Stone & Webster Co.

Stone & Webster has invested substantial efforts to integrate the informational needs of different project participants. Their current approach consists of a common database of project information (such as design description, material costs, etc.) that is based on components or objects [Zabilski 88]. Once the design information is provided to the database, it is available to the construction scheduler in terms of a three dimensional graphic model. The construction planner can interactively define work packages (building components to be associated with each activity), activity sequencing and durations.

Although this approach does not involve any automated schedule generation it is relevant because of: (1) the graphic interface that it provides; and (2) the integration of project information databases. The tools described above have been developed to support mainly industrial construction, which is the bulk of Stone & Webster's business.

2.2.9 Approach at Bechtel Co.

Work at Bechtel Corporation also involves an integrated project information database, developed on the concept of building components. Similarly, it incorporates a user-friendly graphic interface that provides three-dimensional renderings of a facility and its components. This integrated project support system is conceived to assist design and construction of power plants and process facilities.

They use a rule-based approach for generating limited activity sequences [Simons 88]. This consists of a set of "common sense" rules that dictate installation phase precedence relationships. These rules perform the equivalent of sorting the objects to be installed (building components) based on their coordinates. For example, a rule instructs the system to install objects in accordance with their relative heights.

2.2.10 SIPEC

SIPEC is work performed at Stanford by Levitt and Kartam [Kartam 90]. The objective of their research effort was to experiment with domain independent nonlinear planners in the area of construction schedule generation. The complexity of the tool (AI planner) limited the scope of this work to addressing the scheduling of very simplified projects. Activity durations were not considered in SIPEC.

Domain independent nonlinear planners are AI planning tools. A brief overview of this area is provided here so the reader can better understand the essence of this work. Additional information about AI Planners is found in [Chapman 85], [Cherneff 88], [Kartam 89], [Wilkins 84], [Zozaya 88].

The general approach of AI Planning is to model the world as a set of possible states. One state is transformed into another state by an action (also called an operator). A plan consists of identifying a present state, a goal state, and a viable chain of actions that transforms the present state into the goal state. It is claimed that this approach is so general that AI Planners are usable in any planning domain.

Kartam and Levitt obtained access to a nonlinear planner named SIPE, written by D. E. Wilkins [Wilkins 84]. Wilkins refined SIPE to correctly represent interactions between activity subnetworks. The modified planner is called SIPEC. Kartam and Levitt's experiments consisted of representing simplified examples of construction projects in SIPEC in terms of activities and some sequencing constraints. Although limited by the assumed simplifications, SIPEC was able to produce activity networks for the represented examples.

The constraints provided to SIPEC to produce construction plans consisted of a general scheduling heuristic (if A is enclosed by B, then install A first) and a physical relationship among components (supported-by). SIPEC did not consider other component relationships, nor trade interaction, as constraints for activity ordering.

2.2.11 OARPLAN

This is work being performed at Stanford by Levitt, Darwiche, and Hayes-Roth [Darwiche 88]. The objective of this ongoing effort is to continue exploring AI planners for the support of construction planning. Levitt and his colleagues have developed a conceptual framework for representing the entities involved in construction planning. This conceptual framework involves a hierarchical decomposition of those entities, and includes: (1) entities to support the description of building components; and (2)

entities to support the description of activities. The activity description entity (labeled tuple) associates the concepts of action, component and resources.

OARPLAN has been developed to deal with components and actions but does not consider resources at the present time. It is able to develop a sequence of activities to install the structural frame and walls of an example building. Activity precedence is based on a limited set of relationships established among the building components (supported-by, enclosed-by, adjacent-to, and others).

It is recognized by OARPLAN's developers that its input requirements are a major shortcoming. Efforts are underway to attempt a direct link between CAD produced designs and OARPLAN, in order to overcome this limitation. At this time OARPLAN does not deal with activity durations.

2.2.12   Other Research Efforts

In the last year a number of research efforts have been published that attempt to support construction scheduling utilizing a KBS approach. In general, these efforts are at an early stage and therefore it is difficult to expect conclusive contributions at this time. A brief description of the most relevant ones follows.

Kahkonen and Laurikka of the Finnish Technical Research Center are developing ATOP [Kahkonen 90]. ATOP is a prototype system based on the concept of work area definition (or location breakdown, as defined by [Kahkonen 90]). The term work area (location) refers to physical spaces the construction project is decomposed into. ATOP is not intended to automatically identify activities. Rather, the user selects activities for each work area from a standard activity library, via graphic interface. Activity sequencing is hardcoded, and is based on what its authors call typical activity dependencies. Activity durations are based on user-supplied work quantities.

PREDICTE is work performed by Digital Equipment Corporation for Civil & Civic, an Australian construction company [Mcdoff 89], [Register 90], [Stretton 90]. It consists of a KBS to evaluate design alternatives for cast-in-place concrete framed multi-story buildings, from a scheduling perspective. The available publications indicate substantial efforts in supporting user-system dialogue. Through dialogue with the user, PREDICTE identifies the major building features. This input information is used to identify activities and durations. Typical activity sequences, known to the system, are used to determine schedule logic. PREDICTE incorporates scheduling knowledge acquired from a Civic & Civil experienced scheduler. This knowledge acquisition process is apparently extensive. However, the published record is insufficient to assess its reach, and efforts conducive to obtain more information have been unsuccessful.

CONSPLANS is a proof-of-concept prototype KBS developed by Kano at Waseda University and at Stanford University [Kano 90]. This is an experiment in hierarchical planning. The conceptual approach is to produce schedules at a high level of abstraction (low detail level) and then refine them into more detailed activities. Completion dates are dictated to lower level activities from upper level ones. From the available documentation it is not clear how activity sequencing is established. The current prototype can only address oversimplified construction projects.

Moselhi and Nicholas from the Center for Building Studies, Concordia University, Canada, developed ESCHEDULER, a proof-of-concept system [Moselhi 90]. The focus of this effort is to interface a variety of schedule-related software modules (KBS's, relational data bases, etc.). Although

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activity generation is not addressed, ESCHEDULER has limited capabilities to: (1) modify user provided activity durations to account for some productivity affecting factors (weather, learning curve, etc.), and (2) provide a default activity sequence based on pre-established typical sequences.

2.2.13 State-of-the-Art Summary

Tables 2.1 and 2.2 provide an overview of the state-of-the-art survey. Table 2.1* shows that the formalization of scheduling knowledge, especially knowledge of experiential nature, is just beginning. The observable trend of the surveyed research projects is to concentrate on the computer tools study. It is definitely necessary to reach tool usage maturity. However, it is also believed that now the research focus should move towards a deeper understanding of the schedule generation process and of the schedule functions. This is a prerequisite for the production of truly effective scheduling support tools.

As can be observed in Table 2.2, most of the surveyed efforts are biased to supporting the modeling and to some extent the communication functions of a schedule. Much more work lies ahead. The modeling function is far from being fully addressed. The efforts to model the complex interaction of people, equipment, materials, etc. during a construction project have been limited and simplistic. Furthermore, the sparsity of Table 2.2 shows how much more work is necessary to develop KBS tools that competently support all the scheduling functions throughout the different project phases.

This dissertation's main thrust of formalizing scheduling knowledge is described in Chapters 3, 4 and 5. Next chapter, Chapter 3, presents an overview of the methodology used to reach the scheduling knowledge sources.

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* All tables and figures are included at the end of their corresponding chapters.

Table 2.1. General Knowledge Characteristics of Surveyed Prototypes.

RESEARCH EFFORT	APPLICATION DOMAIN OF ACQUIRED SCHE-DULING KNOWLEDGE	ACTIVITY DEFINITION AND SEQUENCING ABILITY	DURATION ESTIMATION ABILITY	EXTENT OF KNOWLEDGE ACQUISITION EFFORT
PLATFORM	Major design and construction activities of oil well-drilling platforms.	None. Focused on schedule updating.	None. Updates given durations.	Moderate effort. Addresses schedule update knowledge.
TIME	Mid-rise building construction.	Proof of concept prototype can define major activities. Activity sequencing limited to formalized constraints.	Based on supplied quantities.	Relevant effort. Identification of some activity definition and sequencing knowledge.
Construction PLANEX	Foundation and frame erection activities of modular building construction.	Prototype defines frame erection and foundation activities. Sequence based on Masterformat coding of components.	Based on supplied quantities.	Minor effort. Focuses on foundation and frame erection activities.
GHOST	Knowledge currently available in Critics is only sufficient to prove concept.	Does not define activities. Focused on activity sequencing by constraint propagation. Limited number of constraints formalized.	None.	Minor effort. Focuses on architecture for knowledge representation.
BUILDER	2-Dimensional drawings of architectural finishes.	Determines a sequence of highly detailed tasks for architectural finishes installation, for simple-layout rooms.	None.	Minor effort. Focuses on limited set of architectural finishes.
Construction Schedule Critic	Mid-rise building construction.	None. Focused on schedule evaluation.	None.	Relevant effort. Addresses schedule evaluation knowledge.
SUPR Model	Not a KBS (focus on data representation).	None. Focused on an integrated construction data representation.	None.	None. Addresses data representation issues.

Table 2.1. (continued)

RESEARCH EFFORT	APPLICATION DOMAIN OF ACQUIRED SCHEDULING KNOWLEDGE	ACTIVITY DEFINITION AND SEQUENCING ABILITY	DURATION ESTIMATION ABILITY	EXTENT OF KNOWLEDGE ACQUISITION EFFORT
Stone & Webster	Not a KBS (focus on data representation and graphical modelling).	Not automated. User develops activities by interacting with the system.	Based on quantities automatically calculated from design data.	Minor effort. Focuses on providing geometrical modelling and data integration.
Bechtel	Mechanical, electrical, piping installation.	User defined activities can be sequenced using a *coordinate-based sorting* of their associated components.	Based on quantities automatically calculated from design data.	Moderate effort. Some task sequencing heuristics are represented. However, focuses on providing geometrical modelling and data integration.
SIPEC	Limited knowledge acquisition. Simplified application examples in house and building construction.	Proof of concept prototype *can define major activities*. Activity sequencing limited to 'enclosed-by' and 'supported-by' constraints.	None.	Minor effort. Focuses on exploration of AI Planners.
OARPLAN	Limited knowledge acquisition. Simplified application examples in building construction.	Proof of concept prototype *can define major activities*. Activity sequencing limited to a few constraints.	None.	Minor effort. Focuses on exploration of AI Planners.

Table 2.2. Summary of Surveyed Support to Construction Schedule Functions.

RESEARCH EFFORT	MODELLING	COMMUNICATION AND TRADE COORDINATION	PROCUREMENT	PROGRESS-CONTROL	RECORDING
PLATFORM	S	S		S	S
TIME	S	S			
Construction PLANEX	P				
GHOST	P				
BUILDER	P				
Construction Schedule Critic		S	S	S	
SUPR Model		P		S	S
Stone & Webster	S	P			
Bechtel	P	P			
SIPEC	S				
OARPLAN	S	S			

P= Primary Support
S= Secondary Support

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3   METHODOLOGY FOR KNOWLEDGE ACQUISITION

3.1   Preliminary Comments

The objective of this Chapter is to describe the available sources of expertise and the construction scheduling knowledge acquisition process used in this investigation. This chapter is not intended to provide a detailed description of methods and techniques available. The interested reader is referred to available publications like [De La Garza 90], [Hayes-Roth 83] and [Waterman 86], that present those in detail.

3.2   Sources of Scheduling Knowledge

Two main potential sources of expertise were initially identified: (1) publications, consisting mainly of those reviewed in Chapter 2, and (2) skilled construction industry schedulers. The interaction with industry schedulers was given priority.

With the possible exception of Gray's work [Gray 86], little attention has been given in published work to acquiring scheduling knowledge from industry practitioners. It is also clear that scheduling knowledge tends to be highly heuristic, intuitive and experiential in nature. This was learned from the observation that construction schedulers (and construction planners in general) acquire their skills by accumulating experience from one construction project to the next.

A consequence of this experiential nature of scheduling knowledge is that it tends to be company-specific. The approach here, however, is to try to identify the common fundamental principles applied by experienced construction planners to generate schedules.

Five construction firms of the Chicago, Indianapolis and St. Louis areas were contacted for the purpose of interviewing their schedulers and learning better how they plan projects. It is noteworthy that all these firms responded positively. A total of seven construction schedulers from these construction firms provided their time and skills for this research work, one scheduler from each of four firms, and three from the other.

A prerequisite to this research project's main objective is to acquire knowledge from experienced schedulers. The participating schedulers had at least 10 years' experience at the time of the interviews, mainly in building construction.

3.3   Interaction With Skilled Construction Schedulers

3.3.1   Overview

In ideal circumstances (scheduler's time availability unlimited, total firm's managerial support, etc.) the technique used for eliciting scheduling knowledge would have been direct observation of real project schedule generation cases, followed by extensive question/answer periods. In reality, however, the availability of the schedulers was limited.

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Given this limitation, two approaches were used to interact with the participating schedulers. The first approach, performed with only two of the schedulers, called for them to guide the interviewer in the construction schedule production of a mid-rise building (10-story apartment building) for which complete design information was available. The second approach, accomplished with all of them, consisted of discussions based on schedules they produced in the past.

In total, 24 meetings were held in a period of 18 months, between June 1988 and November 1989. With an average meeting duration of 2 hours, approximately 50 hours of direct interviewer-scheduler interaction time was accumulated. The following two sections describe the two different approaches for knowledge elicitation in more detail.

3.3.2 Skilled Practitioner-Guided Schedule Generation

The first interviewing approach was performed with only two of the schedulers. The original objective of utilizing this same approach with all of the collaborating schedulers was not attainable because of their time constraints. Six sessions were required with each of them to develop a schedule (refer to Table 3.1).

The intention here was to come as close as possible to direct observation of the schedulers in action, while minimizing their time expenditure. The devised interviewing strategy satisfactorily accomplished this goal. It allowed the two participating schedulers to provide the necessary guidelines and directions to produce a schedule, with relatively minor time consumption on their part. The strategy consisted of extending the interviewer's role from a passive observer role to that of an apprentice. The interviewer's responsibility was to request and follow the guidance of the skilled scheduler. The apprentice's task was to develop a construction schedule for a building for which complete design and site information was available. Emphasis was placed on activity definition and scheduling logic (activity sequencing) determination.

This approach for eliciting knowledge from the skilled construction schedulers was very effective. The material in Chapters 4 and 5 shows the observed schedule generation process basic stages. It was possible to identify the overall approach for reviewing project information, breaking down the construction process into activities, sequencing them, and determining preliminary durations.

This approach's effectiveness can be attributed to several factors. The willingness of the two schedulers to cooperate and their articulateness were extremely important factors, as is the case for any interview-based knowledge elicitation approach. For this particular knowledge acquisition strategy (apprentice guided by skilled practitioner), two other factors were crucial as well: (1) the apprentice's (interviewer) background in the domain allowed him to communicate and execute the assigned tasks; and (2) an adequate and balanced time interval was scheduled between sessions. Enough time between sessions was required by the apprentice to accomplish the tasks assigned in each session. This implied a spacing of at least 1 week between sessions. However, this had to be balanced with the need for keeping continuity in the scheduler's attention. Too long of an intersession interval would negatively affect this continuity. For this reason it was decided to keep the intersession interval to a maximum length of 3 weeks, which at the time seemed an adequate upper limit. After a few sessions it was concluded that this was a reasonable choice.

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3.3.3 Discussions Based on Existing Schedules

This approach consisted basically of unstructured interviews focused on analysis of existing schedules. This was used for interacting with all seven contributing practitioners. For those two schedulers participating as described in the previous section only one additional session .was convened for discussing existing schedules. For the other schedulers, an average of three 2-hour sessions was held. In contrast with the first elicitation method based on the observation of the schedule generation process, the objective here was to promote discussion of schedules produced by practitioners in the past.

The discussions focused on understanding the activity breakdown and on identifying the reasons behind the activity sequencing. Also, some information was acquired on determination of activity duration and on procurement issues.

The interviews were performed individually (only one scheduler present at a time), except for the case of the company that collaborated with three of their people. In this particular situation they were interviewed as a group. No conflicting knowledge was recorded when interacting with this group. This is explained by the ability of these people to reach consensus, probably due to: (1) different scheduling expertise (one specialized in constructing building shells, another in floor finishes and the third in multi-project management), and (2) they have successfully worked together in planning and executing numerous construction projects.

3.3.4 Consistency of Acquired Knowledge

The acquired knowledge from the different interviewed schedulers is in most part coherent and consistent. During the knowledge acquisition phase this was an additional guarantee of the soundness and applicability of the elicited information.

However, early in the elicitation process it was identified that the constraints for activity sequencing are not rigid. For example, one of the schedulers would schedule electrical conduit installation below an elevated slab before installing any other below slab ducts and/or pipes. This differed with the approaches of others who would schedule this conduit installation after all other pipes/ducts would be in place. This concept of sequencing constraint flexibility is discussed in more detail in Chapter 5.

No project can be scheduled using sequencing constraints or rules that would satisfy every scheduler. Each scheduler tends to have a preferred way of sequencing activities. Also, each project may have some unique features that lend themselves to an unusual sequence of activities.

3.4 Overview of Knowledge Formalization Phase

The goal of the knowledge acquisition effort was to capture construction scheduling knowledge, ···here heuristics and experience play such a relevant role. This effort was later complemented with development of a computerizable representation of the information obtained using a KBS platform. Following an approach similar to [De La Garza 88], this was accomplished in two steps: (1) transforming an amorphous body of knowledge into a set of concepts, rules and facts expressed in English language (also called Formalized Knowledge), and (2) representing a subset of this Formalized Knowledge in a syntax understandable by the KBS platform.

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The concepts, rules and facts that constitute the Formalized Knowledge were identified by following a careful process of recording and analyzing the contents of the interviews. The goal of the analysis was to produce coherent English statements representing the acquired Knowledge (rules, concepts, facts). The results of this formalization process are presented in detail in Chapters 4 and 5.

Table 3.1. Structure for Skilled Practitioner Guided
Schedule Generation Sessions.

SESSION NUMBER	SESSION CONTENTS
1	Introduction of interview's objectives. Description of interview approach. Definition of scheduler's role (guidance provider). Definition of interviewer's role (apprentice). Overview of example project information. Tasks assigned by scheduler to interviewer to start developing the schedule.
2, 3, 4, 5, 6	Analysis of miscellaneous project information, as deemed necessary by the scheduler. Identification of tasks to be accomplished by the interviewer for next session. Scheduler's review and feedback of previously assigned tasks accomplished by the interviewer. Final evaluation of the resulting schedule by the scheduler. If scheduler is satisfied with schedule, the exercise is terminated. Discussion to assess accomplishments of interview's objectives.

4 FORMALIZED KNOWLEDGE FOR MID-RISE CONSTRUCTION SCHEDULING

4.1 Overview

This chapter describes the results of formalizing the elicited construction schedule generation knowledge. This knowledge was acquired via interaction with the previously described sources.

Every effort was made to make the knowledge acquisition process as comprehensive as possible within the time and resource constraints. However, the body of knowledge described here is by no means comprehensive. The time spent in the knowledge acquisition phase was around 18 months. In comparison, a junior engineer takes years of intensive exposure to project construction, to become a successful and skilled scheduler. Given this time constraint, the strategy followed was to narrow the scope of this work so that the formalized knowledge coherently and meaningfully addressed a concise area of construction scheduling.

The focus of the current work is:

- Mid-rise residential/office construction schedules. Mid-rise construction is defined here by two limiting boundaries: (1) buildings tall enough to require elevator (typically around five to six stories, depending on local regulations), and (2) not tall enough to require an intermediate mechanical floor (this boundary is fuzzy, and may range between around 10 to 20 stories). This is a sector that is strongly represented in the Chicago, St. Louis and Indianapolis areas. Many construction firms perform mid-rise construction within those locations, making for a rich pool of knowledge sources for this work. In addition, mid-rise residential/office construction involves a number of trades that require coordination and therefore offers good potential for cost and time savings through planning.

- Typical construction. In agreement with J.J. O'Brien [O'Brien 85, p.105], it is believed that although each building construction project is unique, there is a core of common features: All projects were considered unique in early network scheduling, and it was virtually heresy to suggest that the planning factors to be incorporated in networks were repetitive. However, observant CPM schedulers noted that there were many familiar steps inherent in scheduling similar projects.

  The approach here is to formalize the scheduling knowledge that addresses typical mid-rise construction. It is relevant to acknowledge that defining typical mid-rise construction in a general way is very difficult. A somewhat arbitrary, but hopefully acceptable, definition is: Typical mid-rise construction has (1) structural steel or cast-in-place concrete frame, (2) no underpinning nor complex earth-retaining structures required, (3) no more than two underground stories, (4) a first floor consisting of a lobby, (5) typical floors with equal areas ranging between 5000 and 25,000 sq ft, and (6) a single building. No special features like elevated pools, complex atriums, etc. are considered. In addition, typical construction implies common construction practice.

- Project Manager scheduling perspective. There are different levels of detail associated with construction schedules, depending on the managerial level addressed and point in time they are prepared [Levitt 87]. The present work targets the level required by a contractor's project

manager before construction starts. This level allows for an overall view of the construction project. It also requires a sufficiently detailed plan to model the different construction operations to support the project manager's needs.

- **Focus on direct construction operations.** As described in Chapter 2, a schedule supports a variety of functions (modeling of construction process, communication, procurement, etc.). The present work focuses on modeling construction operations and, to a lesser degree, on schedule information communication. Issues dealing with resource procurement, submittals and approvals, etc. are not of primary emphasis during the knowledge acquisition phase. This was decided because: (1) time limitations, especially on the contributing schedulers' part, and (2) modeling the construction process is identified to be the guiding framework for the generation of an initial schedule. When identifying activities and their sequence, the scheduler follows an exercise of mentally visualizing and "constructing" the project.

- **Focus on identifying activity sequencing rationale.** Although the overall approach of estimating activity durations was studied, most of the interaction with skilled practitioners is dedicated to understanding the reasons used to determine activity precedence relationships (scheduling logic). Time constraints made it impractical to comprehend all facets of the schedule generation process. Chapter 5 is dedicated to presenting the identified knowledge for schedule logic determination.

4.2 Major Schedule Generation Issues Identified Through Knowledge Acquisition

The schedule generation process consists of two major phases (refer to Figure 4.1): (1) a phase for identifying the available project information, and (2) the schedule production phase. The first consists of understanding the information necessary to start producing a construction schedule, and is described in Section 4.2.1. The latter includes the tasks associated with producing and adjusting the schedule and is the focus of Sections 4.2.2 and 4.2.3.

4.2.1 Understanding Project Information

Most of the scheduler's effort in this phase is used to identify the project scope. The main relevant project characteristics here are:

- Facility use: is the building an apartment complex, a laboratory, etc.?

- Project location: the geographical area provides construction constraints such as expected weather conditions, building code requirements, market conditions, labor conditions, and other geographically-dependent issues. The specific location is useful to assess local soil conditions, degree of site congestion, ease of access, and other site-specific characteristics.

- Facility size: preliminary notion of the vertical and horizontal dimensions (number of floors, footprint size, depth of excavation, size of typical floor, etc.).

- Principal building systems (foundation, structural frame, enclosure, mechanical and electrical systems, etc.) and major systems alternatives, e.g., pile vs. mat foundation (Appendix D).

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The scheduler's emphasis at the information assimilation phase is also to identify the project features that are unusual or unique, given his/her previous experience. This is a definite effort by the scheduler to classify project features into typical and nontypical. Most of the effort is to understand those features that are unique to or new about this project. There are two major reasons for the scheduler to identify these unusual features: (1) potential delays due to procurement problems (unusual features may be associated with scarce, custom-made items), and (2) potential installation difficulties due to lack of skilled labor, experienced supervisory personnel or specialized equipment.

4.2.2 Schedule Production

The second major schedule generation phase is its actual production. There is iteration and overlap between the understanding of project information and the schedule production phases. Not all of the necessary information is acquired by the scheduler prior to the start of developing the schedule. The main reason to separate them here is to allow for a clearer description in this report. A number of important characteristics of this second phase emerged in this research, and are presented below.

4.2.2.1 Top-Down Approach. The development of a construction schedule generally follows a top-down approach. This process determines general attributes for the overall construction project and then decomposes them into more detailed levels. This is especially necessary when producing a project activity breakdown, and when determining activity durations that concur with the overall project construction pace and completion date requirements.

4.2.2.2 Project Breakdown into Activities. Schedule production involves dividing the project construction goal into a meaningful set of subgoals. This approach is known as hierarchical planning [Cohen 82], and is common throughout construction.

Factors considered by the scheduler to produce this breakdown include delegation of responsibilities (subcontracts, work crews), and identification of work areas. The term work area refers to physical areas or spaces associated with units of work (activities). In building construction, work areas typically coincide with floors or levels. This association exists because reduced activity setup or mobilization effort is required within a floor. For example, there is substantial mobilization and setup time for concrete slab casting and finishing to progress from one floor to another.

However, for some types of work, work areas may also be associated with exterior vertical surfaces. This is the case of exterior walls installation, which is mostly vertical in nature. Exterior walls installation may be broken down into activities considering floors and exterior vertical surfaces as well.

The breakdown of a construction project into activities is performed by combining the responsibility and the work area breakdowns. Figure 4.2 represents a breakdown of project construction into top level subprojects. The breakdown included in Figure 4.2 is an example of a responsibility-based, one-level (or major activity) breakdown. Similarly, Figure 4.3 shows an example breakdown into work areas for: (a) frame erection and (b) exterior wall closure installation. Figure 4.3 depicts a work area breakdown of two of the major activities included in Figure 4.2. In this case, frame erection is topologically subdivided into floors, and exterior wall closure installation into exterior vertical surfaces and floors.

The responsibility and work area breakdown factors were identified in this research as those most commonly used for mid-rise construction projects. However, other factors beyond the scope of this work may also play a role. One that was occasionally observed consists of identifying deliverable user spaces within the schedule. This is especially relevant when the user needs some finished spaces before the rest of the facility is completed. The terms "phased delivery" or "beneficial occupancy" are sometimes used to refer to this approach of delivering different finished spaces at different times. Other possible breakdown factors may reflect: (1) estimating and cost accounting divisions and line items, (2) major equipment requirements, and (3) any other project-specific needs to subdivide the work into component parts [Clough 79]. These other factors were not examined because they were not considered major during the knowledge acquisition process. There are however other research efforts dedicated to improving the understanding of project breakdown factors [Kim 90].

It was also observed that experienced schedulers produce a sequenced activity breakdown. In other words, activities are not defined in random order, but in an order that follows major sequencing constraints. This indicates a relationship between activity breakdown and activity sequencing. Activity sequencing is addressed in more detail in Chapter 5 of this thesis.

4.2.2.3   Pace-controlling Activities.   An important objective of the scheduler is to provide an overall project construction progression pace convenient for all the participants. There are a few major activities that normally dictate the overall pace of project construction. This group of pace-controlling activities is referred to here as the Schedule Backbone. Progression of these activities dictates the pace of many others. This concept of pace-controlling activities is in agreement with earlier discussions of the progress of repetitive activities [Birrell 80] and [O'Brien 75, 85]. The last reference describes the Vertical Production Method Scheduling approach.

An important pace-controlling activity in building construction is frame erection. This can be explained by the fact that this activity creates spaces (floor levels) where most of the construction work is performed. In addition, it is difficult to accelerate the pace of progression of this activity. If it is a steel or a precast concrete frame, progress is generally dictated by the crane's lifting rate. In the case of a cast in place concrete frame, the progression pace is normally dictated by the form installation and removal rate, which in turn depends on the type of form used and on the concrete setting time. Rough-in, exterior wall closure installation and interior finish activities are typically paced by the frame erection, regardless of the frame type used.

Site-preparation and foundation installation may also be part of the schedule backbone. If those site preparation and foundation activities which are a prerequisite of frame erection take longer to complete than the procurement of frame erection materials, the start of the frame erection activity is impacted.

Once the structural frame is complete it is important to install the roof to have a precipitation-proof barrier. This allows the elevator equipment installation to start (traction equipment and platform installation). Elevator installation usually takes as long as interior finishing to be complete. Roof and elevator installation belong to the schedule backbone.

The completion of roof and exterior wall closure installation is required for interior finishing because of the latter's need for an enclosed, dry environment. Unless the exterior walls are composed of small pieces or contain hard to install indentations, the exterior wall closure installation normally follows the progression pace dictated by the frame erection. If the exterior walls consist of large panels (precast

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panels, curtain wall panels, for example), the speed of installation is normally controlled by the speed of the frame erection activity. When the exterior walls are made of materials with labor intensive installation (masonry units, bricks, for example), the speed of installation is slower than that of the frame erection.

4.2.2.4   Estimating Preliminary Activity Durations.   As mentioned, this research work was not targeted to acquire activity duration estimation knowledge and, therefore, the results here described can only be considered as a starting point.

Durations are estimated in two steps. The first step consists of an estimation of a preliminary duration based on: (1) the concept of pace-controlling activities, explained above, (2) an approximate estimate of work quantities, and (3) experience to establish a reasonable activity progression pace, based on planned construction methods and common practice. This represents an unconstrained situation. The second step confirms the preliminary durations via a more detailed quantity estimate and a crew design process. The scheduler allocates resources to execute the work within the preliminary duration, at reasonable resource levels. This is described in more detail in section 4.2.3.

Representative preliminary duration values suggested by the experienced schedulers are presented in Table 4.1. Relevant issues associated with this information are:

- Estimating preliminary activity durations requires consideration of overall project dimensions. Especially relevant is the typical floor area. For most of the projects analyzed with the schedulers, the range for this dimension is between 5000 and 25,000 sq ft per floor. The preliminary duration estimation rules of thumb mentioned here and in Table 4.1 are typical for cases that fall within this range.

- Duration estimates for Site Preparation and Foundation Installation are very uncertain until site conditions are clearly identified, e.g., soil type, water table level, vegetation, demolition requirements, site accessibility. If the project's structural frame is steel, it is advisable to spend as much time for site preparation and foundation installation as the steel takes to be delivered on site. Procurement times of about 12 weeks are common. Thus for steel frames Site Preparation and Foundation are usually not paced activities; steel procurement is.

- If the frame consists of structural steel members with composite metal-concrete decks, steel erection can normally proceed at a rate of one floor per week (refer to Figure 4.4). This is equivalent to saying that the pace is one tier every 2 weeks, because a typical tier length is two stories. For steel erection, the term tier refers to each of the column runs or segments, which normally come with a length of two floors. The term tier is extended to also include the nonvertical members that connect to the column tier. Metal deck installation and concrete deck installation progress behind steel member erection following the same pace.

- In the case of a cast in place concrete frame, a normal pace for frame erection is one floor built every 1 to 2 weeks. This can be reduced through the use of techniques that permit the acceleration of the frame erection pace, like special forming techniques and the use of early strength concrete.

- The frame erection pace normally dictates the rate of the rough-in work, e.g., electrical and mechanical risers and mains.

- Once the structural frame is in place, the goal of the scheduler is to plan the installation of the roof as soon as possible so that elevator platform and equipment installation, which require an impervious roof, can be started. This is because elevators take a relatively long time to complete and their installation is often critical. Also, elevators are normally used to transport laborers and materials to elevated floors.

- The exterior wall closure installation follows the progression pace dictated by the frame erection, unless it is composed of hard to install pieces.

- For duration analysis purposes, floor finishing (interior partitions, floor surfacing, ceiling finishes, etc.) was considered here as a single activity per floor. This level of detail was selected because the activities required to finish a floor are often viewed by schedulers as a complete subproject for which an initial duration estimate is produced as a whole. For the floor areas considered here (5000 to 25,000 sq ft), floor finishing duration ranges between 6 and 8 weeks. Floor finishing normally starts after the floor exterior wall closure is in place.

- Site work, which consists of site preparation and site finishes, normally takes as long as the rest of the project construction. Site preparation is normally one of the first activities in a project. Site finishes normally start after the building is enclosed, because until this occurs the building perimeter area is often occupied by frame erection and exterior wall closure installation equipment and materials.

4.2.2.5   Scheduling Logic. It was observed during the knowledge acquisition experiments that the activity definition process (as described above) is performed so that it follows the expected construction sequence. In other words, the scheduler defines activities and their preliminary sequence simultaneously, as opposed to producing a nonconnected list of activities and then producing precedence relationships. The word preliminary is used to qualify the initial activity sequence produced because this sequence is later adjusted until all the precedence-causing constraints are satisfied. Detailed description of the knowledge used for determining activity precedence relationships (scheduling logic) is provided in Chapter 5.

4.2.2.6   Procurement. An important issue identified from the interaction with the schedulers is the relevance of procurement time. Although the focus of this research is not centered on schedule procurement issues, a brief description of the information obtained from the schedulers on this topic is appropriate.

Procurement time is the time associated with fabrication and delivery of items to be installed during construction. No matter how carefully and precisely construction operations are planned, substantial delays can be expected if there is insufficient or inaccurate consideration of procurement. Items like structural steel, elevators, glazed curtain walls, etc. require careful procurement planning. Table 4.2 lists some typical time requirements observed in this study. As mentioned, atypical items are especially critical from a procurement perspective.

The fact that procurement constraints are not fully addressed is not a limiting factor of this research work. All procurement constraints consist of a time lag between the procured item's time of order, and its availability on site. If this procurement time lag is known, the representation of this information can be accommodated within the model developed here.

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<u>4.2.2.7 Continuity of Work for Repetitive Activities</u>. Mid-rise construction involves the repetition of similar activities through several typical floors. The scheduler strives to take advantage of this characteristic by trying to maintain work continuity for those crews that tackle repetitive tasks. The objective is to maximize crew efficiency by making use of the learning curve effect. The observations here introduced are consistent with earlier findings by [Birrell 80].

4.2.3 Schedule Adjustments

Production of a construction schedule is an iterative process in the sense that the scheduler starts by considering only a few of the constraints and then iteratively adjusts the schedule to satisfy the rest. The following paragraphs describe a number of schedule adjustments.

<u>4.2.3.1 Verification of Preliminary Durations</u>. After durations have been preliminarily determined from approximate quantities and the scheduler's experience, there is a process of validating these durations. The process consists of: (1) determining more precise quantities of work, and (2) allocating resources (manpower and equipment) so that resources are roughly levelled and preliminary durations are closely matched.

This involves determining crew composition and equipment needs, which is beyond the scope of the present work. Research to tackle this issue is described in [Hassanein 88, 89].

Subcontractor participation is another relevant step of the activity duration verification phase. Typically, a considerable proportion of building construction work is performed by subcontractors. Therefore, any good schedule should reflect subcontractor feedback.

<u>4.2.3.2 Imposed Time Constraints</u>. The schedule has to reflect compliance to owner occupancy requirements. Commonly a building is delivered in its entirety. In this case the only needed verification is that the scheduled construction completion date is not later than the required delivery date. In certain cases however, there is a need to produce a phased delivery. This is because different finished floors are required by the owner at different times. The schedule has to reflect this facility phased delivery process.

Other observed types of imposed constraints deal with procurement issues, already mentioned in Section 4.2.2, and with submittal/approval of required designs, shop drawings or specifications. In every case there is an imposed time constraint (milestone) that has to be satisfied by the schedule.

<u>4.2.3.3 Weather Constraints</u>. It is possible to perform any type of work under almost any weather circumstances, if enough protection and resources are available. However, it is expensive and time-demanding to install temporary weather protection for unprotected weather-sensitive activities. Experienced schedulers consider constraints that reflect expected weather conditions.

The weather considerations observed from the participating schedulers are restricted to the Midwest region, the location of most of the scheduling cases analyzed. However, regardless of geographical location, a construction schedule should be checked against local expected weather conditions.

The observed weather considerations include:

- It is preferred not to start Site Preparation and Foundation work before early spring (approximately mid March). This responds to: (1) difficulty of performing earthwork operations in frozen ground, and (2) potential problems of performing foundation concreting in cold weather [ACI 88].

- It is preferred to complete building enclosure (roof, exterior wall closure) by late fall (approximately the end of November) if interior finishing is scheduled during winter time. This allows the progress of interior finishes under an enclosed environment. Heating is then facilitated and moisture protection enhanced.

- It is similarly preferred to complete building enclosure no later than early summer (approximately the beginning of June) if heat/humidity sensitive finishes are to be installed during the summer, like ceiling tile installation.

4.3 Summary

This chapter described the formalized body of knowledge for schedule generation. It focused on the process of understanding project information and on the definition of project activities. It is complemented by Chapter 5, which addresses the knowledge used to logically sequence construction activities.

Table 4.1. Example Values for Activity Preliminary Duration Estimation.

MAJOR ACTIVITIES	PRELIMINARY DURATION ESTIMATION CONSIDERATIONS (1)
Site Preparation and Foundation Installation	Very uncertain duration until site conditions clearly identified. It may vary between 4 weeks (no basement, good soil & weather conditions) up to a year or more (large & complex excavation). Ideally, duration equal to structural steel procurement time (2)
Frame Erection (3) * Steel Frame Erection Or * Cast in Place Concrete Frame Erection	Normally 1 floor/week (see Figure 4.4). Normally 0.5 to 1 floor/week.
Roof Installation (3)	Normally 1 to 2 weeks.
Elevator Installation	Normally 12 to 24 weeks. Depends on elevator type, number of stops.
Exterior Wall Enclosure Installation.	Normally follows the frame erection pace.
Roughing-in	Normally follows the frame erection pace.
Typical-floor Finishes (3)	Normally 6 to 8 weeks. (4)
Site Work	Normally takes as long as the rest of the work.

(1) Based on information provided by schedulers of collaborating firms in 1988-89.
(2) If structural steel frame used.
(3) For a typical-floor area in the range of 5,000 to 25,000 square feet.
(4) Office space with reduced number of partitions.

Table 4.2. Examples of Procurement Critical Items.

ITEM	EXPECTED PROCUREMENT TIME (1)
Structural Steel	12 to 15 weeks.
Elevators	Up to one year. Usually 12 to 24 weeks.
Various Mechanical and Electrical Equipment	Highly variable. Up to one year in certain cases.
Cladding (precast panels, stone, glass walls)	More than one year in certain cases (custom manufactured glass walls). At least 10 to 12 weeks for precast panels.
Miscellaneous non-typical items (unique decorative items, special equipment, special materials, etc.)	Varies depending on availability. Especially critical if custom order.

(1)Based on information provided by schedulers of collaborating firms in 1988-89.
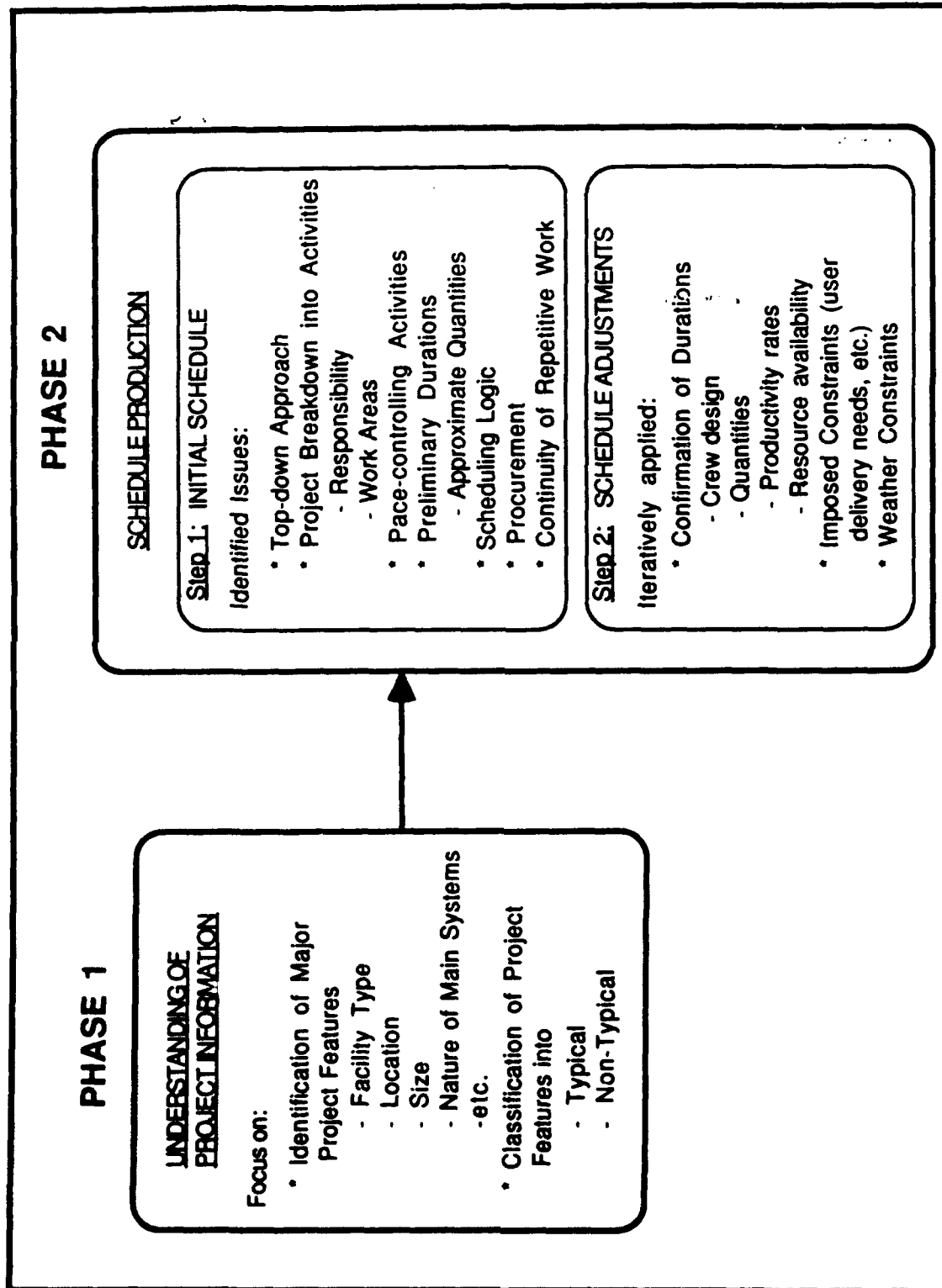
Figure 4.1. Overview of Identified Schedule Generation Process Phases.
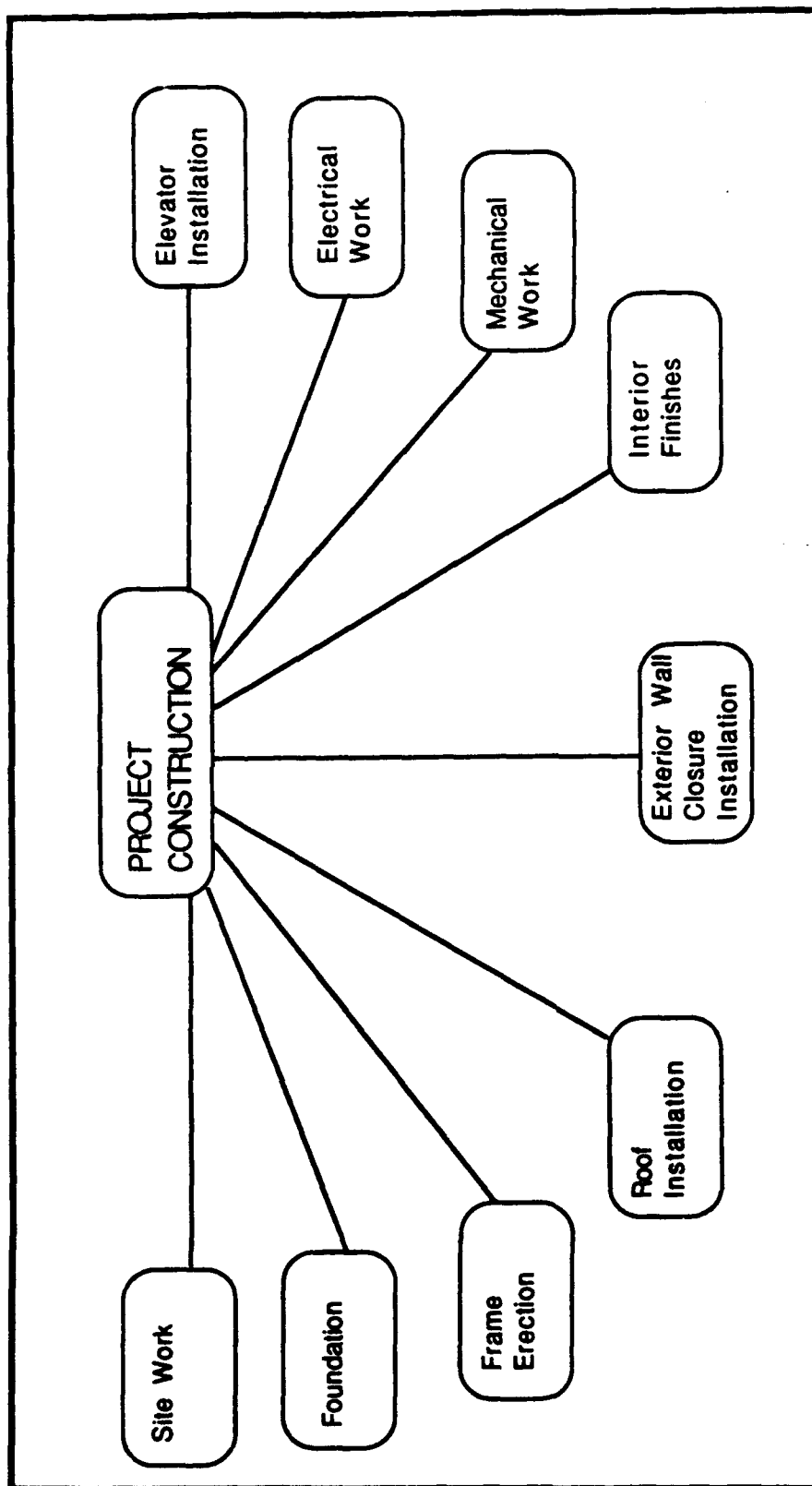
Figure 4.2. Example of Project Construction Breakdown by Responsibility (Sub-projects).

FRAME ERECTION WORK-AREAS

... Floor i-1 | Floor i | Floor i+1 | Floor i+2 ...

a) Cast in place Concrete Frame

EXTERIOR WALL CLOSURE INSTALLATION WORK-AREAS

North Elevation | South Elevation | East Elevation | West Elevation

...   .

South Elev. Floor i-1 | South Elev. Floor i | South Elev. Floor i+1 | South Elev. Floor i+2

b) Curtain Wall Installation
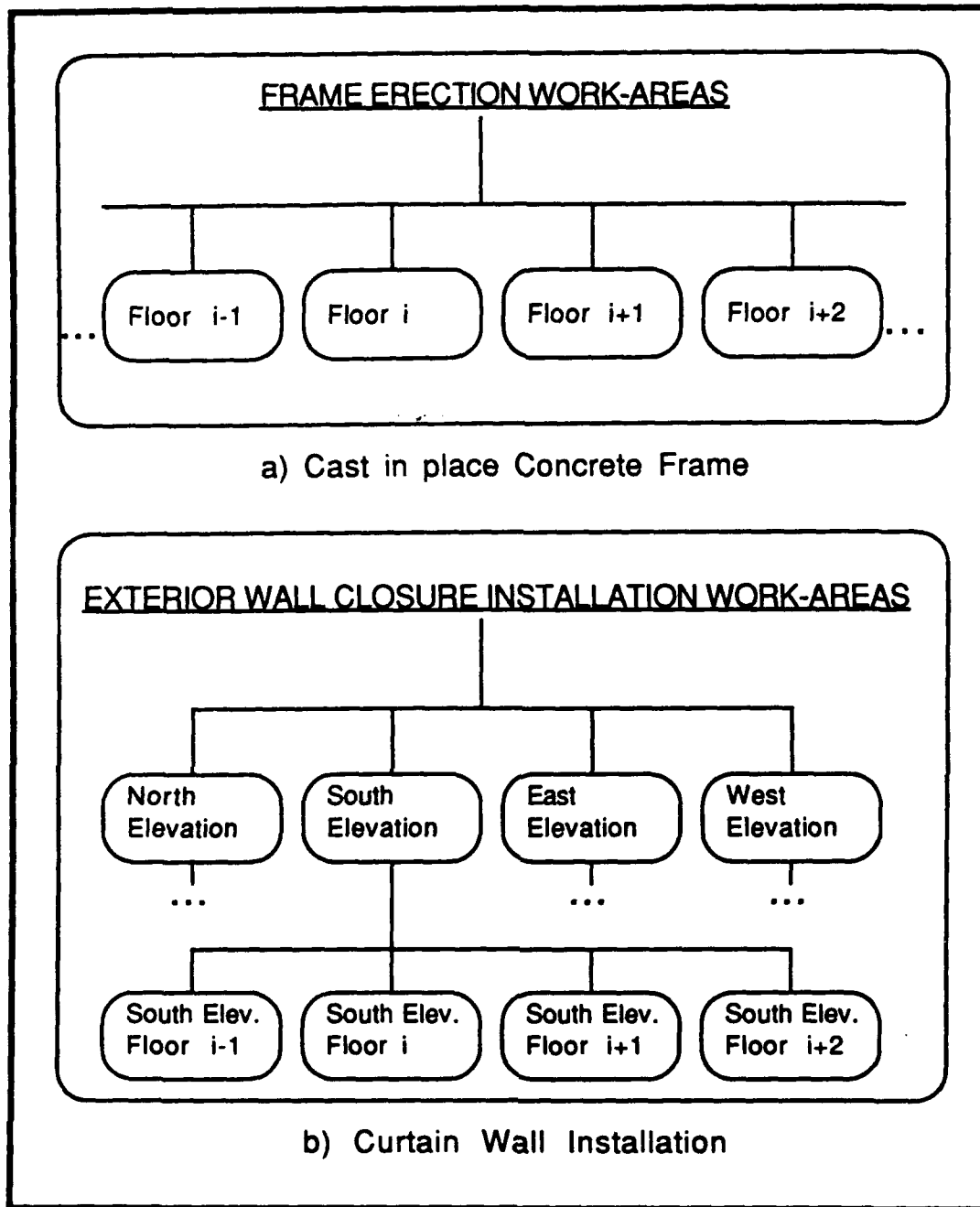
Figure 4.3. Examples of Construction Breakdown by Work-area (Topologically Based).

Activities	Weeks		
	5	10	

Tier Erection
(pace = 1 floor/wk)

Metal Deck
Installation
(pace = 1 floor/wk)

Concrete Deck
Installation
(pace = 1 floor/wk)
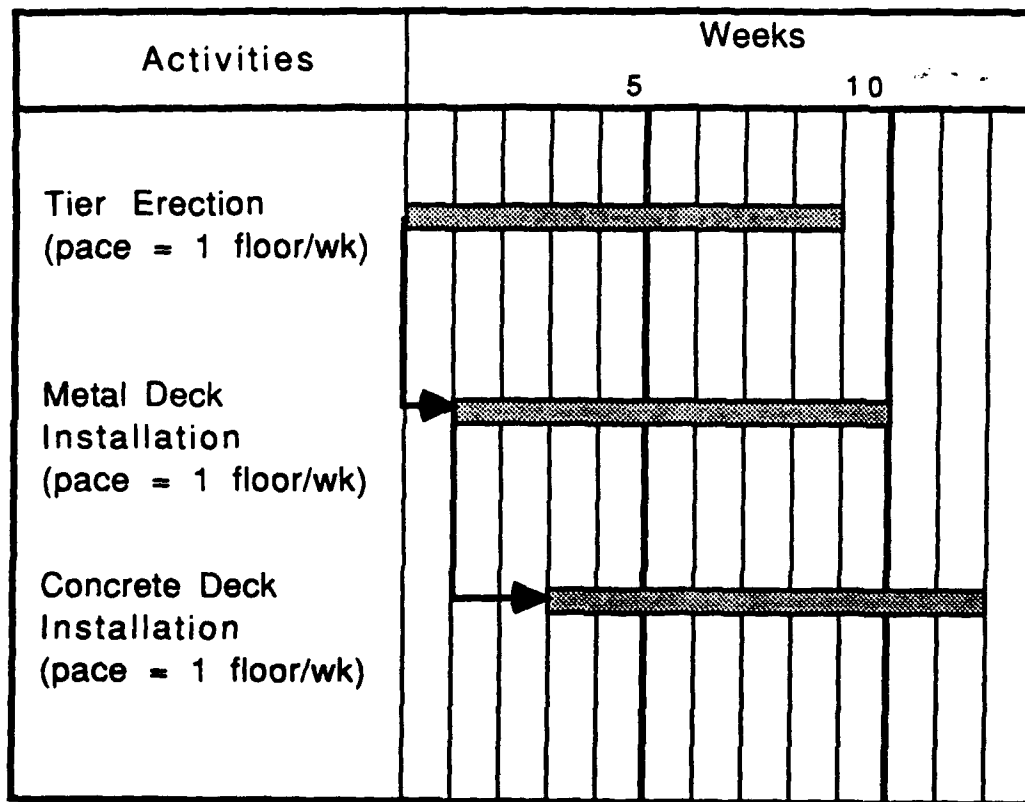
Figure 4.4. Example of Steel Frame Erection Pace.

5   DETERMINING SCHEDULING LOGIC

An essential part of construction planning is the appropriate sequencing of the different activities necessary to deliver the constructed facility. As mentioned in Chapter 4, the scope of this chapter is to understand a number of key factors that dictate activity precedence relationships. Another important focus of this chapter is to analyze how rigid are the constraints imposed by these factors on activity sequencing. This chapter also provides a grammar or language that represents the factors and relationships from which activity sequences are derived, useful for the computer implementation.

5.1   Factors That Govern the Sequencing of Activities

Facility construction is accomplished by assembling, or sometimes demolishing or relocating, components in a particular order or sequence. In this dissertation the focus is only on installation operations related to each of those components. Activities that deal with procurement of resources, submittal/approval of construction documents, acquisition of licenses or permits, etc., although definitely important, are not considered here. In this sense, the ideas presented in this chapter should be considered as an initial step in formalizing sequencing knowledge.

The objective of this chapter is to examine different constraints that govern the sequencing of activities required to construct a facility, and the degree of flexibility associated to these constraints. These constraints have been grouped into four major factors, described in the next few sections, and summarized in Table 5.1. Appendix B provides a listing of these constraints using a rule-like syntax, to facilitate their use by other research efforts. Each constraint is cross-referenced with its rule-like representation in Appendix B.

5.1.1   Physical Relationships Among Building Components

Activity sequencing logic in part depends on the way building components are physically related to each other. Building components can be permanent, like a column or a floor deck, or temporary, like formwork, underpinning or temporary bracing. There are different types of physical relationships among building components that affect the sequencing of their corresponding activities. Most deal with the support of gravity loads, spatial relationships among components and weather protection. The identified physical relationships are discussed in detail below. Examples of each are provided in Figure 5.1.

Supported By. (Rules 1 and 2)

This relationship between two building components indicates that one is providing direct support to the other, at construction time, against the force of gravity. This implies that any activity that acts upon a supported component has to follow the activity that installs the supporting component.

The reciprocal case exists if the activities are removing rather than installing building components. For instance, if a temporary structure (i.e., scaffolding, shoring) is being removed, the supporting components are removed after the supported ones. An exception occurs when it is desired to promote collapse through removal of key supporting components.

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Covered By. (Rules 3 and 4)

An analogous situation occurs for an activity that deals with a component that covers another component. Examples of this relationship are helpful in determining its applicability. A wall is covered by paint. Therefore, the painting of an erected-in-place wall requires the availability of the wall surface. In the reverse case, when a covered component is to be removed, the removal of the covering component precedes the removal of the covered one. For instance, mass excavation material, which is covered by an existing parking lot pavement, may not be excavated until after pavement removal.

Embedded In, Contributing to Structural Function. (Rule 5)

This relationship occurs when one component has to be inside another so that both cooperate for a structural function. An example is standard reinforcement inside a cast in place concrete element. Reinforcement should be placed before concrete is cast. Another example, described in Figure 5.1, deals with a situation in which the first-tier steel columns are embedded in the concrete foundation wall.

An exception to this rule appears to be the installation of post-tensioning reinforcement. Although reinforcement is embedded in precast concrete elements, it is installed afterwards. However, even in this case the reinforcement should be installed prior to the grout.

Embedded In, Noncontributing to Structural Function. (Rule 6)

There are situations in which a component is embedded in another, but there is no structural function that depends on the components being together. Electrical conduit embedded into a masonry wall is a common case that exemplifies this situation. Typically, the embedded component is either installed first or concurrently with the embedding component. The rigidity of this constraint is not as strong as the one implied by the previous constraint. This distinction is discussed in more detail in Section 5.2.

Relative Distance to Support, with Flexibility of Installation. (Rules 7, 8 and 9)

When two components are supported by a common third component, the installation order is affected by their distance to the support and by their installation flexibility. This case is commonly encountered when placing electrical conduit, air ducts, water supply and wastewater pipes under a slab above grade.

Typically if one component is closer to the support than the other, the closer one to the support is installed first. For the situation in which the distance to the support is equivalent, the component with less flexibility of installation is placed first. Flexibility of installation is related to two aspects: (1) the component's material flexibility (PVC conduit is normally more flexible than cast iron pipes), and (2) the importance of position for the component's function (a wastewater drainage pipe for instance has a strict slope constraint).

In some cases a lower component may be used to support the scaffolding for the installation of the higher component. In this particular situation the lower component is providing a service for the installation of the other, and the appropriate sequence could be found by applying the constraint "requirement of service" described in Section 5.1.2.

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Relative Distance to Access. (Rule 10)

This relationship among building components applies when there are several identical components that have to be installed in an area with limited access. Typically, the components are installed in a sequence that initiates with the one farthest from the access point and ends with the closest one. This is especially valid if the components themselves are such that they obstruct the access of the installation crew/equipment. Examples of this situation are pile driving or floor painting.

It is relevant to point out that when the soil-bearing capacity is so poor that it cannot safely support the pile-driving equipment, the constraint described here is not followed. The pile-driving process proceeds with the reverse sequence (from closest to farthest to access point) because the equipment is supported by the installed piles. The supported-by constraint is much more rigid and therefore governs.

Weather Protected by. (Rule 11)

Some building components require a weather protected environment for their installation. This implies that the protected component can be installed only after the protecting component is in place. For example, as indicated in Figure 5.1, nonwaterproof drywall installation should follow temporary or permanent enclosure installation.

There are different kinds of weather sensitivity. Building components can be weather sensitive because of their composition. For example, water is frozen in subfreezing temperatures, so any material that depends on the availability of liquid water can be damaged, e.g., cast-in-place concrete. Another possible reason for weather sensitivity is the installer's (crew or equipment) inability to operate under certain weather circumstances.

Common weather factors are: (1) precipitation, humidity or moisture sensitivity (drywall or paint), (2) cold temperatures sensitivity (water filled pipes prone to freeze are an example), (3) hot temperature sensitivity (e.g., cast in place concrete), and (4) high winds sensitivity (structural steel erection).

Some of these sensitivities cannot be controlled under practical, normal circumstances. This is the case of the erection of structural steel and its sensitivity to high winds. If the wind speed reaches undesirable levels, the erection activity is interrupted. Risk can be reduced, however, by planning the execution of nonprotected activities during a season when the chances of hindering weather conditions occurring are lower.

Another case consists of excavation work affected by frozen ground. It is desirable to avoid scheduling ground excavation during periods when it is expected that the ground will freeze.

5.1.2 Trade Interaction

Construction involves a complex interaction of people, equipment and materials. This is defined here as the Trade Interaction factor.

At a given point in time dozens of crews may be operating on the site, with many of them constrained by the presence and actions of others. This interaction is a primary governing factor for activity sequencing. Activities represent the actions of the different crews, and therefore sequencing is

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substantially affected by the constraints that govern trades. Subcontractors can be thought of as trades in this context. This manifests in several different ways. Examples of trade interaction sequencing constraints are provided in Figure 5.2.

Space Competition. (Rule 12)

The space that a crew and its corresponding equipment occupy can be viewed as a special type of resource in the sense that space availability is a necessary requirement to perform the work. If two different activities are executed by crews or equipment that compete for the same work area, a sequence that recognizes and deals with this competition is needed. For example, crews that operate on a recently finished concrete floor slab may have to wait until the falsework shoring the slab above is removed before they can start work.

Under a pressing time deadline it is not unusual for a contractor to allow more than one crew to operate in the same work area. In this circumstance the productivity of the different crews involved may be affected, but work is still possible. This indicates that the space limitation constraint is not entirely rigid.

Resource Limitations. (Rule 13)

If two activities can be performed simultaneously but compete for the same limited resource, a linear (nonparallel) sequencing of these activities is mandatory. Usually, the activity that is more critical is scheduled first. In the hypothetical example illustrated in Figure 5.2, window installation for floor 5 and floor 6 compete for the same crew.

Unsafe Environment Effects. (Rule 14)

Environment effects are defined here as the modifications in air quality, temperature, humidity, brightness, noise level, etc., that are produced in a work area by a crew and its equipment. Almost any construction activity has environment effects as a byproduct of its progress. In most cases they are tolerable, but if the environment effects are such that the work area is unsafe, the development of the effect-causing activity precludes concurrent progress of any other activity within the affected work area. An example of this situation is fireproofing a steel frame with a sprayed heat-insulating material. No other activity should be performed concurrently within the affected work area. Similarly, welding or any other flame-producing operation should not occur simultaneously, within the affected work area, with the application of substances that produce volatile and flammable fumes, like some paints.

Damaging of Installed Building Components. (Rule 15)

If an activity might damage the work of another activity, then the damageable work should be performed afterwards. This is a common situation in construction, as illustrated by several cases. For instance, cleaning brick masonry with an acidic solution can damage the metallic parts of any other components that are in contact with the bricks (windows, doors, etc.). Similarly, a floor surface like carpet may be affected by the painting crew.

Possible damage to installed components is the reason some floor repetitive activities are sometimes performed from top floors to bottom floors (as opposed to bottom-up). For example, many contractors elect to place and clean face brick from the top down to avoid affecting installed brick and

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window frames. Similarly, it is typical to schedule the finishes of those first floor areas that can be damaged, last. The reason is that the first floor is normally the access floor, and therefore its finishes can be damaged by the crews finishing the other floors, when accessing/leaving the building.

Requirement of Service. (Rule 16)

Quite often a crew (or the equipment it uses) requires a service like water or power supply, vertical transportation, etc. It is necessary then to have the object or system that provides the service available as a requisite for the operation of the crew. The service providing object can be temporary.

A special case of service is the test, inspection or approval of work in place, by a supervisor or management crew, required for certain activities. Only after the work in place has been accepted can the crew continue its operation.

Tests and inspections are often a code requirement. The influence of codes on activity sequencing is discussed in Section 5.1.4.

The constraints for Space Competition, Resource Limitation and Unsafe Environment Effects do not necessarily imply a particular sequence for the affected activities. They just constrain the concurrence of affected activities. It is up to the construction planner to determine the order in which the affected activities should be performed. An experienced planner decides based on what is more advantageous to the project. This is normally project-specific and therefore is beyond the scope of the present research effort. Conflicts identified at the planning stage can be resolved before construction begins.

5.1.3 Path Interference

Refer to Rule 17 in Appendix B. This sequencing constraint relates to path interferences occurring at installation time. When a building component is ready to be installed it has to be transported from site storage to its permanent place (Figure 5.3). This necessarily requires the existence of an interference free path. This path is required not only for the component to be installed, but for all the equipment and personnel necessary for its transportation and installation.

This constraint is extremely relevant for industrial construction, which is not considered in this thesis. This type of construction usually involves the installation of large preassembled units (e.g., prefabricated pipe spools) that have to fit into their final position. Some research has been conducted to deal with this constraint. Modeling software developed at Bechtel represents obstacles to a component's path as mathematical constraints [Simons 88]. Path interferences that might occur are detected in this way.

5.1.4 Code Regulations

Code regulations affect activity sequencing. They are mainly related to: (1) the safety of workers and the general public during construction, and (2) the inspection of the quality of work in place (refer to Rule 19 in Appendix B).

An example of this situation consists of the erection of steel frames (Figure 5.3). Today OSHA requires the installation of a temporary or permanent floor not more than two stories or 30 feet (9.14

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meters) below the actual frame erection operation [ANSI 78], [OSHA 87]. This results in a typical sequence consisting of the installation of floor metal deck staggered two stories behind structural steel erection. This sequence is present due to the imposed code regulation for safety concerns. This sequencing constraint corresponds to Rule 18 in Appendix B.

Another example of a code regulation derived activity sequence is also illustrated in Figure 5.3. In this case, drywall completion is preceded by the inspection of drywall covered electrical work. The BOCA National Building Code specifies that electrical work cannot be covered before it has been inspected and approved [BOCA 90].

5.2 Flexibility of Sequencing Constraints

The different constraints described above possess varied degrees of flexibility. Some of these constraints are practically unavoidable, while others may be bypassed with an increase in construction cost, time, effort or risk. In any case, there is no such thing as a totally inflexible constraint. There is rather a spectrum of flexibility degrees.

The critical question is how to quantify the degree of flexibility. It is difficult to accurately determine the degree of flexibility for any of the constraints described here, because it is project- and contractor-dependent. For example, a contractor may decide to use temporary weather protection to install drywall in a building project, due to a particularly pressing deadline. The same contractor may act differently in another building project if the surrounding circumstances motivate actions in another direction.

For purposes of simplify, however, the sequencing constraints are classified here into two categories: (1) rigid constraints, and (2) flexible constraints. The rigid constraints are such that the activity sequencing imposed by them is not practically modifiable with existing construction methods. An example consists of the supported-by constraint. If a component (e.g., a metal deck) is supported by other components (e.g., a set of steel joists) the installation of the latter has to precede the installation of the former.

Constraints falling in this category (rigid constraints) can be identified among those described in previous sections:

- Supported by
- Covered by
- Embedded in, contributing to structural function
- Requirement of service
- Code regulations.

The constraints imposed by code regulations are treated here as inflexible constraints because it is unlawful to disobey them. Code regulations do change with time, though.

Other constraints respond to common practice and are here classified as flexible constraints:

- Embedded-in, noncontributing to structural function
- Relative distance to support, with flexibility of installation

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- Relative distance to access
- Weather protected by
- Space competition
- Resource limitations
- Unsafe environment effects
- Damaging of installed building components
- Requirement of service
- Path interference.

The flexibility of sequencing constraints is a valuable tool that contractors can use for the benefit of the project in diverse circumstances. For example, it can be used to satisfy stringent completion milestones. Flexibility can also be applied to minimize the impact of procurement delays on the overall project schedule. In any case, whenever a sequencing constraint is bypassed, an increase in risk, time, effort, or cost can be expected.

5.3   Activity Concurrence and Scheduling Logic

This section focuses on the relevance of activity concurrence to the different scheduling constraints. Activity concurrence is here defined as the situation in which two given activities are planned to be performed during overlapping periods of time. Certain sequencing constraints can be applied to a great extent independently of the timing of their affected activities. For example, the supported-by constraint can be applied to establish precedence, independent of the start and finish times of affected activities.

However, some sequencing constraints become active only if the affected activities are concurrent. An example consists of an activity affecting the environment, and an activity sensitive to the environment effect provoked by the former, to be performed in the same work area. A sequencing constraint preventing concurrent execution of these two activities should be applied only if the sensitive activity is planned to be performed concurrently with the environment-affecting activity.

The constraints that require activity concurrence to apply are here called activity-overlap dependent, and are:

- Space competition
- Resource limitations
- Unsafe environment effect.

This activity-overlap dependence implies that a constraint violation can only be detected after the activities are located in time, i.e., start and finish times have been determined on a trial basis.

5.4   Summary

This chapter focused on the discussion of the activity sequencing acquired knowledge. Together with Chapter 4 they constitute a description of the formalized scheduling knowledge.

The next stage in this dissertation is to incorporate a subset of this knowledge into a prototype KBS. Chapter 6 describes the implementation efforts and the resulting schedule generation computer support tool.

Table 5.1. Identified Categories of Activity Sequencing Factors.

GOVERNING FACTOR	GENERAL DESCRIPTION
Physical Relationships Among Building Components	Building components are spatially restricted, weather protected or gravity supported by other components. Activity sequencing has to respond to these inter-component relationships.
Trade Interaction	Activity sequencing also responds to the different ways in which the different crews and their processes/tools/ equipment affect each other during the construction phase.
Path Interference	Building components have to be moved around the job-site in order to be installed. Activity sequence has to guarantee an interference-free path for the displacement of any component and its installing crew and equipment.
Code Regulations	Activity sequencing is also responsive to construction phase safety considerations, and to inspection/accep-tance requirements.

RELATIONSHIP	EXAMPLE CASE	DERIVED ACTIVITY SEQUENCE
Supported by	Metal Roof Deck *SUPPORTED BY* Roof Frame	Erect Roof Frame → Metal Roof Deck Installation
Covered by	Foundation Wall *COVERED BY* Bituminous Asphalt Waterproofing	Foundation Wall Erection → Foundation Wall Waterproofing
Embedded in, Contributing to Structural Function	Columns First Tier *EMBEDDED IN* Foundation Wall	Erection First Tier Structural Steel → Foundation Wall Erection
Embedded in, non-Contributing to Structural Function	Electrical Conduit (Wall Segment i) *EMBEDDED IN* Wall Segment i	Electrical Conduit Installation (Wall Segment i) ↔ Wall Installation (Segment i)

Figure 5.1. Examples of Sequences Derived from Relationships among Components.
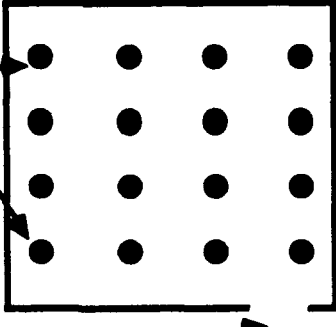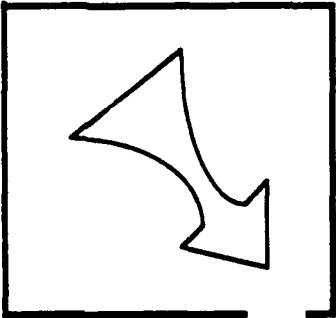
RELATIONSHIP	EXAMPLE CASE	DERIVED ACTIVITY SEQUENCE
Flexibility of Installation	Cast Iron Waste Water Pipe *LESS FLEXIBLE THAN* Electrical Conduit	Gravity-drained Waste Water Pipe Installation → Electrical Conduit Installation
Relative Distance to Access	Driven Piles Site Access	General Direction of Pile Driving Operation *(From Farthest to Closest to Access, except if soil is unable to support pile driving equipment. In this case the reverse direction is followed)*
Weather Protected by	Non-Water-Resistant Drywall *WEATHER PROTECTED BY* Enclosure	Enclosure Installation → Drywall Installation

Figure 5.1. (continued)

INTERACTION TYPE	EXAMPLE CASE	DERIVED ACTIVITY SEQUENCE
Space Competition	Concrete Slab Shores *OCCUPIES SPACE REQUIRED BY* Interior Wall Layout Crew	Floor i Slab Shore Removal → Floor i-1 Interior Wall Layout
Resource Limitation	Window Installation Floor i *COMPETES FOR CREW WITH* Window installation Floor i+1	Window Installation Floor i — *Cannot be Concurrent With* → Window Installation Floor i+1
Unsafe Environment Effects	Rough Plumbing Crew *IS SENSITIVE TO* Steel Fireproofing Spray	Structural Steel Fireproofing — *Cannot be Concurrent With* → Rough Plumbing

Figure 5.2. Examples of Sequences Derived from Trade Interaction Constraints.

INTERACTION TYPE	EXAMPLE CASE	DERIVED ACTIVITY SEQUENCE
Damaging of Installed Building Components	Floor Carpet *MAY BE DAMAGED BY* Wall Painting Crew	Wall Painting → Floor Carpeting
Requirement of Service	Elevator Installation Crew *REQUIRES SERVICE* Electrical Power	Power Supply Equip/Cabling Installation OR Temporary Power → Elevator Installation

Figure 5.2. (continued)
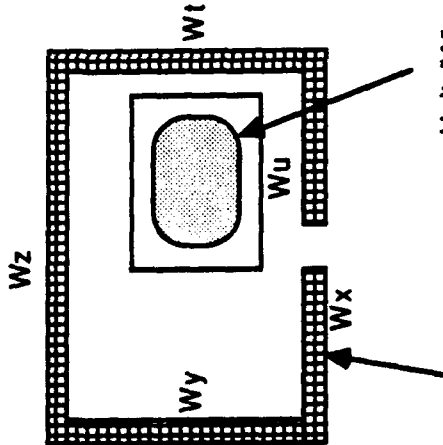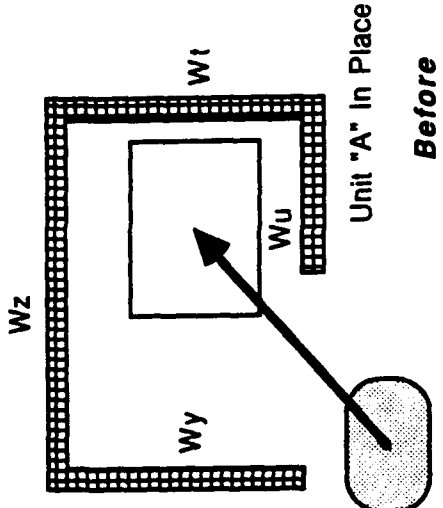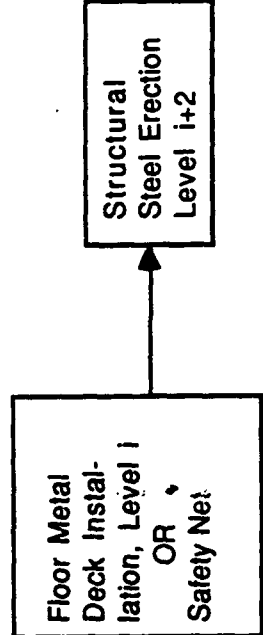
FACTOR	EXAMPLE CASE	DERIVED ACTIVITY SEQUENCE
Path Interference (2 D)	Wall Segments "W x,y,z,t,u" (Roof not shown)	Unit "A" In Place *Before* Completion of All {Wx, Wy, Wz, Wt, Wu, Roof}
Code Regulations (safety)	*A floor or safety net shall be provided within two stories or 30 ft (9.14 m.), whichever is less, below and directly under that portion of each tier of beams on which any work is being performed* (From [ANSI 78])	Floor Metal Deck Installation, Level i OR Safety Net → Structural Steel Erection Level i+2

Figure 5.3. Examples of Sequences Derived from Path Interference Constraints and Code Regulations.

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FACTOR	EXAMPLE CASE	DERIVED ACTIVITY SEQUENCE
Code Regulations (Inspection)	*Work in connection with an electric system shall not be covered or concealed until such work has been inspected and permission to conceal such work has been approved* (From [BOCA 90])	

(1) The drywall installation cannot have progressed to the point of hiding electrical work to be inspected.

Figure 5.3. (continued)

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6   IMPLEMENTATION WORK

6.1   Prototype Scope and Objectives

The main objective of the developed prototype system, named CASCH for computer-assisted scheduling, is to serve as a tool to represent the acquired scheduling knowledge. As such it is a valuable aid in formalizing this knowledge. The production of the prototype was an exercise that forced a clearer understanding and a more structured representation of the acquired knowledge. It was not intended to be a comprehensive listing of all building systems and their possible alternatives. However, it does identify those more often encountered and more relevant to the scope of this study of scheduling.

The general objective of the prototype is reached by embodying a subset of the acquired knowledge into the selected software environment. The targeted knowledge areas to represent consist of: (1) understanding project information, limited to project features represented in the knowledge base, (2) producing a meaningful project construction breakdown into activities, (3) logically sequencing the identified activities, and, (4) determining preliminary activity durations. In addition, this implementation work also involves coding a number of procedures that support these different processes (for example, CPM calculations), that will be described later.

The prototype implementation has been developed with the intention of minimizing user input. User input is reduced to responding a few questions about the building to be constructed (20 to 25 questions, depending on project characteristics). Within an hour, the prototype produces a schedule of construction activities addressing common project features. This schedule is here called a schedule template, and can be tailored by the user to fit the unique project features not considered by the system's analysis. This tailoring is possible because of the prototype's interactive nature.

This chapter describes in detail the implementation and its results. First, there is an overview of the different knowledge representation tools used. Then the three modules of the knowledge base are examined, as well as the procedural approach to perform CPM calculations. Next, an example of operation of the system demonstrates the performance of the prototype and the ability of the acquired knowledge to produce schedule templates.

6.2   General Prototype Characteristics

6.2.1   Selected Computer Platform

The implementation work was performed using the Knowledge Engineering Environment (KEE™), distributed by Intellicorp. It runs on a Compaq 386 Deskpro machine with 12 Megabytes of RAM and a 130 Megabyte hard disk. KEE™ tools especially useful to this research project are: (1) the object-oriented representation scheme, (2) the rule based representation scheme, (3) true forward/backward chaining mechanisms for rule inferencing, and (4) the graphics tool kit. The object-oriented and rule based representation schemes serve to incorporate factual and heuristic knowledge in the knowledge base. These terms are explained in more detail in Appendix A, Sections 1.1 and 1.2, respectively. The forward and backward chaining mechanisms consist of processes followed by a KBS to reach the intended goal. They are described in more detail in Section 2.3 of Appendix A.

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6.2.2 Blackboard Approach for Knowledge Communication

The prototype uses a modular approach to store scheduling knowledge. As illustrated in Figure 6.1, the different knowledge modules interact by following a blackboard architecture approach. This approach allows independent knowledge-bases (here called knowledge modules) to communicate to find a solution to the current problem. This cooperation of knowledge modules is based on the ability to post and retrieve information in a storage area (the "blackboard"). This approach offers the enhanced modularity of the knowledge-base. Independent knowledge modules are easier to develop and maintain.

In this prototype, the blackboard for information posting is the Context, or collection of information for the current problem. All the knowledge modules post and retrieve information to and from the Context. The posted/retrieved information consists of elements that describe the current problem. For instance, when the module that determines activity sequencing completes its task, it posts a new fact in the Context ("The activities have been sequenced"). Another example is the posting of objects that represent building systems, subsystems and components. The Building Systems Knowledge Module posts in the Context objects like "Metal-deck-level-4" with all of its attributes. This object is later retrieved by other modules to identify its associated activity and the precedence relationships of its activity with other activities.

6.2.3 Use of Object-Oriented Representation

This implementation makes extensive use of the object-oriented features provided by KEE™. A number of different types of project-related entities, described in more detail in section 6.3, are represented as objects. A partial list includes building systems, components, and activities.

The object-oriented scheme allows the representation of: (1) schedule-related elements, for example activities, as objects, and (2) schedule-related element characteristics and interrelationships, for example activity duration and precedence, as attribute-value pairs. In addition, the object-oriented scheme allows to attach procedures to objects, which facilitates the representation of actions performed on these objects. This is the case with CPM calculations performed on activities. Programming is more efficient because of inheritance. For example, every new CPM-activity instance learns how to perform CPM calculations from its parent object, CPM-activity.

6.2.4 Use of Rule-Based Representation

Activities are created with rules via a data-driven (forward chaining) mechanism. Each building component is matched by an activity creating rule and as a consequence an activity is created that installs or removes the component as needed. The forward chaining inferencing is appropriate because the activity creation rules are triggered until all components have been associated to an activity.

Activity sequence is also produced by a forward chaining mechanism triggered by activity creation. The forward chaining rule inferencing mechanism is used here because of its nature: as soon as a new activity is known, all possible sequencing consequences are applied, as dictated by the rules.

6.2.5 Use of LISP Programming

As mentioned, an important part of the object-oriented representation is the ability to attach methods to different objects. These procedures are implemented here by Common LISP functions. The

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principal operations performed with attached LISP procedures include: (1) assistance in the generation of components particular to a building, (2) CPM calculations, and (3) elimination of precedence redundancies.

The advantage of using Common LISP to support method encapsulation is portability. In the particular case of the CPM Kernel, for instance, the basic functions were ported relatively easily from a Goldworks™ (GC-LISP) environment into the KEE™ environment where the prototype resides.

6.3 Prototype's Knowledge Modules

6.3.1 Building Systems Knowledge Module

The objective of this module is to allow the system to acquire the required project data to produce and sequence activities. This is accomplished by providing the prototype with information about different building systems and their components.

6.3.1.1 Building Systems. A building is composed of various systems. A breakdown of these building systems into subsystems is provided. Subsystems are further decomposed until the decomposition reaches the component level. Building components (called components for short) are part of subsystems that are generally installed or removed by a single crew, and, in general, are made of a single material. Exceptions to this rule are cast in place concrete components, like footings or columns. Part 1 of Appendix C, and Appendix D provide a description of the different systems, subsystems and components presently included in the prototype. An example of a building system and its decomposition to the component level is illustrated in Figure 6.2.

This decomposition of a building into systems and subsystems closely follows the Building Systems Index (BSI) breakdown for two main reasons: (1) it is an accepted standard, and (2) it is a systems-oriented breakdown, which matches the intention here of representing building decomposition into systems. The CSI Masterformat standard although originally considered was not used because its breakdown approach is primarily responsibility oriented.

A goal of this module is to have a pool of generic objects used at runtime by the user to describe a particular building. This allows the different systems and subsystems to have alternative and optional subsystems or components, respectively. Figure 6.3 provides an overview of all the systems, subsystems and components currently included in the prototype. Alternatives and options are indicated in the figure.

Another goal for this module is to handle incomplete project information. This is performed by storing a default alternative. The user may change this default alternative as desired. Preliminary defaults are set in the knowledge base as follows: (1) for "floor-structure", the default alternative is "steel-floor-structure", (2) for "roof-covering" the default alternative is "roof-membrane", and (3) for "exterior-skin" it is "masonry-wall-windows."

If a subsystem alternative is known at runtime, the user selects it. Otherwise, the user can select the default alternative. Default subsystems and components are also indicated in Figure 6.3.

The user may change, add, delete systems, subsystems, or components to improve the model representing a specific facility.

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<u>6.3.1.2   Building Components</u>. Components are described in this knowledge module generically. This provides a pool of components from which to create those particular to a given building under analysis.

Components are classified in two different ways. One depends on whether the component is to be installed or removed. Installable components, like metal floor deck or concrete foundation wall, are those to be permanently installed in the delivered building. Removable components, like excavation soil, are those to be removed as part of the construction process.

Another classification of components is related to their repetitiveness. Some components are repeated from one work area to another. This is the case of metal floor deck, which is repeated for every elevated floor. Four types of repetitiveness-classified components exist in this module: (1) floor-repetitive components, repeated for every floor, like concrete columns, (2) elevated-floor-repetitive components, repeated for every floor above grade (e.g., metal-floor-deck), (3) above-grade-repetitive components repeated for all levels above ground, like exterior windows, (4) tier-repetitive components that refer specifically to structural steel, plus, nonrepetitive components, not repeated from one work area to another, like the soil to be excavated. Grade level is the lowest level (lowest basement level, or first floor if no basement is present). Ground level corresponds to street level, which normally is the first floor.

The system currently represents all components of the same nature within a work area as a single work item. For instance, all footings within the same work area are aggregated as a single work item. The system can be extended to represent each component individually. However, this extension would be meaningful only if the amount of input component data is increased substantially, to differentiate similar components within the same work area, in terms of location, exact dimensions, etc. This would necessarily increase the user effort required for providing the system input, assuming that the data is fed manually.

Figure 6.4 provides examples of generic components. The characteristics of a component are described by its attribute-value pairs (or slot-value pairs). In this figure there are several characteristics stored in the component slots. They can be classified into four major groups:

- Higher-Level System. This describes the system or subsystem of the component. Concrete column footing is-part-of the Footing Foundation, for instance. The reciprocal characteristic is also represented (Footing Foundation contains concrete column footing).

- Component Location. The physical location of the component and of the crew that installs or removes the component are also represented. This information is relevant to model the use of construction spaces by activity resources (labor and equipment). Space can be treated as a service that is provided by an activity. It is also a resource that can be competed for. Locations are represented by following a work area oriented discretization of the jobsite. Figure 6.5. provides an illustration of how the jobsite is subdivided into work areas, also called here construction spaces.

    Two component slots relate to the notions of location and work area. One is the approx-location slot, which provides information about the work area where the component's final position is located. The other is the oper-space slot, which points to the work area used by the crew that installs/removes the component.

The oper-space slot actually identifies a construction space as a resource for installing/removing a component. In some cases more than one construction space is required by the installing crew. For instance, when installing an exterior masonry wall, normally two construction spaces are required: (1) the elevated floor where the installing crew is operating, and (2) the space occupied by the scaffold, in this case the backfilled building perimeter, at ground level.

- Relationships with other Components. As presented in Section 5.1.1, a variety of physical relationships relating one component to others are instrumental in determining activity precedence links. The current version of the prototype supports a few of these relationships and their reciprocals: covered-by, embedded-in, supported-by and weather-protected-by.

- Trade Interaction. Information that describes trade interaction factors is also represented in component slots. Currently implemented slots include: (1) may-damage, which refers to another component that may be damaged by the installation of the component, and (2) provides-service, which refers to a component providing service (power, water supply, etc.) to a crew/equipment installing another component at construction time.

6.3.1.3 Runtime Use of the Building Systems and Components Knowledge.

When the user uses the prototype to generate a building's construction schedule, the Building Systems Knowledge Module generates the particular building systems, subsystems and components, given the user input. Each building system is expanded into subsystems, using the module's knowledge and querying the user whenever a selection from alternative subsystems has to be made. Similarly, subsystems are expanded further until the component levels are reached. Information storage for the particular building is performed by using generic objects (systems, subsystems and components) from the knowledge base and replicating them into the Context as guided by the user's answers. Figure 6.6 complements this description.

For example, expanding the Structural Frame system involves: (1) copying of the Structural Frame system object into the Context, (2) similarly, the subsystem Floor Structure (which is-part-of the Structural Frame) is copied into the Context, (3) next, the user is prompted to select the type of Floor Structure (in this case Steel Floor Structure), (4) this selected alternative is copied into the Context, (5) the components that are part of this selected alternative (Structural Steel Tier, Metal Floor Deck and Concrete Floor Deck) are replicated as many times as required, given their repetitiveness type. In the case of the example illustrated in Figure 6.6 (six stories, one basement, two-story long tiers), the specific components replicated from the generic ones are: (1) four Structural Steel Tiers, (2) six Metal Floor Decks (levels 1 through 6), and (3) six concrete decks (levels 1 through 6).

6.3.2 Activity Identification and Preliminary Activity Duration Estimation Knowledge Module

The objective of this knowledge module is to represent the top-down approach for construction scheduling. As introduced in Chapter 4, this top-down approach is a process of repeatedly subdividing the overall construction project into activities.

6.3.2.1 Project Breakdown.

The breakdown of a project into activities is represented in the prototype by having three levels of detail to describe activities (refer to Figure 6.7). The most general activity (first-level) is called Building Construction. It is decomposed into several major activities (second-level), namely, Site Preparation and Foundation Work, Frame Erection, Rough-in Work, Roof

Work, Skin Installation, Floor Finishing, Elevator Work, and Site Finishing. These major activities are themselves subdivided into more detailed activities (called third-level activities, or CPM-activities) that directly act to install or remove the particular building components being processed.

The breakdown into second-level activities reflects a responsibility oriented breakdown. The third level activity decomposition responds to the installation/removal of components broken down following the work area and responsibility factors.

6.3.2.2 Determination of Preliminary Activity Durations. As mentioned, the knowledge acquisition phase emphasized activity definition and activity sequencing. Although some knowledge was also acquired on how activity durations are estimated, it is not as elaborate nor complete. Furthermore, the acquired knowledge applies only to a certain range of building sizes. The acquired knowledge concentrated on buildings with an area ranging between 5000 and 25,000 sq ft per floor. These limitations imply that the prototype's current duration estimation process is not fully configured.

To establish preliminary activity durations, the prototype requires input from the user. The approach, consistent throughout this implementation work, is to reduce the user effort to a reasonable minimum. Therefore the user prompts are targeted only to obtain general building size information sufficient to estimate approximate quantities. More detail is given in the following paragraphs, on how duration estimation is performed. Table 6.1 summarizes the information used to estimate activity durations.

- Site Preparation and Foundation Work Durations. The knowledge acquired for site preparation and foundation work duration estimate provides only general guidelines as presented in Chapter 4. Large uncertainty exists here, due to all the unknown circumstances that can potentially affect these durations, e.g., water table level, unexpected soil conditions, etc. It was also learned in this research that there is typically a 12- to 15-week time lag for structural steel delivery. It is expected that the foundation work progress during this 12 to 15-week period is such that the arrival of the steel coincides with the availability of the column foundation components (pile caps, footings, etc.).

  This information provides guidance only in determining the duration for the second-level activity Site Preparation and Foundation Work. To determine durations for third-level activities the prototype: (1) requests user provided information to calculate approximate quantities (for instance, the amount of excavation can be approximately computed given the building footprint and the number of floors below ground), and (2) uses these approximate quantities and productivity rates based on [Means 89] to compute a duration. Table 6.1 describes the general building size information asked of the user and how it is used to determine approximate quantities. It also includes corresponding productivity rates used to determine preliminary activity durations.

- Frame Erection Durations. The preliminary duration determination knowledge available here consists of frame erection activity progression paces. This pace concept is applicable here due to the repetitive nature of these activities. If the frame is steel, the structural tiers are installed with a pace of one floor per week. This same pace applies to metal deck installation and concrete deck installation.

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- **Roof Work Duration.** The prototype provides a default duration of 2 weeks for this activity, regardless of the type of roof installed.

- **Skin Installation Durations.** In the prototype the skin installation pace follows the frame erection, no matter what type of skin is used. This implies a progress rate of one floor per week. Exterior-wall and window installation have default durations of 1 week per floor.

- **Rough-in-Work Durations.** Rough-in work typically follows frame erection. Accordingly, the prototype defined pace is one floor per week. This includes electrical and mechanical risers and mains installation with a duration of 1 week per floor. Wall studs installation progresses at the same rate.

- **Elevator Work Duration.** Elevator installation normally ranges between 12 and 24 weeks. In the prototype, a default duration of 12 weeks is assigned to this activity.

- **Interior Finishing Durations.** As mentioned, interior finishes are described in the prototype as a single activity per floor. Information received from the interviewed schedulers indicates that once the space is available, the finishing of a floor may take between 5 and 9 weeks. Typical floor finishing duration is in the prototype determined based on a user's qualitative description of the quantity of interior partitions:

   - Finishing the first floor has a default value of 9 weeks. The Lobby area is always more time consuming to finish.

   - If there is a reduced number of interior partitions in typical floors, the default duration is 5 weeks; otherwise it is 7 weeks.

The user may adjust any or all durations as desired.

6.3.3 Activity Sequencing Knowledge Module

The objective of this knowledge module is to deduce a logical sequence (precedence relationships) for all third-level activities. This sequencing is performed by representing some of the constraints described in Chapter 5.

The selected constraints are the result of a consideration of their schedule production importance and the prototype representation limitations. All of the sequencing constraints formalized in Chapter 5 are relevant for activity sequencing. However, their degree of flexibility is different. The approach for selecting the constraints to represent in the prototype was to give priority to the rigid ones. As a consequence, the following ones are implemented:

- supported-by
- covered-by
- embedded-in, contributing to structural function
- requirement of service

The prototype also incorporates the damaged-by-installation and weather-protected-by constraints, which are considered flexible.

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At the present time the code regulation constraints, dealing with safety concerns, can be represented as a requirement of service, i.e., safety.

There is a limited capability to deal with sequencing constraints that require activity time concurrence (or activity overlap) to apply. Refer to Section 5.3 for more detail on the nature of these constraints. The prototype has the capability to detect overlapping activities, and in some limited cases explained later in this section it can apply activity-overlap dependent constraints.

A number of sequencing constraints are at present unsupported, namely, relative distance to access, relative distance to support, and path interference. This is because the prototype does not represent exact location and dimensions of modeled objects. However, relevant efforts that address this specific issue have been performed elsewhere [Simons 88].

CPM calculations are more efficient if redundant activity links are eliminated. The specific redundancy elimination procedures are described in detail later in this section.

6.3.3.1   Rule-based Deduction of Precedence Relationships. Deduced sequence is represented by utilizing CPM-activity (third-level) activity slots. Table 6.2 summarizes the slots used to represent sequence.

Activity sequence is primarily deduced with rules. Table 6.3 provides the list of constraints currently implemented in the prototype in rule form. Figure 6.8 provides a rule example and Part 2 of Appendix C includes the sequencing rules incorporated at present in the prototype. A rule identifies a pair of activities that satisfies its condition for sequencing constraint application. Once the match of the activity pair required by the condition occurs, the rule establishes a precedence link between the two activities.

Consider the activities column-footing-installation and steel-erection-tier-1. Because the column footings directly support the first steel tier, this pair of activities is matched by the rule that applies the supported-by sequencing constraint. As a consequence, the two activities are connected with a precedence link (Figure 6.9). This is performed by adding the name of the new predecessor to the preceded-by slot of the succeeding activity, and adding the name of the new successor to the succeeded-by slot of the preceding activity. The prototype also records the precedence link justification. This is accomplished with the predecessor's precedes-justification slot and the successor's preceded-by-justification slot.

It is important to stress that because the prototype deduces activity sequence, it can also store deduced sequencing justifications. The advantage for the user is that not only does the system generate activity precedence relationships, it is also capable of showing the reasons to substantiate these precedence relationships.

6.3.3.2   Application of Activity-Overlap Dependent Sequencing Constraints. Most of the Trade Interaction constraints described in Chapter 5 (space competition, resource limitation, unsafe environment effects) are activity-overlap dependent. This implies that for these constraints to become active, affected activities have to overlap in time. For example, if two activities use the same resource, they only compete for it if they require it simultaneously.

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A procedure is used by the prototype to identify activities that have an interaction conflict and overlap in time. Currently the prototype represents crew requirement conflicts by activities of the same nature performed in different work areas. For example, the activities, window-installation-level-2, and window-installation-level-3 may simultaneously require the same installing crew. If there is a conflict, it is identified and resolved by creating a precedence link.

The implemented criteria to apply this precedence link is that the activity in the lower work-area (floor) precedes. It is recognized that this criteria is not sufficient to provide a satisfactory sequence in every possible case.

6.3.3.3 Elimination of Redundant Links.
One of the actions accomplished by the prototype is the elimination of redundant precedence relationships. This is performed with the aid of an active value. The reader is referred to Appendix A, Section 1.1, for additional detail on the concepts of object-oriented representation and active value.

The active value in this case involves a procedure that is attached to the preceded-by slot of every CPM-activity. Every time a new value (new preceding activity label) is added to this slot, the procedure is executed. Three possible outcomes can be obtained from the execution of this procedure: (1) if the new precedence link is redundant, the procedure eliminates it, (2) if the new precedence link makes an existing precedence link redundant, the latter is removed, and (3) if the new precedence link is not redundant and does not make any other link redundant, no change is made. Figure 6.10 graphically illustrates this concept.

When a redundant precedence link is eliminated, the link justification is kept. For instance, in Figure 6.10, the fact that the precedence link "Activity A precedes Activity C" is eliminated does not imply that Activity C ceases to require A as a prerequisite. The representation scheme used in the prototype (precedence and justification slots) allows elimination of the redundant links without losing information about prerequisite activities.

6.4 CPM Kernel

The CPM Kernel is a procedural module, written using KEE™'s object-oriented environment. The objective of this module is to perform CPM calculations on the CPM-activities. The alternative of performing these calculations with an existing Project Management System (PMS) was also considered. However, it was decided to implement the CPM Kernel within the same environment as the prototype for several reasons: (1) to avoid computational overhead forced by the linking of KEE™ and a PMS, (2) to allow iteration cycles schedule-generation-modifications/CPM-calculations, and (3) to learn how to use KEE™ effectively. The CPM Kernel development was the first opportunity for the author to work with KEE™, and was instrumental in becoming familiar with its different features.

The CPM Kernel operates on the three levels of activities represented in the prototype. The operations depend on the activity type and are performed by attached methods (Table 6.4):

- **Operations on Third-Level Activities (CPM-activities):** The actual CPM calculations are performed only at this activity level. Each activity inherits a procedure that verifies whether all predecessors have communicated their early times. If this is true for an activity, this triggers another procedure to communicate (broadcast) their early times to their successors.

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These two procedures enable the forward pass. The backward pass is performed similarly, with two other attached procedures. Finally, there is another procedure that computes activity float.

- <u>Operations on Second- and First-Level Activities</u>: These activities are treated as hammock activities. A hammock activity is an activity that is used to summarize or aggregate a group of more detailed activities. A procedure attached to second- and first-level activities computes start/finish times and duration. It receives early start and finish times from all CPM-activities that belong to the particular hammock activity. It identifies the hammock activity start time as the smallest of the received start times. Similarly, the finish time is defined as the largest of the received CPM-activity finish times.

6.5 Demonstration Run

A prototype-assisted schedule generation session is presented here, with the objective of demonstrating the ability of the knowledge incorporated in the prototype to develop schedule templates. Also, this description is used to illustrate the different prototype features introduced in previous sections, with the aid of figures containing screen dumps.

The goal of developing a construction schedule is addressed in each session by progressing through a sequence of subgoals or operations. Table 6.5 summarizes these operations. Whenever necessary, a complementary explanation is provided to assist in understanding how the prototype works.

6.5.1 Identification of Specific Building Components

This step is an attempt to mimic the scheduler's understanding of project information. The prototype prompts the user for specific building information that is used by the Building Systems Knowledge Module to identify the systems, subsystems, and components particular to the building under study. As mentioned, the system is limited to addressing typical building features.

The generic pool of objects described in Section 6.3.1 is used to produce specific systems, subsystems, and components. Figures 6.11 and 6.12 present a partial view of the generic building systems, subsystems, and components represented in the prototype. The attributes of one of these systems, namely the Structural-Frame system, are displayed in Figure 6.13 The information they contain is used to further subdivide the Structural-Frame system into subsystems (Floor-Structure and Roof-Structure).

Figure 6.14 shows some of the attributes of the generic component Concr-Deck. The supported-by slot, for instance, contains information that will be decoded by the system to identify the gravity support of each specific concrete deck replicated from this component, as explained in Appendix C, Part 1.

At this point the system is ready to begin a new scheduling session. The prototype prompts the user for information destined to identify specific building systems, subsystems, and components. Components are associated with work areas, therefore information is required to determine the number of floors above and below ground. Figure 6.15 shows that for this particular building there are 6 floors above ground and one basement. Through a series of menus, like the one illustrated in Figure 6.16, the user describes building characteristics. In this figure, Footing-Foundation is selected as the alternative

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for column foundation. Table 6.6 summarizes the input provided for this demonstration run.

The result of this step is a collection of specific objects (building systems, subsystems, and components) that represent the building under analysis. Figure 6.17 provides a partial view of the specific components posted in the Context. The presence of components associated with the different levels is apparent. Figure 6.18 shows a specific component replicated from the Concr-Deck generic component displayed in Figure 6.14. Concr-Deck-Level-4 is supported-by another specific component, Metal-Deck-Level-4.

6.5.2 Identification and Sequencing

Once the prototype has determined the objects that compose the building, it is ready to identify activities that install or remove these objects. This activity identification action is triggered by a user query, as displayed in Figure 6.19. The result of this process consists of a three-level activity breakdown. The top-level activity, called Building-Construction, is decomposed into several second-level activities, as seen in Figure 6.20. Third-level activities, partially viewed in Figure 6.21, install or remove components. These detailed activities are also called CPM-activities.

Figures 6.22 and 6.23 illustrate the activity sequencing results with two examples. The first example shows that Column-Footing-Installation precedes Steel-Erection-Tier-1 and Slab-on-Grade-Installation. These precedence links are justified because the Concr-Column-Footing supports the Structural-Steel-Tier-1, and the Concr-Slab-on-Grade covers the Concr-Column-Footing. The second example has the Cast-Concr-Deck-Level-4 activity preceded by the Metal-Deck-Installation-Level-4. This is justified by the fact that the Metal-Deck-Level-4 supports and is covered by its corresponding concrete deck. If a redundant precedence link is detected, the prototype deletes it. The associated justification is preserved.

6.5.3 Preliminary Activity Durations

The user triggers the preliminary activity duration estimation process by executing the method Pre-Determine-Durations, attached to Building-Construction (Figure 6 24). Information about approximate quantities and sizes is requested from the user, as shown in Figure 6.25. Table 6.6 contains a summary of all the input provided for the particular building used in this example, including quantity and size information.

6.5.4 Activity-Overlap Dependent Sequencing Constraints

At this point the prototype has all the information needed to perform the forward and backward passes. Once early and late times are calculated, the prototype is in position to apply activity-overlap dependent sequencing constraints. As mentioned, these are constraints that are triggered only if the affected activities overlap in their execution times.

For instance, as illustrated in Figure 6.26, the activities for window installation are performed in parallel for levels 3 to 6. Assuming that a single crew is in charge of window installation, this implies a resource conflict. The user triggers a procedure that detects this conflict and sequences the conflicting activities performing window installation from lower to upper levels. Figures 6.27 and 6.28 respectively show the triggering of the procedure and the resulting conflict resolution sequence.

6.5.5 Network and Barchart Output

Figures 6.29-31 show the main result communication options offered by the prototype. Figure 6.29 displays part of the network of activities.

In addition to the network displays, the prototype also provides barchart graphs (Figures 6.30 and 6.31). As can be observed in Figure 6.30, there is the option of displaying summarized schedule information for the second-level activities. If desired, the user can request barcharts to display the CPM-activities included in any of the second-level activities. Figure 6.31 shows the activities pertaining to Site Preparation and Foundation Work.

The schedule template produced by the prototype results in a total duration of 32 weeks. This duration does not consider weather delays, mobilization, cleanup, punch list nor demobilization.

Table 6.1. General Building Size Prototype Input and Utilization for Preliminary Duration Computation.

REQUESTED INPUT	UNIT	UTILIZATION
1. Site area to be cleared	acres	Determine clearing activity duration (2 acres per week) (1)
2. If building demolition involved, amount (volume) of demolition	cu-ft	Determine building demolition duration (75,000 cu-ft per week) (1)
3. If pavement demolition involved, amount (area) of demolition	sq-ft	Determine pavement demolition duration (13,500 sq-ft per week) (1)
4. Number of floors above ground	floor	Determine work areas for floor repetitive activities
5. Number of floors below ground	floor	a. Determine work areas for floor repetitive activities b. Determine depth of excavation (assumed floor height for each underground floor = 10 ft)
6. Building footprint area	sq-ft	Determine area of excavation. With 5., determination of duration of excavation (3,200 cu-yd per week) (1)
7. Building footprint perimeter	lin-ft	Determine perimeter of excavation. With 5., determination of duration of foundation perimeter wall installation (125 cu-yd per week)(1)
8. Area of typical floor	sq-ft	Confirm range for validity of assumption '1 floor=1 work area'
9. Density of floor partitioning	one of: low, high	Determine duration of typical floor finishing. If 'low', duration = 5 weeks per floor If 'high', duration = 7 weeks per floor (2)

(1) Utilized crew sizes and productivity rates are adapted from [Means 89].
(2) Values obtained from interviews with construction schedulers.

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Table 6.2. CPM-Activity Precedence Describing Slots.

SLOT	DESCRIPTION
Preceded-by	List of activities that immediately precede present activity
Precedes	List of activities immediately preceded by present activity. Automatically updated whenever the precedes slot is modified, via an active value attached to the preceded-by slot.
All-pred-propagated	Flag that is turned to 't when all predecessors have propagated their early times to the activity (forward pass)
All-succ-propagated	Flag that is turned to 't when all successors have propagated their late times to the activity (backward pass)

Table 6.3. Summary of Currently Implemented Activity-overlap Independent Sequencing Constraints.

CONSTRAINT	RECIPROCAL CONSTRAINT	CLARIFYING COMMENTS
Covered-by	Covers	In the prototype, for removing activities implies opposite sequence (if something to be removed is covered by an object, first remove the covering object).
Damaged-by Installation	Installation-Damages	
Embedded-in	Embeds	Represents the 'Embedded-in contributing to structural function', described in Section 5.1.1.
Provides-Service-to	Provided-Service-by	This can be extended to cover Code Regulations when one component provides safety to the installation of another.
Supported-by	Supports	In the prototype, for removing activities implies opposite sequence (if something to be removed supports another object, first remove the supported object).
Weather-Protected-by	Weather-Protects	
Yields-Construction-Space	Operational-Space	This is used when one component delivers the space required for the installation of another.

Table 6.4. Overview of Attached Methods for CPM Calculations.

OBJECTS	CPM ATTACHED PROCEDURES DESCRIPTION
CPM-Activities (third-level activities)	1. Forward propagation of Early Times to successors (Forward Pass) 2. Backward propagation of Late Times to predecessors (Backward Pass) 3. Detection of 'Ready-to-Propagate-Forward' status 4. Detection of 'Ready-to-Propagate-Backward' status 5. Computation of float
First and Second Level Activitites	1. Computation of Start/Finish Times and Duration based on Hammocking of third level activities

Table 6.5. Operations Performed by the Prototype for a Scheduling Session.

OPERATION	MAJOR CHARACTERISTICS
Identification of specific building components	Uses: (1) knowledge about building systems, sub-systems and components; and (2) input from user.
Activity identification and sequencing	Associates activities to each installable and removable component. Establishes sequence with rules listed in Appendix A6. Performs redundancy check.
Preliminary activity duration determination	User inputs general building size data, which used by the prototype to produce default activity durations, as shown in Table 6.1.
Applying activity-overlap dependent sequencing	Limited detection of conflicts (crew competition) among activities. Resolution of conflict by addition of precedence links.
Schedule output display	Limited network display. Barcharts of second-level and third-level activities.

Table 6.6. Building Information Input for the Demonstration Run.

PROJECT CHARACTERISTIC	VALUE
Levels above ground	6
Levels below ground	1
Location energy supply equipment	basement level
Location cooling equipment	roof
Location heating equipment	equipment penthouse
Demolition	150,000 cuft
Column Foundation alternative	Footings
Structural Frame alternative	Steel Frame
Steel tier length	2 stories each
Steel sprayed fireproofing	Required
Roof alternative	Built-up roof
Enclosure alternative	Masonry walls and windows
Site area to be cleaned	2 acres
Typical floor area (same as footprint area)	15,600 sqft
Footprint perimeter	500 ft
Frame Erection progression pace	1 floor per week (same as default)
Qualitative degree of typical floor partitioning	moderately partitioned

KNOWLEDGE-BASE

| Building Systems Knowledge Module (Refer to Figs. 6.2, 6.3, 6.4) | Activity Identification and Activity Duration Pre-Determination Knowledge Module (Refer to Fig. 6.7) | Activity Sequencing Knowledge Module (Refer to Figs. 6.8, 6.9, 6.10) |

CONTEXT

(BLACKBOARD for Current Schedule Information Posting and Retrieval)
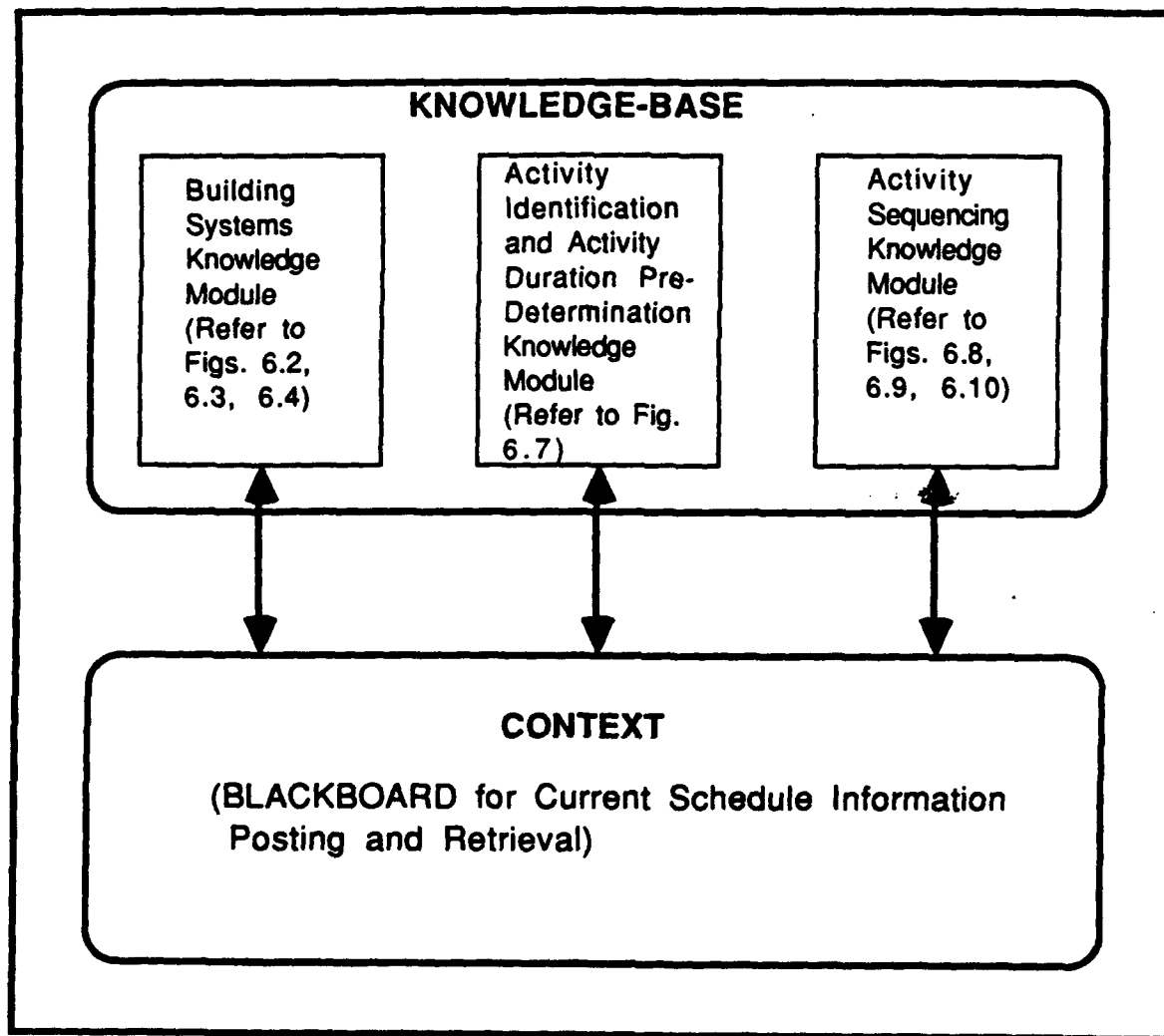
Figure 6.1. Prototype's Blackboard Architecture.
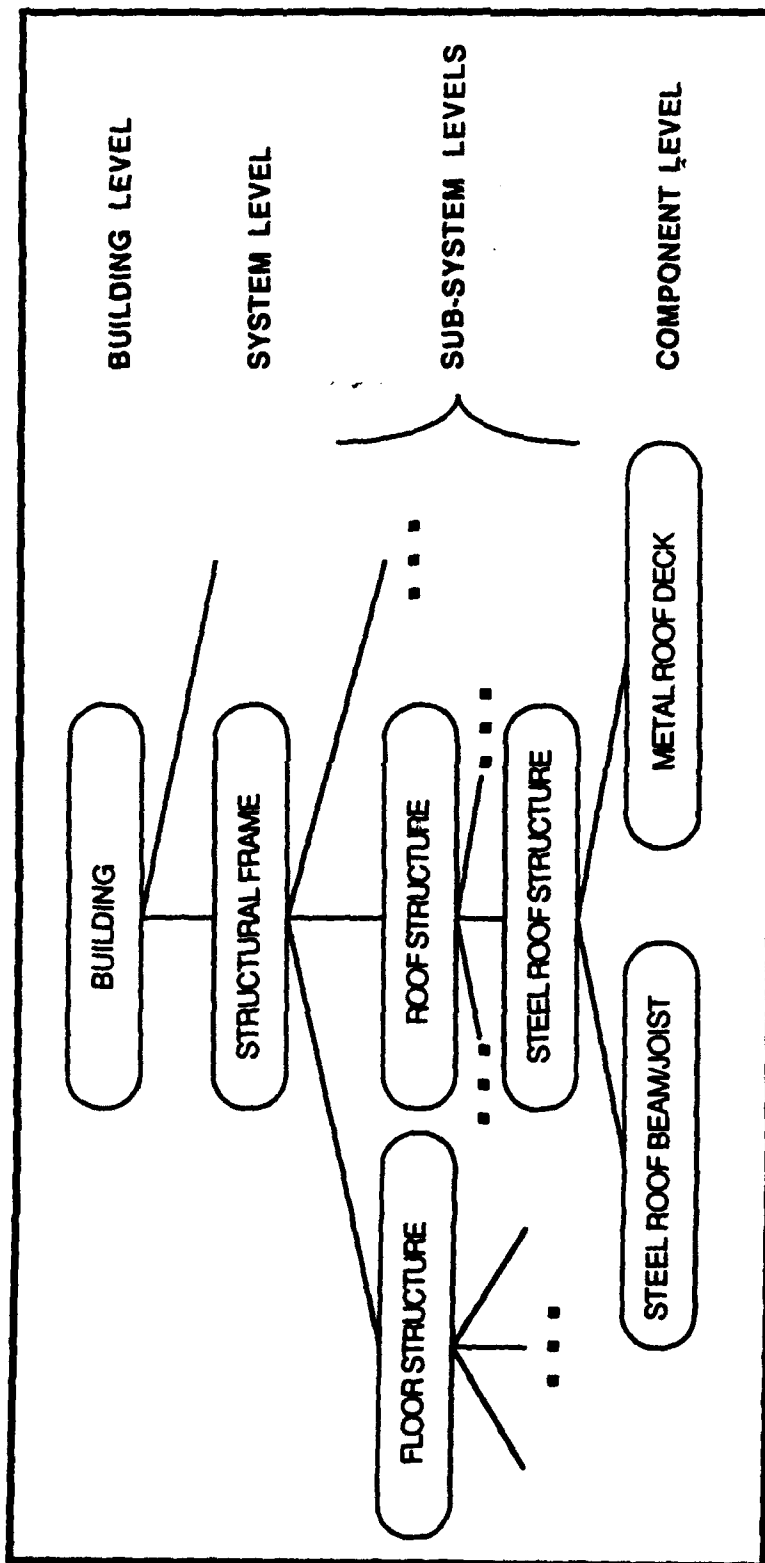
Figure 6.2. Example of System, Sub-systems and Components.
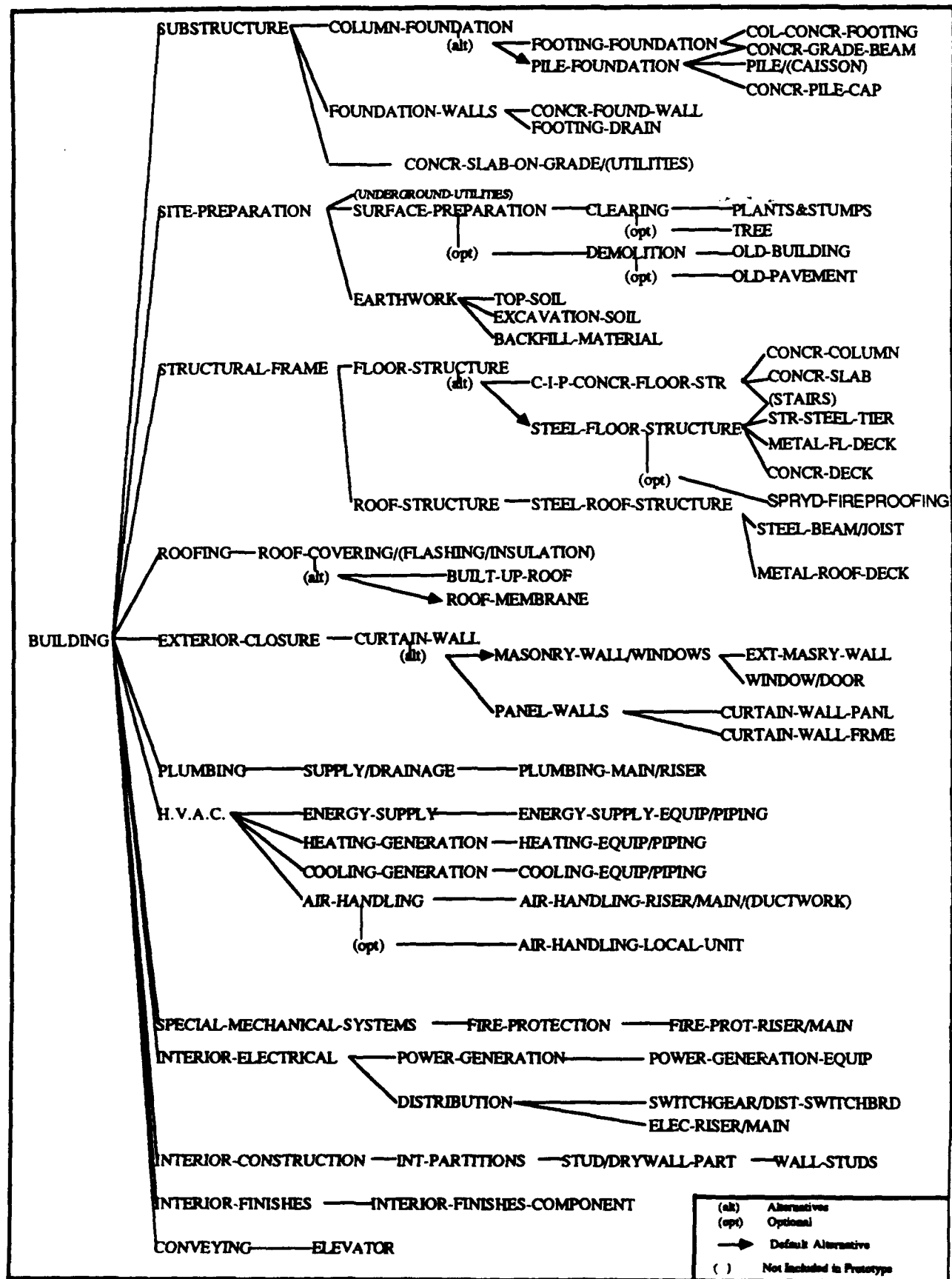
Figure 6.3. Overview of Systems, Sub-systems and Components.

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CONCR-COLUMN-FOOTING [1]

Belongs-to-class: Installable-Component

Approx-location: Excavated-Footprint

Covered-by: Concr-Slab-on-Grade

Installed-by: Column-Footing-Installation

Is-part-of: Footing-Foundation

Oper-space: Excavated-Footprint [2]

Supports: (Initial tier Structural-Steel) (Initial level Concr-Columns)

EXCAVATION-SOIL [1]

Belongs-to-class: Removable-Component

Approx-location: Cleared-Footprint

Covered-by: Top-Soil

Is-part-of: Earthwork

Oper-space: Cleared-Footprint

Removed-by: Mass-Excavation

Supports: (Old-Building Old-Pavement Top-Soil)

(1) Only attributes with non null values are shown.
(2) Although the current prototype version does not have here the oper-space "Cleared-Site", where the crane might be located, this slot can have multiple values and therefore the two oper-spaces can be represented.

Figure 6.4. Example of Installable and Removable Components.

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CONCR-COLUMN-FOOTING [1]

Belongs-to-class: Installable-
Component

Approx-location: Excavated-
Footprint

Covered-by: Concr-Slab-on-Grade

Installed-by: Column-Footing-
Installation

Is-part-of: Footing-Foundation

Oper-space: Excavated-Footprint [2]

Supports: (Initial tier Structural-
Steel) (Initial level
Concr-Columns)

EXCAVATION-SOIL [1]

Belongs-to-class: Removable-
Component

Approx-location: Cleared-
Footprint

Covered-by: Top-Soil

Is-part-of: Earthwork

Oper-space: Cleared-Footprint

Removed-by: Mass-Excavation

Supports: (Old-Building Old-
Pavement Top-Soil)

(1) Only attributes with non null values are shown.
(2) Although the current prototype version does not have here the oper-space "Cleared-Site", where the crane
might be located, this slot can have multiple values and therefore the two oper-spaces can be represented.

Figure 6.4. Example of Installable and Removable Components.

Figure 6.6. Example of Expansion of Structural Frame System for a 6-Story Building.
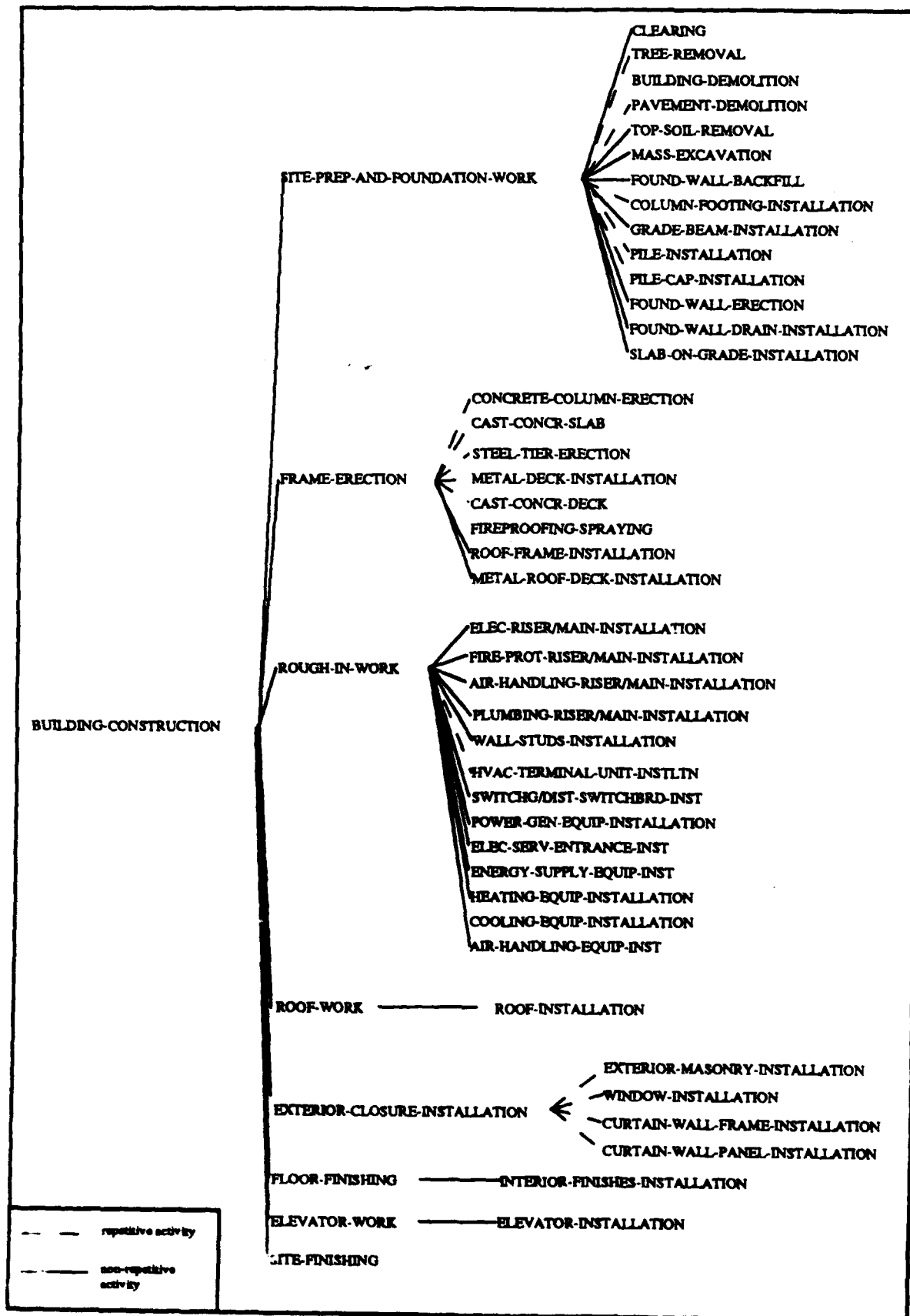
Figure 6.7. Activity Breakdown.

Supported-by Precedence-Deducing Rule for Installing Activities

EXTERNAL FORM:

```
(IF (?ACTIVITY-X IS IN CLASS INSTALL-ACTIVITY)
     (THE INSTALLS OF ?ACTIVITY-X IS ?COMPONENT-X)
     (THE SUPPORTED-BY OF ?COMPONENT-X IS ?COMPONENT-Y)
     (?ACTIVITY-Y IS IN CLASS INSTALL-ACTIVITY)
     (THE INSTALLS OF ?ACTIVITY-Y IS ?COMPONENT-Y))

 (THEN (THE PRECEDED-BY OF ?ACTIVITY-X IS ?ACTIVITY-Y)
       (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY-X IS
           (SUPPORTS ?COMPONENT-Y ?COMPONENT-X))
       (THE PRECEDES-JUSTIFICATION OF ?ACTIVITY-Y IS
           (SUPPORTED-BY ?COMPONENT-X ?COMPONENT-Y))))
```

Figure 6.8. Example of Sequencing Rule.

STEEL-ERECTION-TIER-1

INSTALLS: Structural-Steel-Tier-1

PRECEDED-BY: Column-Footing-
Installation

PRECEDED-BY-JUSTIFICATION: (supported-
By Structural-Steel-Tier-1 Concr-
Column-Footing)

Example of Successor Representation[1]

COLUMN-FOOTING-INSTALLATION

INSTALLS: Concr-Column-Footing

SUCCEEDED-BY: Steel-Erection-Tier-1

PRECEDES-JUSTIFICATION: (supports
Concr-Column-Footing Structural-Steel-
Tier-1)

Example of Predecessor Representation[1]

(1) Only relevant slots are shown

Figure 6.9. Example of Precedence Relationship Representation.

CASE 1
New Link is redundant
therefore it is eliminated

CASE 2
New Link makes an Existing
Link redundant, which is eliminated

CASE 3
New Link does not create
redundancy

NOTATION: Existing Link
New Link
Eliminated Redundant Link
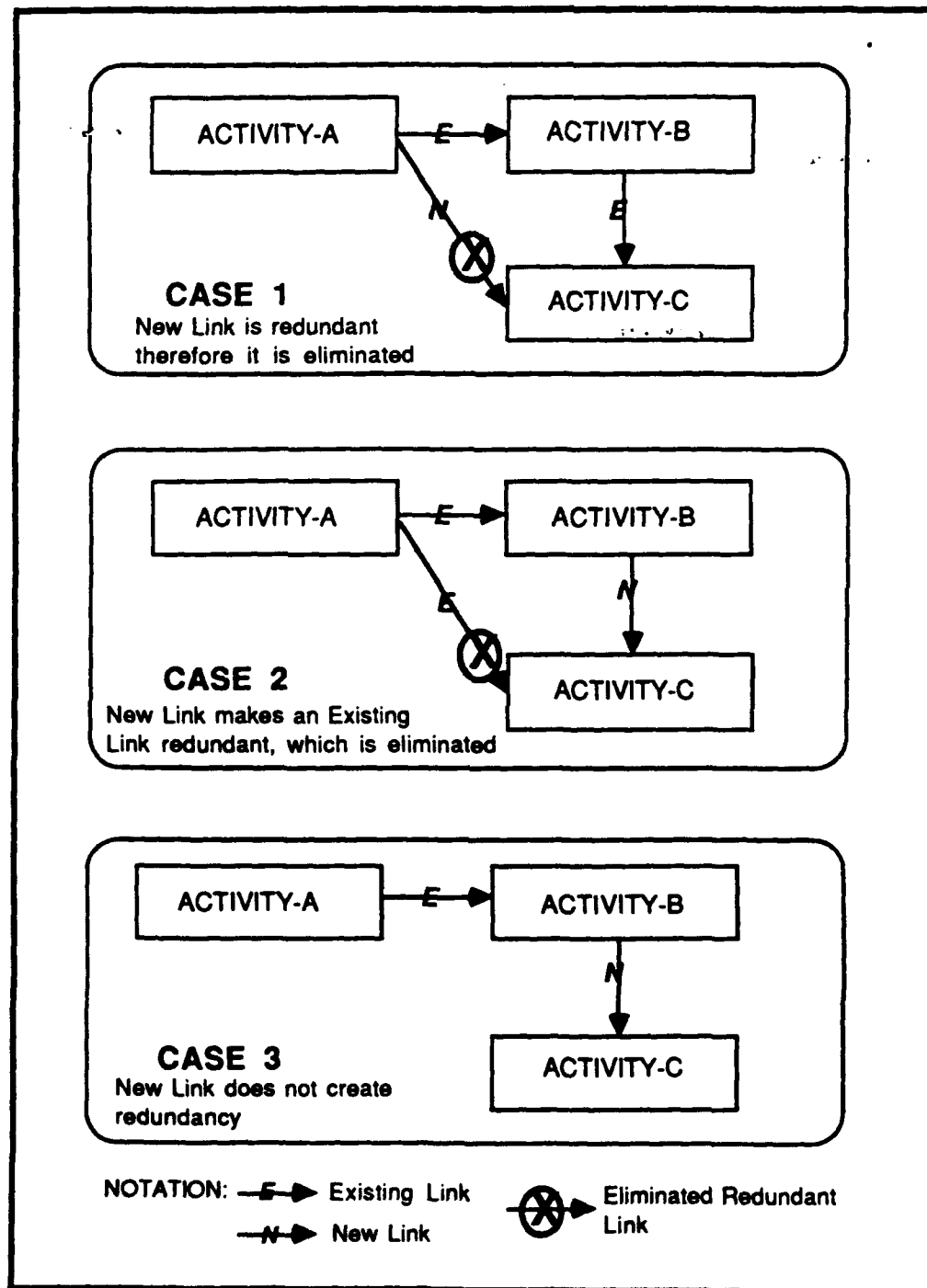
Figure 6.10. Examples of Redundancy Cases.
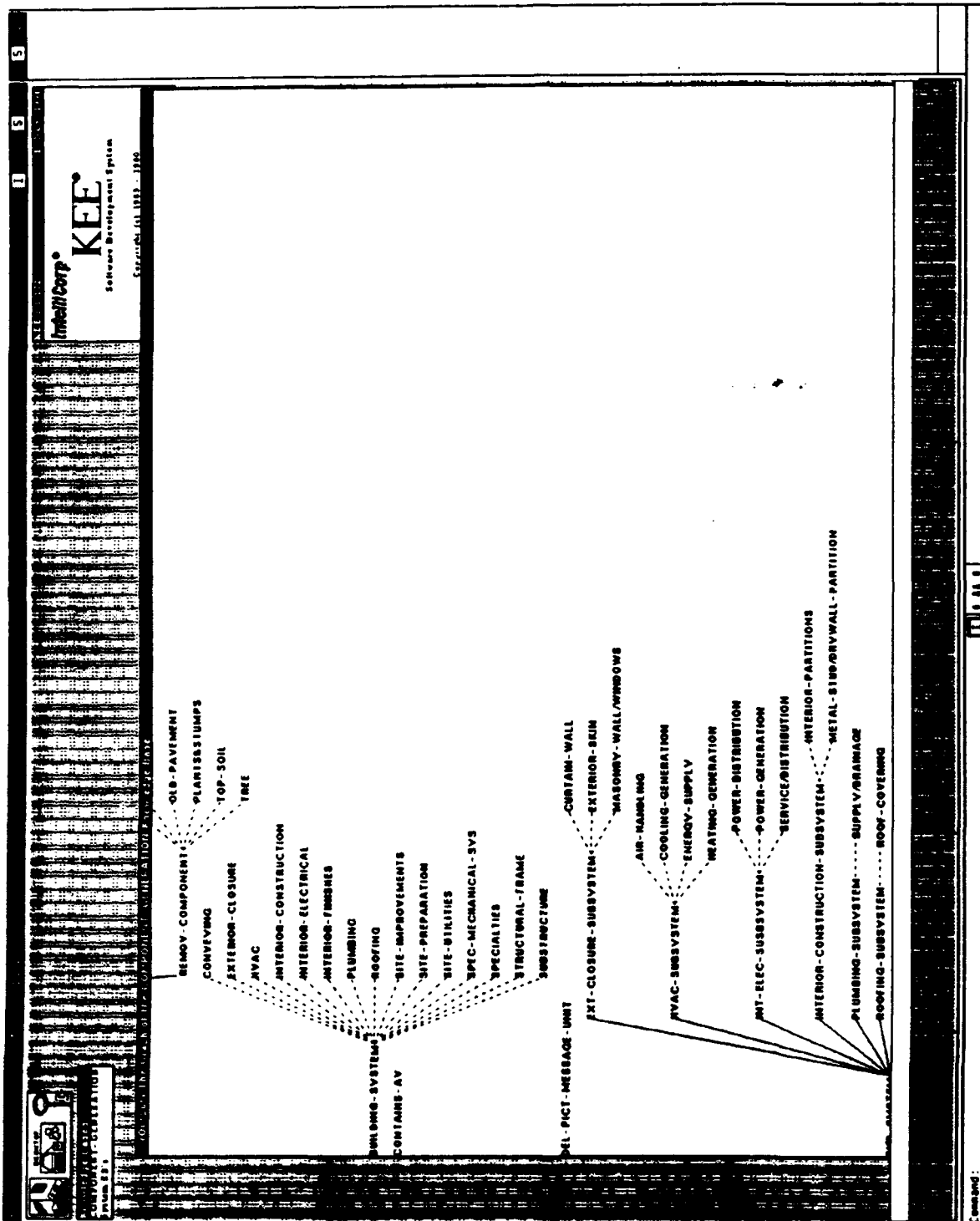
Figure 6.11. Overview of Generic Building Systems.
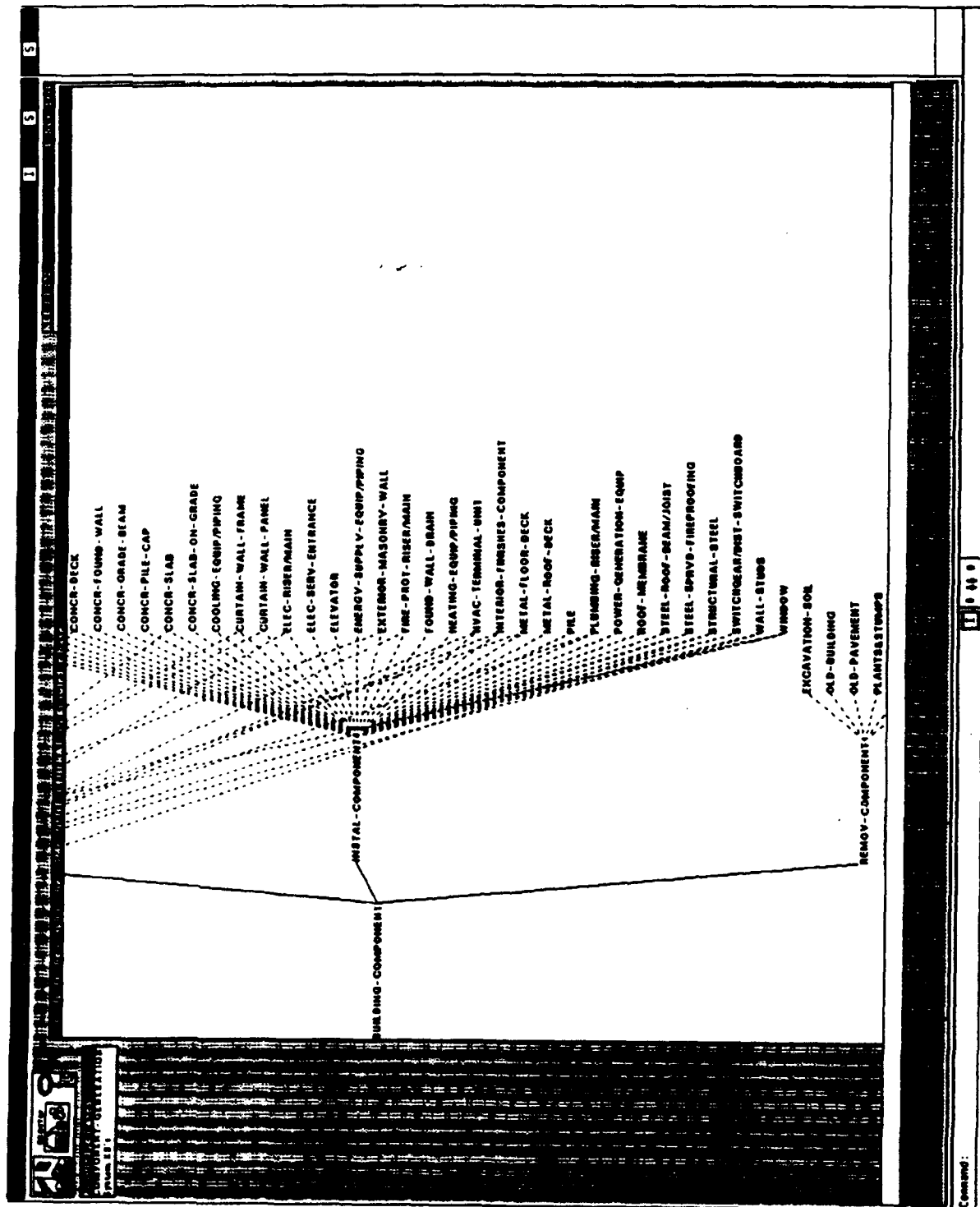
Figure 6.12. Partial Overview of Generic Building Components.
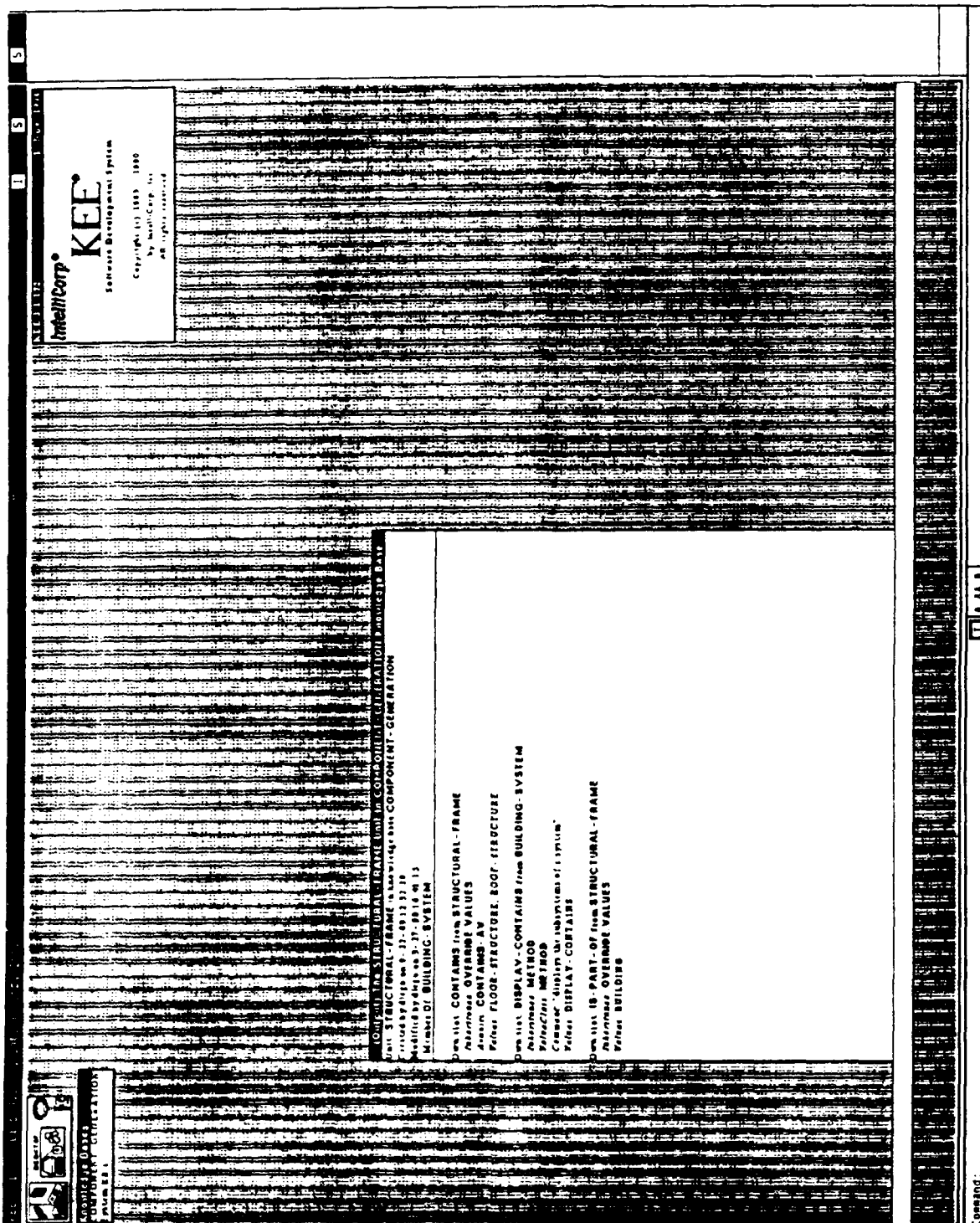
Figure 6.13. Generic Structural Frame System.

Figure 6.14. Generic Concrete Deck Component.
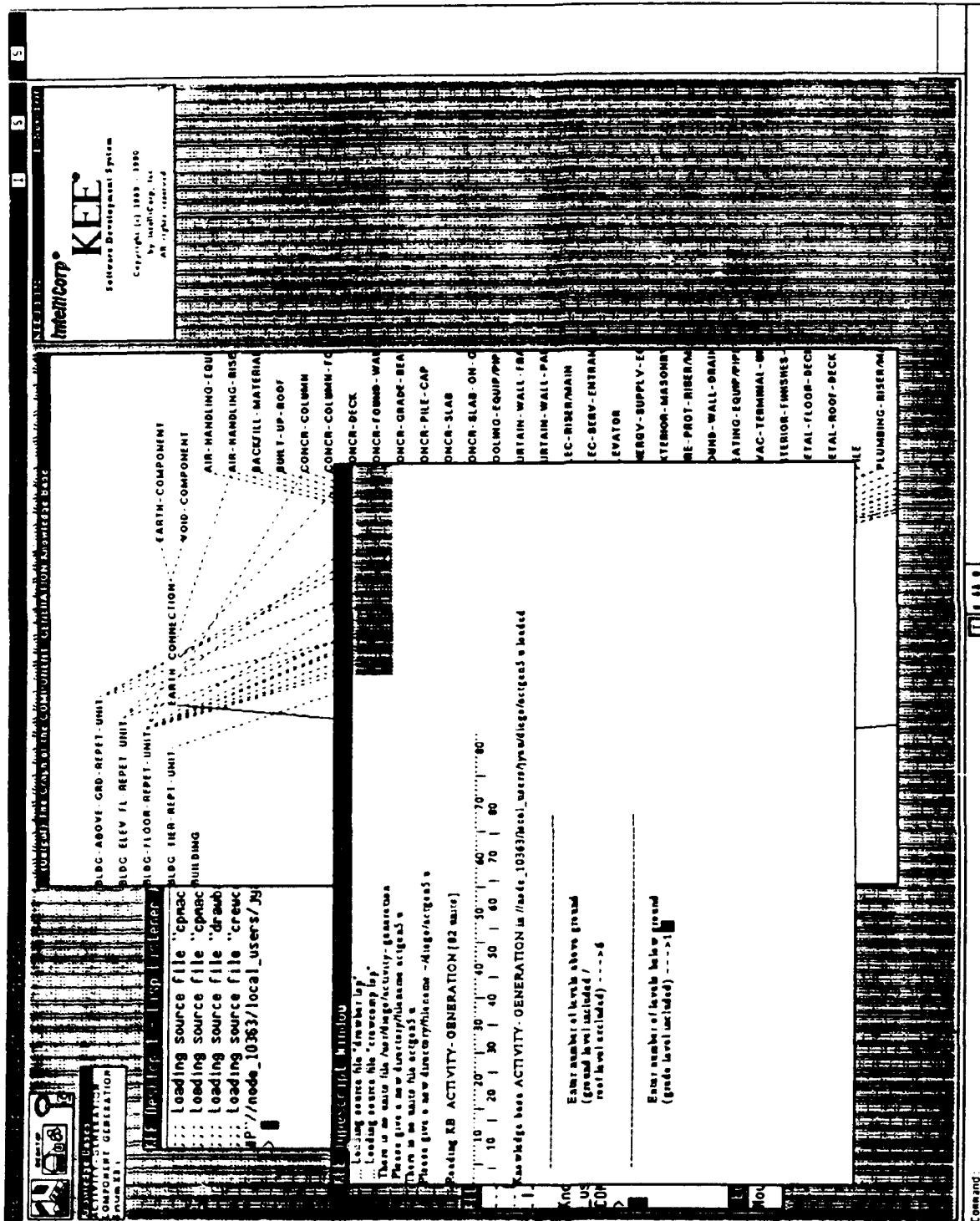
Figure 6.15. Levels Above and Below Ground Input.

Figure 6.16. Foundation Alternative Menu.
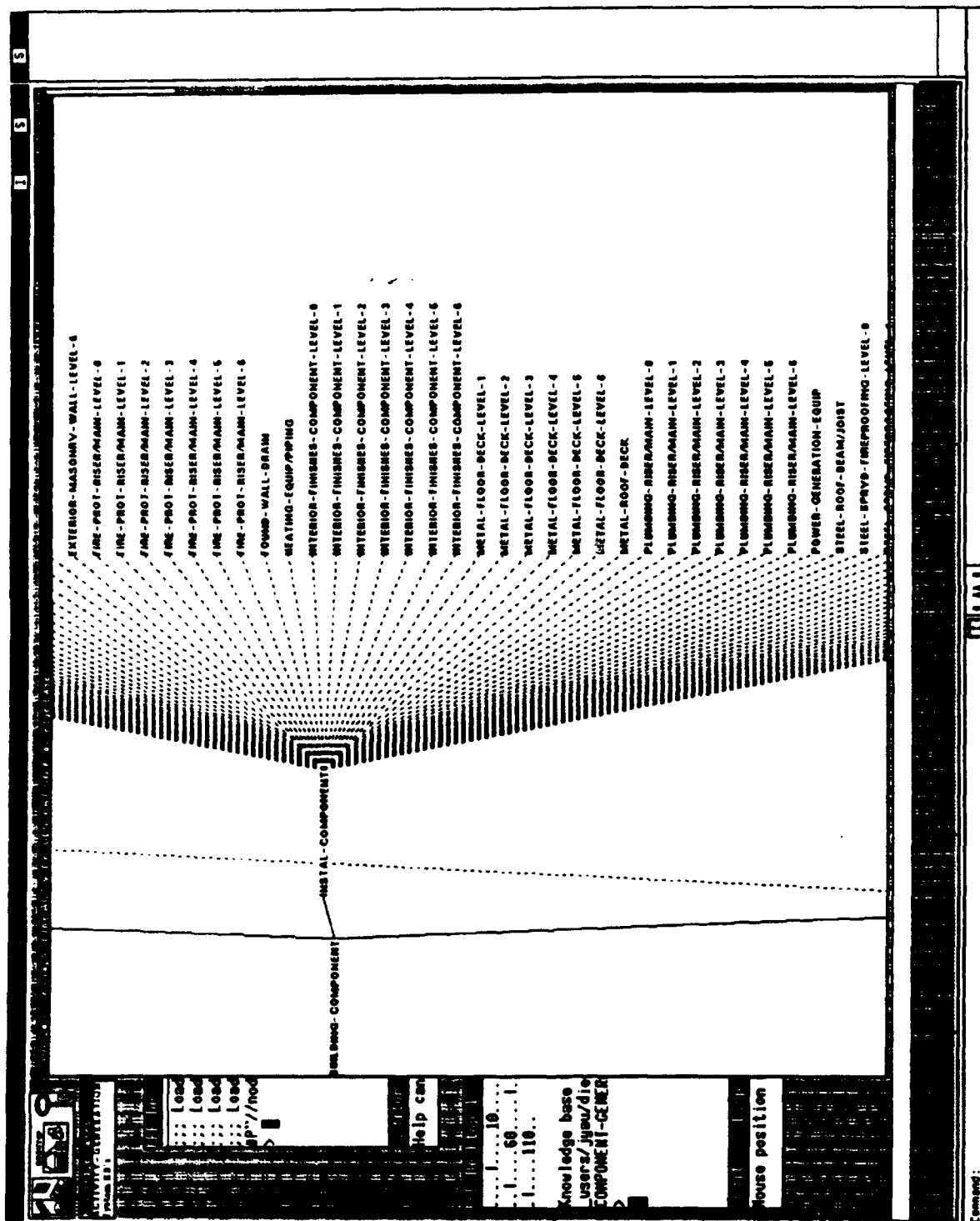
Figure 6.17. Partial Overview of Specific Components.

Figure 6.18. Partial Overview of Specific Component Concr-deck-level-4.

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Figure 6.19. Triggering of Activity Identification and Sequencing Process.
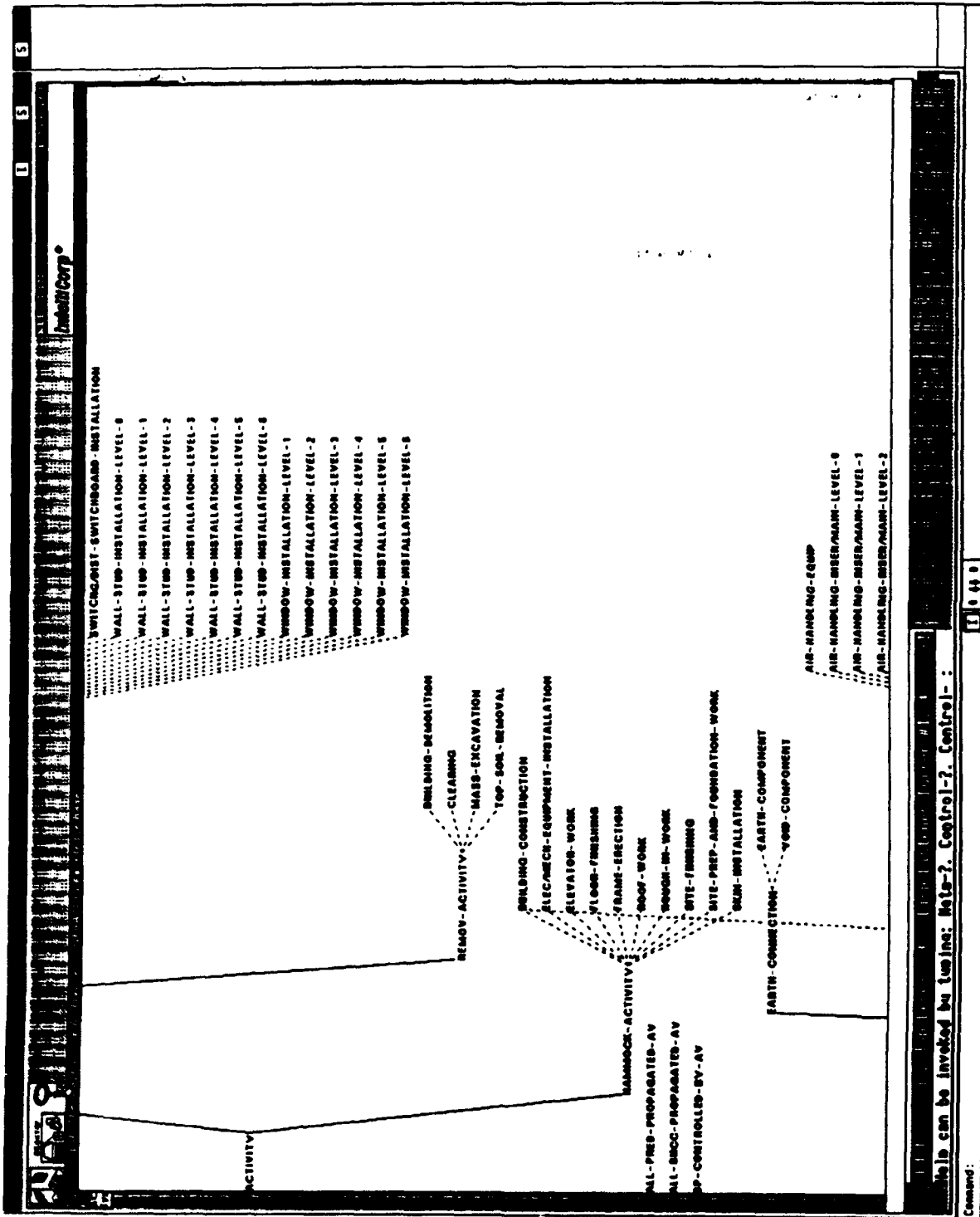
Figure 6.20. Major (Second Level) Activities.
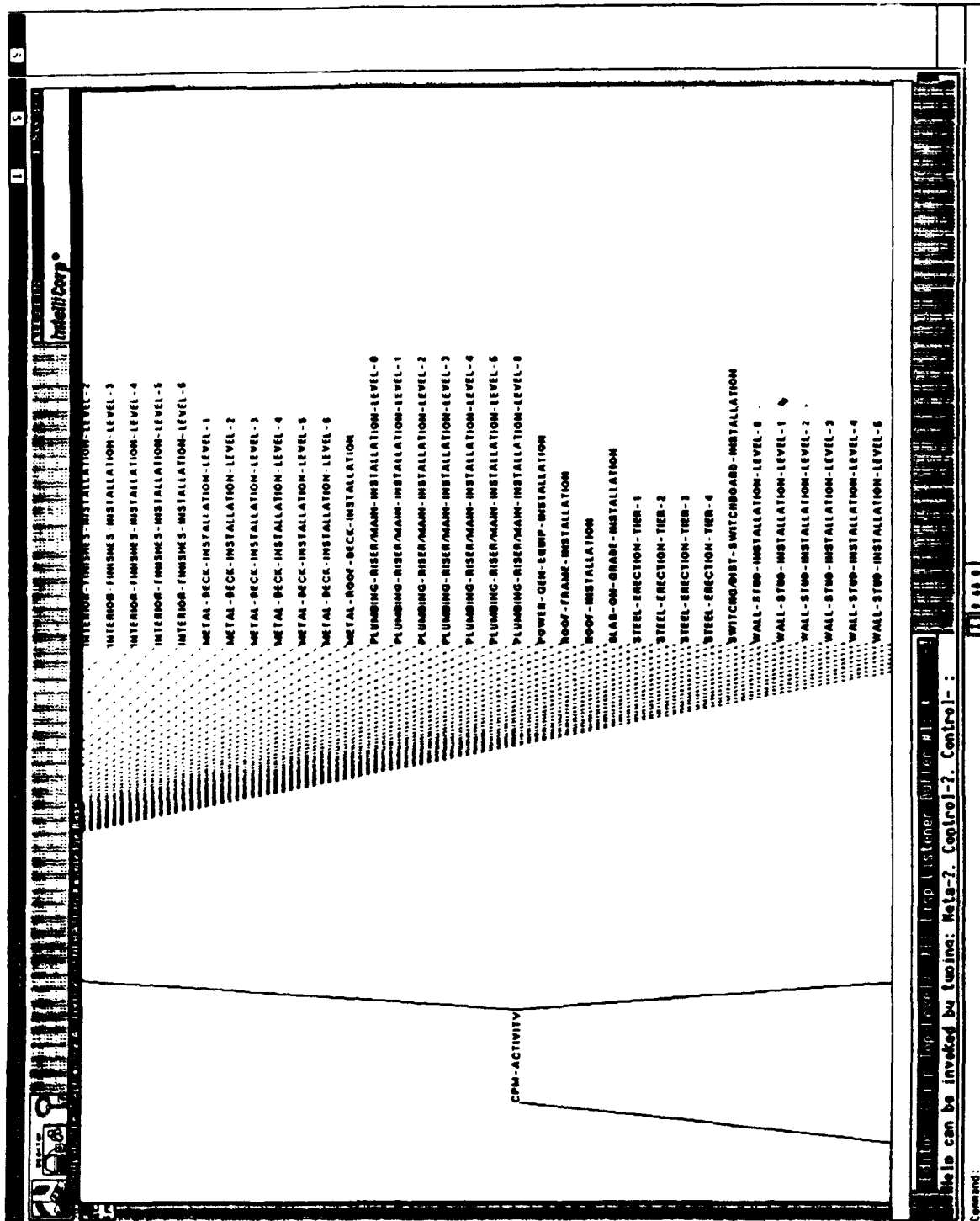
Figure 6.21. Partial Overview of CPM-Activities.

Figure 6.22. Partial Overview of Activity Column-footing-installation.

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Figure 6.23. Partial Overview of Activity Cast-concr-deck-level-4.
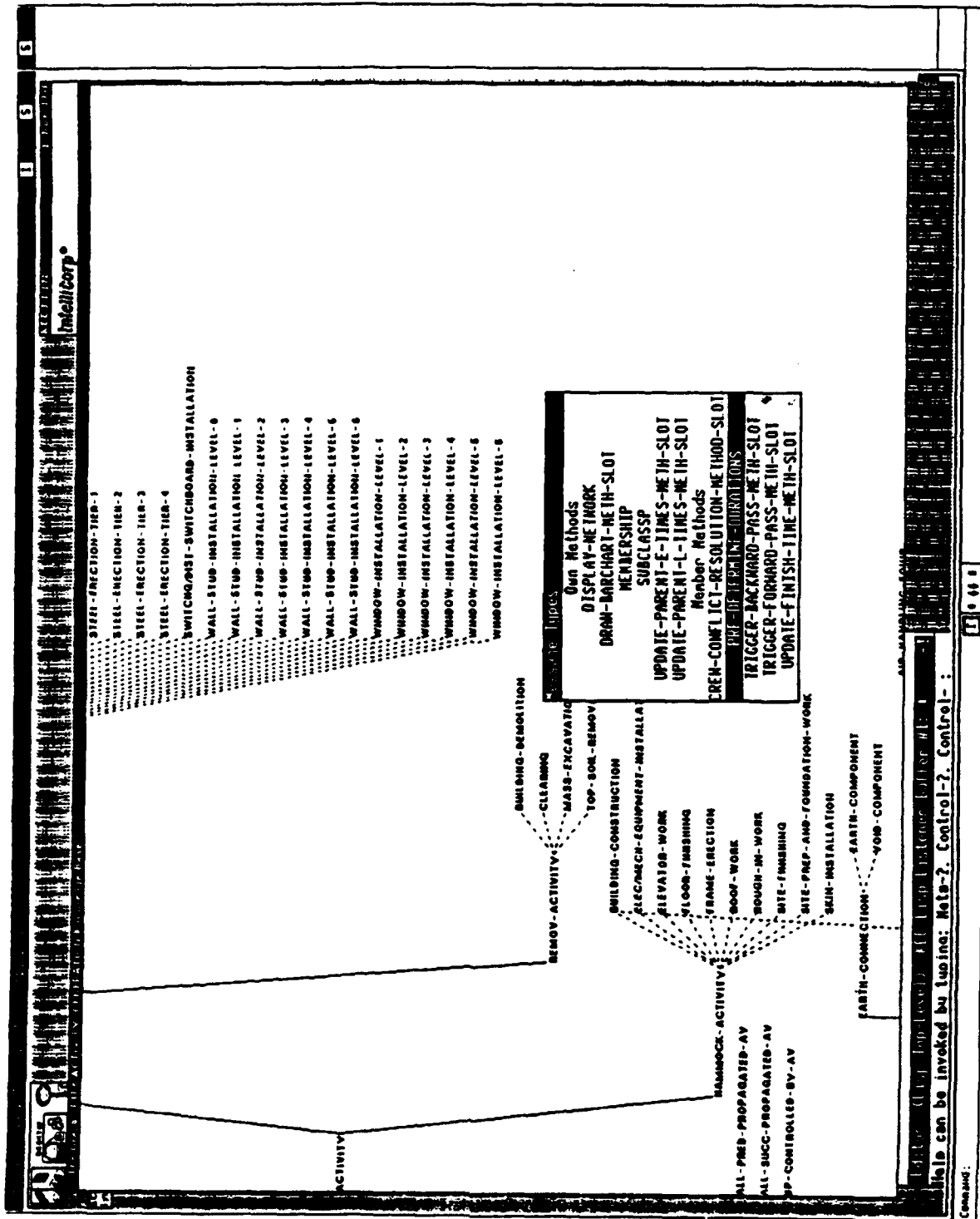
Figure 6.24. Preliminary Duration Estimation Message to "Building-construction".

Figure 6.25. Building Size Information Requested from the User.
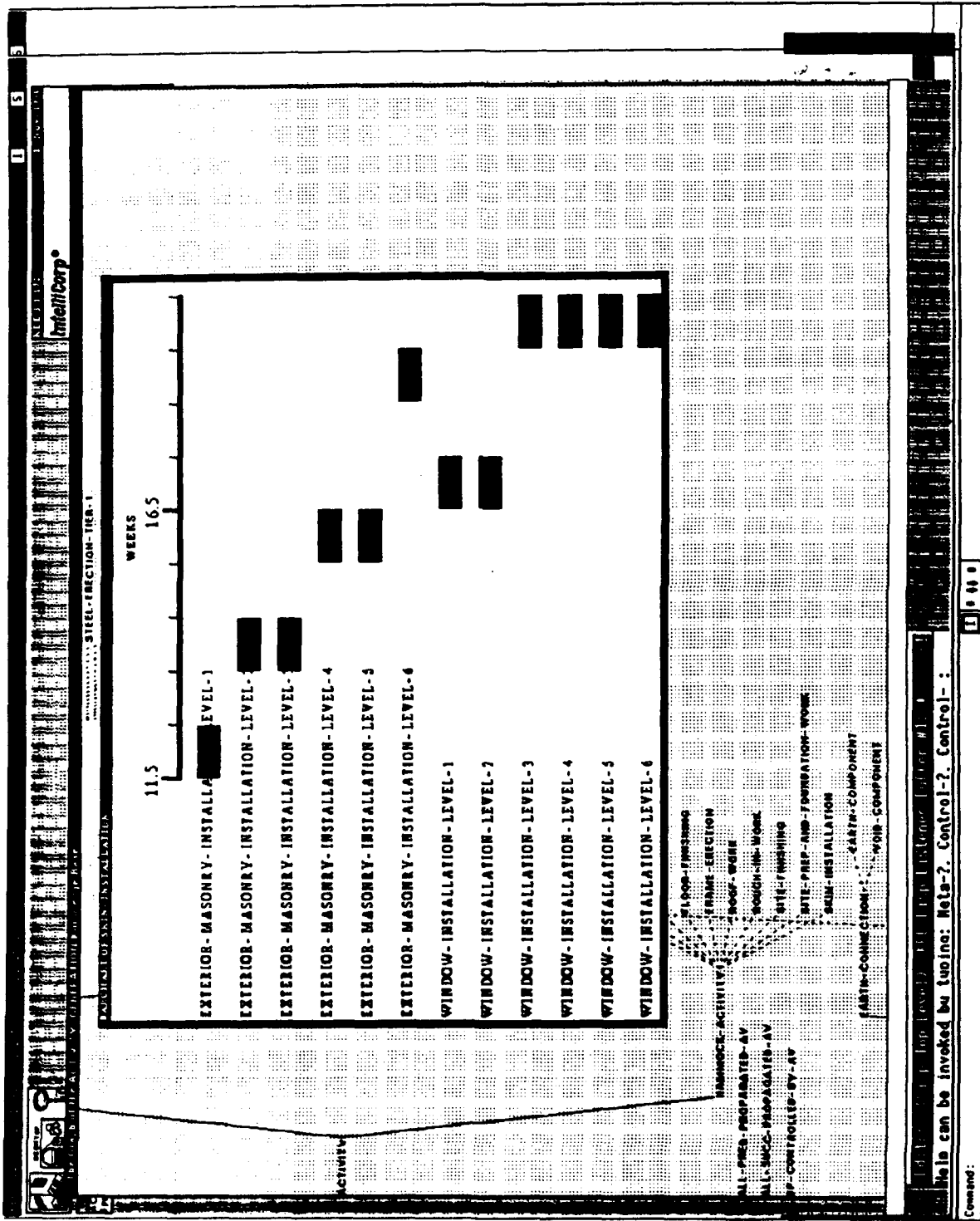
Figure 6.26. Barchart Showing Crew Conflict.

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Figure 6.27. Triggering of Conflict Resolution Process.
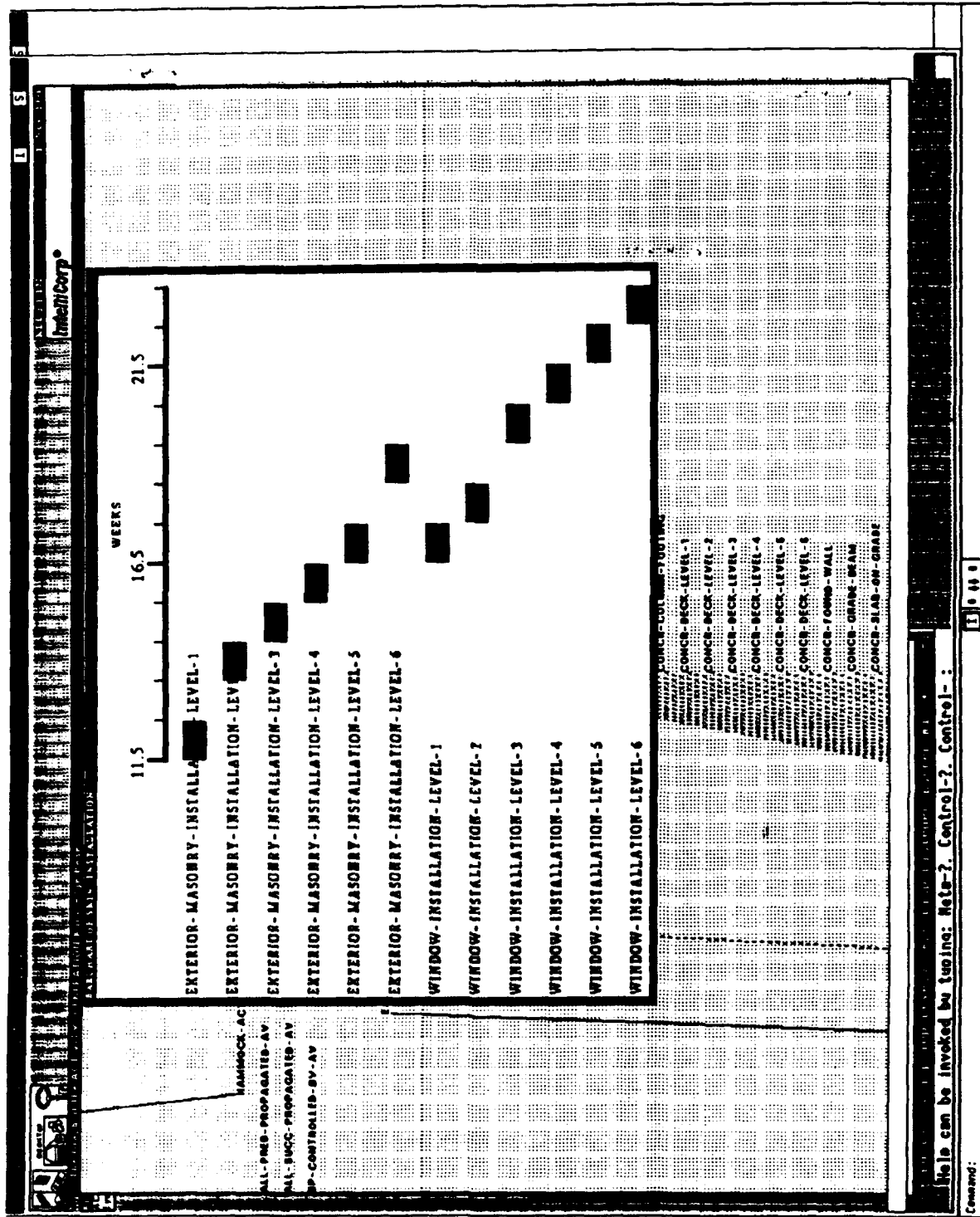
Figure 6.28. Barchart After Conflict Resolution.
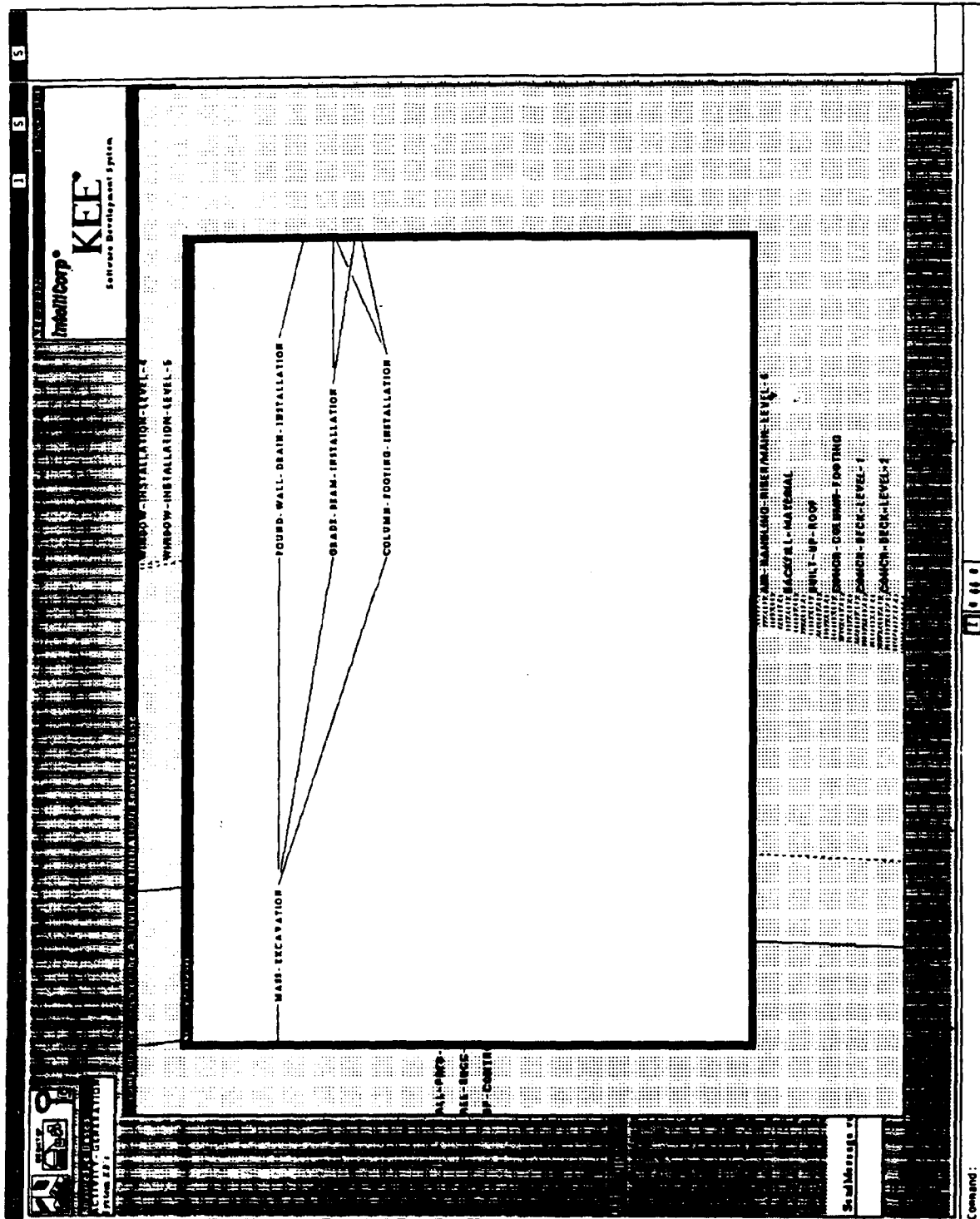
Figure 6.29. Network Close-up.
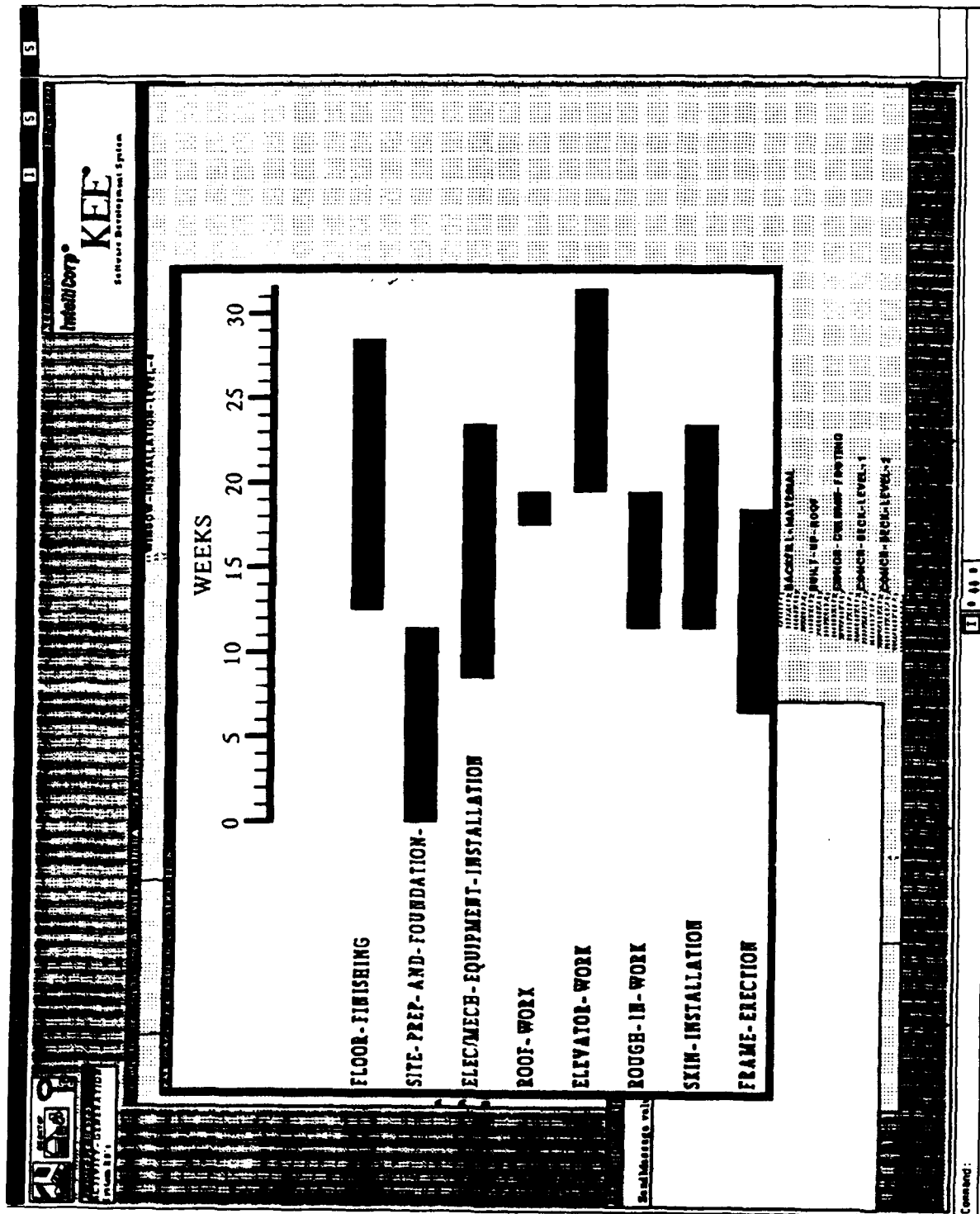
Figure 6.30. Barchart of Major (Second Level) Activities.

Figure 6.31. Barchart of Site Preparation and Foundation Work CPM-Activities.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Concluding Remarks

Two primary contributions of this research effort are the capture of information that experienced schedulers use for scheduling, and the synthesis of that information into a formalized body of building construction scheduling knowledge. Because of the complexity and extent of the knowledge required for successful planning in construction, this effort is only the beginning of a larger necessary effort. However, this work is a step toward assembling a fundamental understanding of construction planning expertise.

This dissertation has also implemented a subset of the formalized body of scheduling knowledge by developing and using a prototype KBS. This prototype is able to produce a schedule template with information about the planned building project provided manually.

Testing and validation of this work confirm the soundness of the approach. However, additional development, validation and testing are necessary to produce a truly complete and practical tool.

7.2 Summary of Main Contributions

7.2.1 Formalization of Scheduling Knowledge

The main contribution of this research effort is the formalization of knowledge for mid-rise residential/office construction scheduling. This was founded on the interviewing of seven experienced schedulers from five different construction companies.

An overall top-down approach for schedule generation was formalized. It addresses: (1) understanding project information, and (2) breaking down the construction process into activities considering the responsibility and work area factors.

The formalized body of knowledge also includes the description of key factors used to determine activity sequencing. One of these factors is the physical relationships among building components. Activity sequencing also responds to the interaction of people, equipment, etc. at the job site. Safety regulations and the requirement of an interference-free path for components and their installation crew also affect the sequencing of activities.

Although the formalization effort did not primarily address activity duration estimation, it did incorporate some knowledge used for determining preliminary activity durations. Rules of thumb were observed and formalized, and found to be helpful for estimating approximate activity durations.

7.2.2 Implementation of a Prototype KBS for Schedule Generation

The Prototype KBS served as an aid to formalize and represent the acquired knowledge. In addition, it demonstrates the feasibility of delivering scheduling knowledge in a way that enables user interaction. In this sense the prototype is a step forward in the process of providing enhanced computer support to the construction scheduler.

To the knowledge of the author this implementation work has been the first to take a comprehensive approach to model the major elements within a construction project that affect the schedule (facility systems, subsystems and components, activities, construction spaces, etc.). Especially relevant is the treatment of the interaction among trades as a factor that constrains sequencing logic.

7.3 Recommendations for Future Work

7.3.1 Expansion of Formalized Body of Scheduling Knowledge

This dissertation advances the formalization of construction scheduling knowledge. However, there are a number of principal areas of scheduling knowledge that have not been addressed by this or other research efforts.

Successful project construction involves a satisfactory balance of quality, cost, and schedule, for all parties involved. More research is necessary to understand the process of adjusting and refining project plans. For instance, a relevant issue is the use of the flexibility of scheduling logic. When and how is it appropriate to change activity sequences, are two of the questions to answer.

Research is also required to study the process of determining activity durations. The relevance of a number of factors should be further explored. For instance, activity duration is related to the crew size and composition. The heuristic approach for crew design should be further investigated.

With few exceptions, such as [De La Garza 88], understanding of the construction scheduling process has centered on the development of initial schedules. Although the generation of valid initial schedules is very important, it also important to monitor and control the schedule execution.

The present work was focused on the study of typical building construction. It is important to extend the knowledge formalization to the experienced scheduler's handling of nontypical building project features.

Furthermore, there is a large variety of construction project types. This research effort concentrated on acquiring scheduling knowledge for mid-rise buildings only. This knowledge acquisition effort should be expanded to cover other construction project types.

7.3.2 Enhancement of Scheduling Support Tools

One of the primary advantages delivered by computers is their ability to support timely and effective communication. This potential should be employed to develop tools that are able to address the schedule information needs of different project participants. For instance, the owner may be interested in the delivery timing of different floors, or the designer in the expected shop drawing approval times. This information should be available from the project schedule.

This work focused on the development of initial construction schedules, but can be extended to cover the construction execution phase, so that the schedule monitoring and control are also supported.

The recording of project schedule information to gain experience for the scheduling of future projects is another area of potential research. The subject of machine learning offers promising

technologies allowing schedule generation systems to gain usable information from a current schedule, applicable to future ones. For example, the area of analogical reasoning compares new problems with a set of known problems for which solutions are known. The solution to the problem closest to the problem on hand is transformed to develop a viable solution for the new problem [Carbonell 82]. This offers the possibility of generating construction schedules (or parts of them) based on records of previously and successfully used schedules.

7.3.3 Tool Integration

There is a consensus in the research community that there is a need to integrate the supporting tools used in facility production, from early design through construction and operation [Howard 89], [Wilson 87]. This integration should be a factor in counterbalancing the detrimental communication obstacles due to the fragmentation of the construction industry.

One area that needs further development is the electronic communication of design information to schedule generation tools. At present a human interface is necessary between computer-assisted design (CAD) tools and computer assisted construction planning tools (i.e., scheduling, cost estimating). The construction planning task could be facilitated by a direct, electronic communication of CAD represented design to construction planning tools. There are two basic approaches to foster this integration: (1) develop CAD systems that allow the representation of design objects (or components) and their attributes, like materials, etc., or (2) develop smarter construction planning tools that through feature recognition are able to identify design objects within CAD files. Ground-breaking efforts are in process to tackle this issue [Cherneff 88], [Simons 88]. However, much remains to be done.

Another dimension of the integration issue is to allow cost estimating and control tools to tie with schedule generation and control tools. Some research efforts address this [Grobler 88, 89], [Yau 90]. A continuation of these efforts is strongly encouraged.

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APPENDIX A: Overview of Knowledge-Based Systems Technology

Knowledge-Based Systems (KBS) technology is the result of the maturing and evolution of several years of Artificial Intelligence research work. The first operational KBS's were developed in the seventies, with Mycin being a well known, early example [Shortliffe 76]. Mycin was developed as a tool to assist in the diagnosis and treatment of some bacterial infections.

Mycin, Prospector, Xcon and other successful software tools demonstrated the value of the KBS approach in a broad spectrum of disciplines [Shortliffe 76], [Duda 79], [McDermott 80]. The advantage offered by the KBS approach is explained by three main characteristics [Fenves 87]: (1) ability to store factual and heuristic knowledge by utilizing symbolic representation, (2) substantial knowledge updating flexibility, facilitated by a clear separation of the stored knowledge (knowledge-base) and the problem solving control structure (inference engine), and (3) ability to explain followed courses of action, in the solution of a problem.

It is the objective of this research to use newer and more powerful computer tools to support construction scheduling. This support goes beyond providing network representation and CPM calculations. KBS technology is used here to incorporate scheduling expertise and heuristics into the scheduling supporting tool. The following sections provide a brief overview of the different techniques that are used to represent construction scheduling knowledge.

1.   Knowledge Representation Approaches

Two basic knowledge representation approaches have been used in the present work. An overview is presented in the following sections.

1.1   Object-Oriented Representation

This knowledge representation alternative is based on the notion of unit, frame, schema or object (all these terms are used in the literature to label the same concept). An object is an encapsulation of characteristics (attributes, values and behavior) that together describe a unique notion. Figure A.1 illustrates this through an example. An object-oriented representation implies that one can store knowledge in discrete modules. Factual knowledge can be represented as attribute-value pairs of an object. Procedural knowledge, also called here behavior, can be represented in terms of methods. Methods, also called procedures, are pieces of code that are triggered by sending a message to their encapsulating object.

An object-oriented representation also implies the advantage of allowing inheritance to help determine the characteristics of an object. Objects belong to classes from which they can inherit attributes, attribute-values or methods. As shown in Figure A.1, the activity instance "A" inherits from the Activity class all of its attributes and behavior. Values are determined locally.

An object-oriented representation also brings the advantage of modularity. This substantially reduces the knowledge updating/modification effort. The existence of inheritance contributes to a reduction in the knowledge-base development effort. Attributes, attribute-values or methods of a new object can be inherited from a parent class if available, as opposed to re-creating them.

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Another useful feature of an object-oriented environment is the active value concept. An active value consists of an object attribute that constantly monitors its own value. A prespecified reaction is triggered every time that a given action is performed on the attribute value. The prespecified action is defined via an attached procedure. The triggering action can be one of: (1) reading the attribute value, (2) deleting the attribute value, (3) adding a new value to the attribute, and (4) replacing an old attribute value by a new one. Figure A.2 provides an example. In this case an active value is attached to the "preceded-by" slot of an activity. The triggering action consists of the addition of a new value to the "preceded-by" slot, which implies the creation of a precedence link. The reaction in this case is to run a procedure that checks for redundancy of each new precedence link.

1.2 Rule-Based Representation

Rules are typically used to represent heuristics or rules of thumb that are applied to massage known facts to infer new facts. A rule is an expression of the form "IF <premise> is true THEN <consequence> is true". Figure A.3 illustrates this concept with a rule that determines a precedence link given known facts about the components installed by the activities. As can be seen in the example, variables can be present within the antecedent and consequent parts of the rule. This allows the rule to have a more general effect and reduces rule-base development time (one general rule is equivalent to multiple specific rules).

The <premise> and <consequence> are used to match known facts or desired goals of the current problem, depending on the control strategy in use. More detail on control strategies available is provided in Section 2.3 of this appendix.

2. Structure of a Knowledge-Based System

A KBS combines the capability of general purpose symbol-processing tools with specific knowledge about the particular domain (also called topic or area) of the problem being solved. There is in addition a user interface that facilitates a user-system bidirectional communication. The next few paragraphs briefly describe the fundamental parts encompassed by a KBS.

2.1 The Knowledge Base

This is where the domain-specific knowledge acquired from experienced humans is stored. This knowledge can be represented in different ways. The two more broadly used are a rule-based representation and the frame or object representation.

Knowledge can be factual ("piles are an alternative for column foundation," for instance), or procedural ("all construction activities should be logically sequenced"). As can be observed, procedural knowledge involves actions (or rules) that may be useful to massage problem information. An object can be viewed as a collection of facts (attributes with their values describe object facts) and procedures (attached methods).

2.2 The Context

The Context consists of the KBS's working memory. All the information about the current problem (input and inferred) is kept in the Context. All procedural knowledge is applied to massage the information on the Context with the objective of reaching the goal (or problem solution). The Context is used in the present work as the mechanism through which the different modules of the knowledge base communicate information. This mechanism is commonly referred to as Blackboard Architecture, and is discussed in Section 6.2.2, in more detail.

2.3 The Inference Engine

As its name indicates, this KBS component is used to infer or reach the goal requested by the KBS user. It contains domain-independent operators used to manipulate the Context with the domain-specific rules stored in the knowledge-base. These rules are applied with a control strategy that can be goal driven (backward chaining), data driven (forward chaining), or a mix of these two.

The goal driven control strategy attempts to create a chain of rules that links the desired goal backwards to the Context's initial state. The data driven strategy uses the rules to infer all possible new facts from the Context initial state. The inference is stopped whenever the desired goal is reached.

2.4 The User Interface

This KBS component supports effective communication between the KBS and its user. Especially relevant are the functions of: (1) requesting pertinent problem information from the user, (2) providing description of the reached conclusion, and (3) providing support for its course of action in reaching the conclusion (explanation).

3. Steps To Apply a KBS Approach

A KBS approach involves four basic phases or steps. The first phase consists of the knowledge elicitation process. People with extensive experience and ideally highly successful in the domain (or field of application of the KBS) are interviewed. An unstructured set of facts, rules of thumb, etc. is the result of this knowledge elicitation phase.

The next step is to formalize the elicited knowledge, to form a coherent and structured body of knowledge. Then follows the knowledge representation phase which entails the incorporation of the formalized knowledge into a KBS platform. Finally, the KBS is validated and tested using as many cycles as necessary to fine tune its operation.
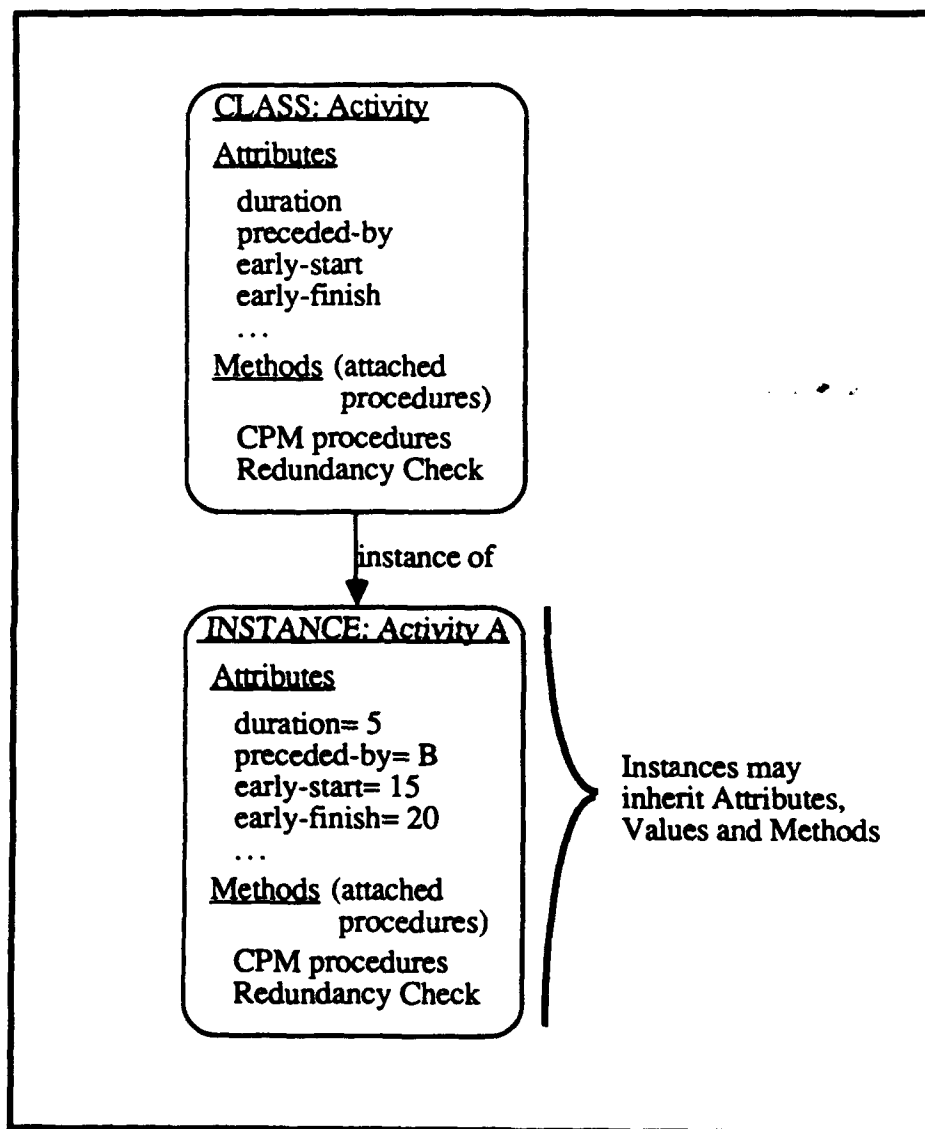
Figure A.1. Example of Main Object Features.
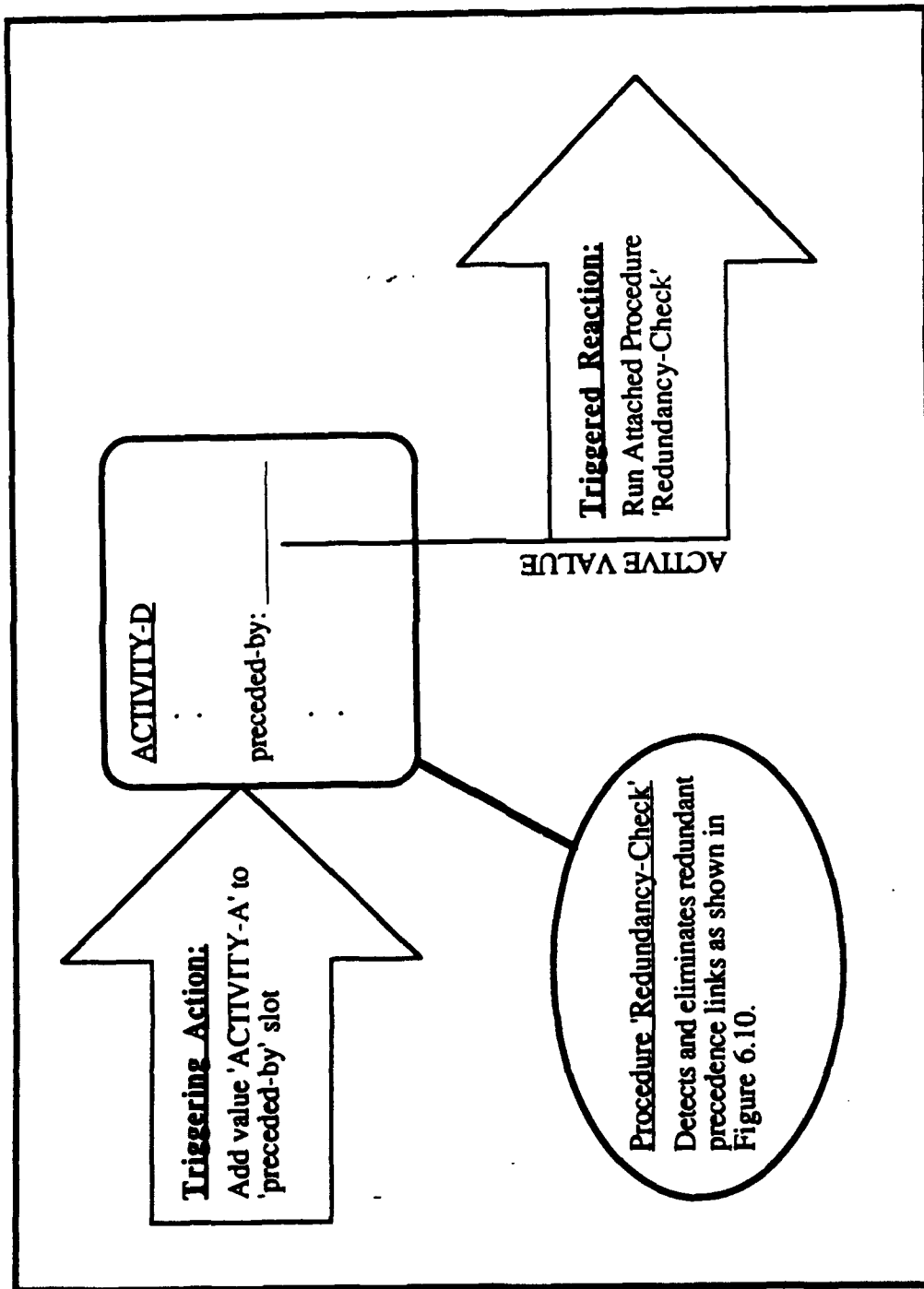
Figure A.2. Example of the Active Value Concept.

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```
  IF
  ?ACTIVITY-AA INSTALLS ?COMPONENT-CA    ⎫
  ?ACTIVITY-AB INSTALLS ?COMPONENT-CB    ⎬  <premise>
  ?COMPONENT-CA SUPPORTS ?COMPONENT-CB   ⎭  (conditions
                                              joined by
                                              implicit "AND")

  THEN

  ?ACTIVITY-AA PRECEDES ?ACTIVITY-AB        <consequence>
```

```
?XYZ = Variable
```
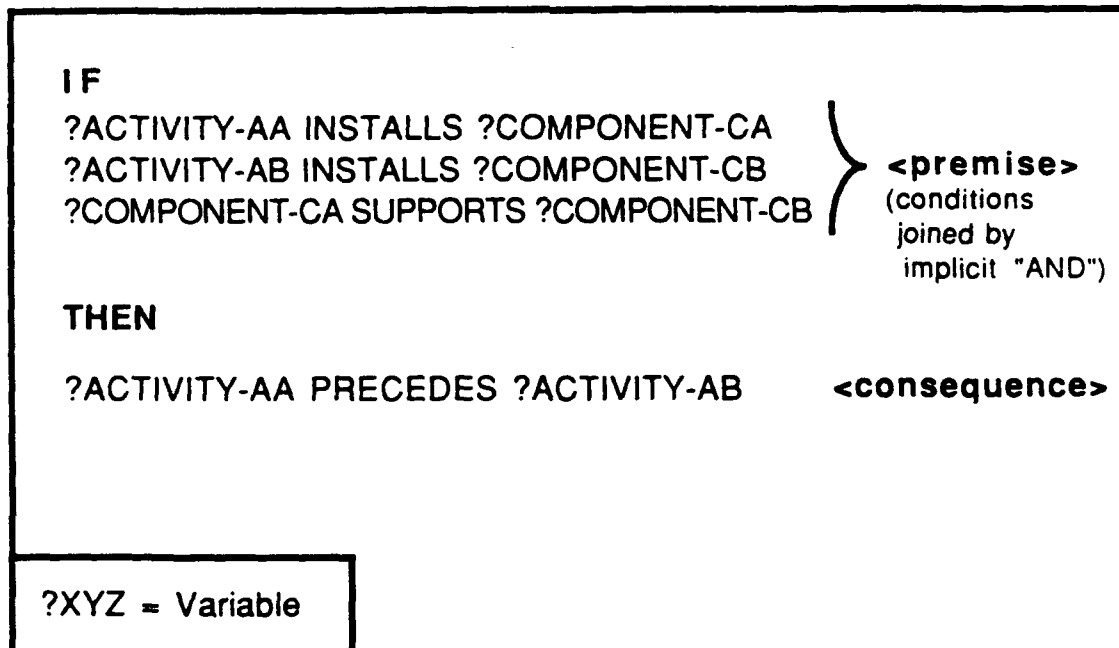
Figure A.3. Main Rule Features.

APPENDIX B: Sequencing Constraints Written With Rule-Like Syntax

This appendix provides a listing of the formalized activity sequencing constraints in an English, rule-like syntax.   Each rule is in the form "IF <PREMISE> THEN <CONSEQUENCE>".   The <PREMISE> consists of a set of facts implicitly joined by an "AND." This means that all of the facts in the <PREMISE> have to be true for the rule to apply.

As discussed in Chapter 5, every sequencing constraint has some degree of flexibility.   This flexibility is here described by utilizing two classifications: (1) very low flexibility (rigid constraints, labeled [R]), (2) common practice, but rather flexible, labeled [CP].

[Gray 86] partially addressed implications of rules 1, 3, 9, 11 and 16.   Other researchers considered only a simplified model of a structure, or part of a structure, or did not generate activities nor sequences.   Therefore, the enhancements of rules 1, 3, 9, 11 and 16 and the formalization of the others are an original contribution of this research.

Each of the constraints listed in this appendix is cross-referenced with its corresponding section in Chapter 5.   This is done by indicating the page number of its corresponding section in parenthesis, after the constraint name.

1.   **CONSTRAINTS ADDRESSING PHYSICAL RELATIONSHIPS AMONG BUILDING COMPONENTS.**

1.1   Supported By (p. 41)

1.1.1   Rule 1

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
      (ACTIVITY-Y INSTALLS COMPONENT-Y)
      (COMPONENT-X SUPPORTS COMPONENT-Y)

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [R]

1.1.2   Rule 2

IF   (ACTIVITY-X REMOVES COMPONENT-X)
      (ACTIVITY-Y REMOVES COMPONENT-Y)
      (COMPONENT-X IS-SUPPORTED-BY COMPONENT-Y)

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [R]

> 1.1.2.1 Commentary to Rule 2: An exception to Rule 2 occurs when the removal of supporting components is desired to promote collapse.

1.2.   Covered By (p. 42)

1.2.1   Rule 3

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
        (ACTIVITY-Y INSTALLS COMPONENT-Y)
        (COMPONENT-Y COVERS COMPONENT-X)

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [R]

1.2.2   Rule 4

IF   (ACTIVITY-X REMOVES COMPONENT-X)
        (ACTIVITY-Y REMOVES COMPONENT-Y)
        (COMPONENT-Y IS COVERED-BY COMPONENT-X)

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [R]

Embedded-in, Contributing to Structural Function (p. 42)

1.2.3   Rule 5

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
        (ACTIVITY-Y INSTALLS COMPONENT-Y)
        (COMPONENT-Y EMBEDS COMPONENT-X)
        (COMPONENT-X CONTRIBUTING-TO-STRUCTURAL-FUNCTION-OF COMPONENT-Y)

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [R]

Commentary to Rule 5: This rule is especially rigid if the contribution to structural function is at installation time. Otherwise there are exceptions, like in the case of post-tensioning reinforcement (for post-tensioned concrete). However, even in this case, the post-tensioning reinforcement is installed prior to the embedding matrix (grout).

1.3   Embedded-in, Non-Contributing to Structural Function (p. 42)

1.3.1   Rule 6

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
        (ACTIVITY-Y INSTALLS COMPONENT-Y)
        (COMPONENT-Y EMBEDS COMPONENT-X)
        (COMPONENT-X   NON-CONTRIBUTING-TO-STRUCTURAL-FUNCTION-OF   COMPO-
        NENT-Y)

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

1.4   Relative Distance to Support (p. 42)

1.4.1   Rule 7

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
      (ACTIVITY-Y INSTALLS COMPONENT-Y)
      (COMPONENT-Z SUPPORTS COMPONENT-X)
      (COMPONENT-Z SUPPORTS COMPONENT-Y)
      (DISTANCE (COMPONENT-X COMPONENT-Z)
       IS-LESS-THAN
       DISTANCE (COMPONENT-Y COMPONENT-Z))

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

1.5   Flexibility of Function (with equivalent distance to support) (p. 42)

1.5.1   Rule 8

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
      (ACTIVITY-Y INSTALLS COMPONENT-Y)
      (COMPONENT-Z SUPPORTS COMPONENT-X)
      (COMPONENT-Z SUPPORTS COMPONENT-Y)
      (DISTANCE (COMPONENT-X COMPONENT-Z)
       IS-EQUIVALENT-TO
       DISTANCE (COMPONENT-Y COMPONENT-Z))
      (POSITION (COMPONENT-X)
       MORE-IMPORTANT-FOR-DESIGNED-FUNCTION-THAN
       POSITION (COMPONENT-Y))

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

1.5.1.1 Commentary to Rule 8: This rule applies when: (1) two components are supported by the same third component, (2) their distance to this supporting component is equivalent, and (3) one of the components has more stringent position requirements in order to adequately perform its designed function (e.g., slope, for pipe drainage, minimization of duct turns, to reduce pressure losses).

1.6   Flexibility of Component Material (with equivalent distance to support and equivalent flexibility of function) (p. 42)

1.6.1   Rule 9

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
      (ACTIVITY-Y INSTALLS COMPONENT-Y)
      (COMPONENT-Z SUPPORTS COMPONENT-X)
      (COMPONENT-Z SUPPORTS COMPONENT-Y)

```
(DISTANCE (COMPONENT-X COMPONENT-Z)
 IS-EQUIVALENT-TO
 DISTANCE (COMPONENT-Y COMPONENT-Z))
(POSITION (COMPONENT-X)
 EQUALLY-IMPORTANT-FOR-DESIGNED-FUNCTION-AS
 POSITION (COMPONENT-Y))
(FLEXIBILITY (COMPONENT-X-MATERIAL)
 IS-LESS-THAN
 FLEXIBILITY (COMPONENT-Y-MATERIAL))
```

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

1.6.1.1 Commentary to Rule 9: Given that all conditions present in the premise of Rule 8 are equivalent for two components, the flexibility of the component materials normally dictates the installation sequence.

1.7   Relative Distance to Access (p.42)

1.7.1   Rule 10

```
IF      (ACTIVITY-X INSTALLS COMPONENT-X)
        (ACTIVITY-Y INSTALLS COMPONENT-Y)
        (DISTANCE-TO-ACCESS (COMPONENT-X)
         IS-LARGER-THAN
         DISTANCE-TO-ACCESS (COMPONENT-Y))
```

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

Commentary to Rule 10: This is applicable to areas with limited access only.

1.8   Weather Protected By (p. 43)

1.8.1   Rule 11

```
IF      (ACTIVITY-X INSTALLS COMPONENT-X)
        (ACTIVITY-Y INSTALLS COMPONENT-Y)
        (COMPONENT-X WEATHER-PROTECTS COMPONENT-Y)
```

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

2. CONSTRAINTS ADDRESSING TRADE INTERACTION

2.1 Space Competition (p. 44)

2.1.1 Rule 12

IF   (ACTIVITY-X USES WORK-AREA-X)
       (ACTIVITY-Y USES WORK-AREA-X)

THEN (ACTIVITY-X CANNOT-BE-CONCURRENT-WITH ACTIVITY-Y) [CP]

2.2 Resource Limitations (p. 44)

2.2.1 Rule 13

IF   (ACTIVITY-X REQUIRES RESOURCE-X)
       (ACTIVITY-Y REQUIRES RESOURCE-X)
       (1 UNIT-OF RESOURCE-X IS-AVAILABLE)

THEN (ACTIVITY-X CANNOT-BE-CONCURRENT-WITH ACTIVITY-Y) [CP]

2.3 Unsafe Environment Effects (p. 44)

2.3.1 Rule 14

IF   (ACTIVITY-X PRODUCES ENVIRONMENT-EFFECT-X)
       (ENVIRONMENT-EFFECT-X AFFECTS WORK-AREA-X)
       (ACTIVITY-Y USES WORK-AREA-X)
       (ACTIVITY-Y IS-PERFORMED-BY CREW-Y)
       (CREW-Y USES EQUIPMENT-Y)
       (ACTIVITY-Y INSTALLS COMPONENT-Y)
       (COMPONENT-Y IS-MADE-OF MATERIAL-Y)
       ((CREW-Y IS-SENSITIVE-TO ENVIRONMENT-EFFECT-X)
        OR (MATERIAL-Y IS-SENSITIVE-TO ENVIRONMENT-EFFECT-X)
        OR (EQUIPMENT-Y IS-SENSITIVE-TO ENVIRONMENT-EFFECT-X))

THEN (ACTIVITY-X CANNOT-BE-CONCURRENT-WITH ACTIVITY-Y) [R]

    2.3.1.1 Commentary to Rule 14: It is the responsibility of the contractor to protect the workers against unsafe environment effects. Although the sequencing constraint represented by Rule 14 might not be rigid, it is illegal to disregard safety issues and unwise to ignore worker discomfort.

2.4   Damaging of Installed Building Components (p. 44)

2.4.1   Rule 15

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
       (ACTIVITY-Y INSTALLS COMPONENT-Y)
       (ACTIVITY-X MAY-DAMAGE COMPONENT-Y)

THEN   (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

2.5   Requirement of Service (p. 45)

2.5.1   Rule 16

IF   (ACTIVITY-X INSTALLS COMPONENT-X)
       (ACTIVITY-Y INSTALLS COMPONENT-Y)
       (COMPONENT-X PROVIDES-SERVICE-TO ACTIVITY-Y)

THEN   (ACTIVITY-X PRECEDES ACTIVITY-Y) [R]

2.6   Constraints Addressing Path Interference (p. 45)

2.6.1   Rule 17

IF   ((ACTIVITY-X INSTALLS COMPONENT-X)
       (ACTIVITY-Y INSTALLS COMPONENT-Y)
       (COMPONENT-Y OBSTRUCTS-PATH-OF COMPONENT-X))

THEN   (ACTIVITY-X PRECEDES ACTIVITY-Y) [CP]

       2.6.1.1 Commentary to Rule 17: The premise "(COMPONENT-Y OBSTRUCTS-PATH-OF
COMPONENT-X)" implies that COMPONENT-Y obstructs the installation path of: (1) COMPONENT-
X, (2) the crew installing COMPONENT-X, or (3) the equipment used to install COMPONENT-X.

2.7   Constraints Addressing Code Regulations (p. 45)

2.7.1   Rule 18

IF   ((COMPONENT-X IS FLOOR-LEVEL-(i - 2))
       OR (COMPONENT-X IS SAFETY-NET-LEVEL-(i - 2)))
       (ACTIVITY-Y INSTALLS STEEL-MEMBERS-LEVEL-(i))

THEN   (COMPONENT-X PROVIDES-SERVICE-TO ACTIVITY-Y) [R]

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2.7.1.1 Commentary to Rule 18: It is unlawful to disobey code regulations, so they are classified as rigid.

2.7.2 *Rule 19*

IF   ((ACTIVITY-X TESTS COMPONENT-X
      OR (ACTIVITY-X INSPECTS COMPONENT-X))
      (ACTIVITY-Y INSTALLS COMPONENT-Y)
      (COMPONENT-Y COVERS COMPONENT-X)

THEN (ACTIVITY-X PRECEDES ACTIVITY-Y) [R]

APPENDIX C: Supplementary Prototype Information

This appendix is composed of two parts. Part 1 contains information about the building systems, subsystems and components known to the prototype. Part 2 lists the rules that are used to establish activity sequencing.

A comprehensive listing of the prototype's code is not included in this report because of space limitations. However, any reader interested in obtaining it should contact the author at:

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Berkeley, CA 94720

Part 1: INFORMATION ON BUILDING SYSTEMS, SUBSYSTEMS AND COMPONENTS STORED IN THE PROTOTYPE'S KNOWLEDGE-BASE.

1.1 Overview.

This appendix provides detailed information about the building systems, subsystems, and components currently included in the Building Systems knowledge module of the prototype's knowledge-base. It is specifically complementing Section 6.3.1.

1.2 Objective.

The objective of this appendix is to describe the specific building systems, subsystems, and components that belong to any particular project that is covered by the prototype's systems, subsystems, and components. The information presented here is particularly detailed in describing building components. Summary pages introduce each of the building systems (i.e., Substructure, Site-Preparation, etc.), their subsystems and components. This summary page is followed by a detailed description of the components of each building system. All of the component slots, with non-null value, are shown.

It is important to highlight that the Building Systems Knowledge Module contains information that is generic. This is information that has to be flexible enough so to be adjusted to describe any particular building being processed. The objects included in this appendix when taken together comprise a generic object pool. The information included in the component slots is encoded in such a way that specific component relationships can be automatically deduced by the system. For example:

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From the information present in the generic component <u>metal-floor-deck</u>, the prototype has to be able to represent specific information about "Building A." In "Building A," among many other pieces of information, it is known that "the metal deck in level 2 is supported-by the structural steel tier 1" (Fact A). Similarly, it is known that "the metal deck in level 4 is covered by the concrete deck[1] in level 4" (Fact B).

The metal-floor-deck component included in this appendix (p. 133) has encoded information that is automatically decoded by the prototype system to produce Fact A and Fact B. The notation used to encode the generic components information is discussed below.

1.3   Notation.

Building components have attribute values (slots) especially relevant for activity sequencing. These values describe relationships to: (1) other components (like supported-by, covered-by, etc.), (2) construction spaces (like approx-location and operational-space), and (3) activities (installed or removed by). A special notation was created to allow the generality of the components. In particular, this notation allows cloning a generic component like "metal-floor-deck" for as many floors as necessary and produce for each "metal-floor-deck-level-i" appropriate relationships to related objects.

An example of an attribute value is: for the generic component "concr-deck" there is an attribute called "supported-by" (p. 130). In this case, its attribute-value is "(ALL (SAME METAL-FLOOR-DECK))". This attribute value is encoded with a particular notation described below.

An attribute value of a generic component can fall into three different cases:

- CASE 1: attribute value = <object id>

This is the trivial case in which there are no parentheses enclosing the value. The decoded attribute value is identical to <object id>. For example, for component "concr-pile-cap," and attribute "supported-by", the value is (p. 132): concrete pile cap supported-by= pile

Since the value "pile" is not enclosed in parenthesis, the specific attribute supported-by of "concr-pile-cap" has a value of "pile"

- CASE 2:   attribute value = (<keyword> <object id>),
            with <keyword> = {FIRST, LAST}

In this case the component to which the attribute value belongs is of repetitive nature. The object described by <object id> is not repetitive.

---

[1]   "Concrete-deck" refers in the prototype to the concrete slab placed on top of a metal deck (usually to become a composite metal/concrete slab). "Concrete-slab" refers in the prototype to the all-concrete slab which is part of a cast in place concrete frame.

If <keyword> = FIRST, then only the <u>first</u> of the decoded components will be related to the object <object>. For example, if a pile foundation is the foundation alternative used, the generic component "structural-steel-tier" is supported-by (p. 132):

structural-steel-tier supported-by: (FIRST concr-pile-cap)

Only the first decoded component "structural-steel-tier-1" will be

supported-by: concr-pile-cap

If <keyword> = LAST, only the <u>last</u> of the decoded components will be related to the object <object id>. For example, the way of expressing that only the last of the levels of "steel-sprayed-fireproofing" covers the "metal-roof-deck" is (p. 133):

steel-sprayed-fireproofing covers: (LAST metal-roof-deck)

- CASE 3:   attribute value = (<keyword> <object id>);
            with <keyword> = {INITIAL, TERMINAL}

In this case the object to which the attribute value points to is of repetitive nature (<object id>). The component that possesses the attribute value is itself nonrepetitive.

If <keyword> = INITIAL, then the decoded component will only be related to the <u>initial</u> decoded object from <object id>. This is the reciprocal to FIRST. For example, if a pile foundation is the foundation alternative used, the generic component "concr-pile-cap" (p. 130),

concr-pile-cap supports: (INITIAL structural-steel-tier)

The specific component "concr-pile-cap", decoded from the generic one will support:

concr-pile-cap supports: structural-steel-tier-1

If <keyword> = TERMINAL, then the decoded component will only be related to the last of the objects decoded from <object id>. This is the reciprocal to LAST. For example, the generic component "metal-roof-deck" (p. 133):

metal-roof-deck covered-by: (TERMINAL steel-sprayed-fireproofing)

The specific component decoded from "metal-roof-deck" is (if there are 6 levels or floors, level-6 is <u>terminal</u>):

metal-roof-deck covered-by: steel-sprayed-fireproofing-level-6

- CASE 4:   attribute value = (<keyword1> (<keyword2> <object id>))
            with <keyword1> = {ALL, ALL-XPT-F, ALL-XPT-L},
      and   <keyword2> = {SAME, PREV, NEXT, ONE-TO-MANY, MANY-TO-ONE}

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In this case both the component that possesses the attribute value and the related object are repetitive in nature.

<keyword1> qualifies the component as follows:

If <keyword1> = ALL, all of the decoded specific components will be related to the specific object that results from the interpretation of (<keyword2> <object id>).

If <keyword1> = ALL-XPT-F, all except the first of the specific components decoded will be related to the resulting object.

If <keyword1> = ALL-XPT-L, all except the last of the specific components decoded will be related to the resulting object.

<keyword2> qualifies the <object id> as follows:

If <keyword2> = SAME, the decoded component will be related to the <object id> located in the same level (or floor).

If <keyword2> = PREV, the decoded component will be related to the <object id> located in the previous level (or floor).

If <keyword2> = NEXT, the decoded component will be related to the <object id> located in the next level (or floor).

If <keyword2> = ONE-TO-MANY, the decoded component is a structural-steel-tier. Structural steel comes in tiers that are two or three stories long, and therefore one tier may be related to several objects of the same nature (for instance, one tier supports two or three metal-floor-decks, depending on its length).

If <keyword2> = MANY-TO-ONE, this is the reciprocal relationship. In the case of the example, several metal-floor-decks are supported by one steel tier.

1.4   Building Systems, Subsystems and Components.

(start on next page)

SUBSTRUCTURE

COLUMN-FOUNDATION

    ALTERNATIVES: **FOOTING-FOUNDATION: COLUMN-CONCR-FOOTING**
                                          CONCR-GRADE-BEAM

                      PILE-FOUNDATION: CONCR-GRADE-BEAM
                                          PILE
                                          CONCR-PILE-CAP

    FOUNDATION-WALLS: CONCR-FOUND-WALL
                                FOUNDATION-WALL-DRAIN

    SLAB-ON-GRADE: CONCR-SLAB-ON-GRADE

COMPONENT:	COLUMN-CONCR-FOOTING
APPROX-LOCATION:	EXCAVATED-FOOTPRINT
COVERED-BY:	CONCR-SLAB-ON-GRADE
INSTALLED-BY:	COLUMN-FOOTING-INSTALLATION
OPER-SPACE:	EXCAVATED-FOOTPRINT
SUPPORTS:	(INITIAL TIER STRUCTURAL-STEEL) (INITIAL LEVEL CONCR-COLUMN)

COMPONENT:	CONCR-GRADE-BEAM
APPROX-LOCATION:	EXCAVATED-FOOTPRINT
COVERED-BY:	CONCR-SLAB-ON-GRADE
COVERS:	PILE
INSTALLED-BY:	GRADE-BEAM-INSTALLATION
OPER-SPACE:	EXCAVATED-FOOTPRINT
REMOVES-CONSTR-SPACE:	EXCAVATED-FOOTPRINT
SUPPORTS:	CONCR-FOUND-WALL
YIELDS-CONSTR-SPACE:	FOUNDATION-IN-PLACE-FOOTPRINT

COMPONENT:	PILE
APPROX-LOCATION:	EXCAVATED-FOOTPRINT
COVERED-BY:	CONCR-GRADE-BEAM
INSTALLED-BY:	PILE-INSTALLATION
OPER-SPACE:	EXCAVATED-FOOTPRINT
SUPPORTS:	CONCR-PILE-CAP

COMPONENT:	CONCR-PILE-CAP
APPROX-LOCATION:	EXCAVATED-FOOTPRINT
COVERED-BY:	CONCR-SLAB-ON-GRADE
INSTALLED-BY:	PILE-CAP-INSTALLATION
OPER-SPACE:	EXCAVATED-FOOTPRINT
SUPPORTED-BY:	PILE
SUPPORTS:	(INITIAL TIER STRUCTURAL-STEEL) (INITIAL LEVEL CONCR-COLUMN)

COMPONENT:	CONCR-FOUND-WALL
APPROX-LOCATION:	EXCAVATED-PERIMETER
COVERED-BY:	BACKFILL-MATERIAL
EMBEDS:	(INITIAL TIER STRUCTURAL-STEEL)
INSTALLED-BY:	FOUNDATION-WALL-ERECTION
OPER-SPACE:	EXCAVATED-PERIMETER
SUPPORTED-BY:	CONCR-GRADE-BEAM
SUPPORTS:	BACKFILL-MATERIAL

COMPONENT:	FOUNDATION-WALL-DRAIN
APPROX-LOCATION:	EXCAVATED-PERIMETER
COVERED-BY:	BACKFILL-MATERIAL
INSTALLED-BY:	FOUND-WALL-DRAIN-INSTALLATION
OPER-SPACE:	EXCAVATED-PERIMETER

COMPONENT:	CONCR-SLAB-ON-GRADE
APPROX-LOCATION:	FOUNDATION-IN-PLACE-FOOTPRINT
COVERS:	CONCR-FOOTING CONCR-PILE-CAP CONCR-GRADE-BEAM
INSTALLED-BY:	SLAB-ON-GRADE-INSTALLATION
OPER-SPACE:	FOUNDATION-IN-PLACE-FOOTPRINT
REMOVES-CONSTR-SPACE:	FOUNDATION-IN-PLACE-FOOTPRINT
SUPPORTS:	(DEF POWER-GENERATION-EQUIP) SWITCHGEAR/DIST-SWITCHBOARD (INITIAL LEVEL WALL-STUDS) (INITIAL LEVEL INTERIOR-FINISHES-COMPONENT)
YIELDS-CONSTR-SPACE:	LEVEL-0

SITE-PREPARATION

SURFACE-PREPARATION: CLEARING: PLANTS&STUMPS
                         OPTIONAL: **TREE**
                         OPTIONAL: **DEMOLITION: OLD-BUILDING**
                         OPTIONAL: **OLD-PAVEMENT**

EARTHWORK: TOP-SOIL
            EXCAVATION-SOIL
            BACKFILL-MATERIAL

COMPONENT:	PLANTS&STUMPS
APPROX-LOCATION:	UNCLEARED-SITE
COVERS:	TOP-SOIL
OPER-SPACE:	UNCLEARED-SITE
REMOVED-BY:	CLEARING
SUPPORTED-BY:	TOP-SOIL
YIELDS-CONSTRUCTION-SPACE:	CLEARED-SITE

COMPONENT:	TREE
APPROX-LOCATION:	UNCLEARED-SITE
OPER-SPACE:	UNCLEARED-SITE
REMOVED-BY:	TREE-REMOVAL
SUPPORTED-BY:	TOP-SOIL

COMPONENT:	OLD-BUILDING
APPROX-LOCATION:	UNCLEARED-SITE
OPER-SPACE:	UNCLEARED-SITE
REMOVED-BY:	BUILDING-DEMOLITION
SUPPORTED-BY:	EXCAVATION-SOIL

COMPONENT:	OLD-PAVEMENT
APPROX-LOCATION:	UNCLEARED-SITE
OPER-SPACE:	UNCLEARED-SITE
REMOVED-BY:	PAVEMENT-DEMOLITION
SUPPORTED-BY:	EXCAVATION-SOIL

COMPONENT:	TOP-SOIL
APPROX-LOCATION:	CLEARED-SITE
COVERED-BY:	PLANTS&STUMPS
COVERS:	EXCAVATION-SOIL
OPER-SPACE:	CLEARED-SITE
REMOVED-BY:	TOP-SOIL-REMOVAL
REMOVES-CONSTR-SPACE:	CLEARED-SITE
SUPPORTED-BY:	EXCAVATION-SOIL
SUPPORTS:	PLANTS&STUMPS TREE
YIELDS-CONSTR-SPACE:	CLEARED-OPEN-SITE CLEARED-FOOTPRINT

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COMPONENT:	EXCAVATION-SOIL
APPROX-LOCATION:	CLEARED-FOOTPRINT
COVERED-BY:	TOP-SOIL
OPER-SPACE:	CLEARED-FOOTPRINT
REMOVED-BY:	MASS-EXCAVATION
REMOVES-CONSTR-SPACE:	CLEARED-FOOTPRINT
SUPPORTS:	OLD-BUILDING OLD-PAVEMENT TOP-SOIL
YIELDS-CONSTR-SPACE:	EXCAVATED-FOOTPRINT EXCAVATED-PERIMETER

COMPONENT:	BACKFILL-MATERIAL
APPROX-LOCATION:	EXCAVATED-PERIMETER
COVERS:	FOUND-WALL-DRAIN CONCR-FOUND-WALL
INSTALLED-BY:	FOUND-WALL-BACKFILL
OPER-SPACE:	EXCAVATED-PERIMETER
REMOVES-CONSTR-SPACE:	EXCAVATED-PERIMETER
SUPPORTED-BY:	(INITIAL LEVEL CONCR-SLAB) (INITIAL LEVEL CONCR-DECK) CONCR-FOUND-WALL
YIELDS-CONSTR-SPACE:	BACKFILLED-PERIMETER

STRUCTURAL-FRAME

FLOOR-STRUCTURE:
    ALTERNATIVES: **C-I-P-CONCR-FLOOR-STRUCTURE: CONCR-COLUMN
                      CONCR-SLAB**

**STEEL-FLOOR-STRUCTURE: STRUCTURAL-STEEL-TIER
                                   METAL-FLOOR-DECK
                                   CONCR-DECK**
                                   OPTIONAL: **STEEL-SPRYD-FIREPROOFING**

**ROOF-STRUCTURE: STEEL-ROOF-STRUCTURE: STEEL-ROOF-BEAM/JOIST
                                      METAL-ROOF-DECK**

COMPONENT:	CONCR-COLUMN
APPROX-LOCATION:	(ALL (SAME LEVEL))
INSTALLED-BY:	(ALL (SAME COLUMN-ERECTION))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(FIRST CONCR-PILE-CAP) (FIRST CONCR-FOOTING) (ALL-XPT-F (PREV CONCR-SLAB))
SUPPORTS:	(ALL-XPT-L (NEXT CONCR-SLAB)) (LAST STEEL-ROOF-BEAM/JOIST)

COMPONENT:	CONCR-SLAB
APPROX-LOCATION:	(ALL (SAME LEVEL))
COVERED-BY:	(ALL (SAME INTERIOR-FINISHES-COMPONENT)
INSTALLED-BY:	(ALL (SAME CAST-SLAB))
OPER-SPACE:	(ALL (PREV LEVEL))
SUPPORTED-BY:	(ALL (PREV CONCR-COLUMN))
SUPPORTS:	(ALL (SAME CONCR-COLUMN)) (ALL (SAME EXTERIOR-MASONRY-WALL)) (ALL (SAME CURTAIN-WALL-FRAME)) (ALL (PREV PLUMBING-RISER/MAIN)) (ALL (PREV AIR-HANDLING-RISER/MAIN)) (ALL (PREV AIR-HANDLING-LOCAL-UNIT)) (ALL (PREV FIRE-PROT-RISER/MAIN)) (ALL (PREV ELEC-RISER/MAIN)) (FIRST BACKFILL-MATERIAL) (ALL (SAME INTERIOR-FINISHES-COMPONENT))
YIELDS-CONSTR-SPACE:	(ALL (SAME LEVEL))

COMPONENT:	STRUCTURAL-STEEL-TIER
APPROX-LOCATION:	(FIRST FOUNDATION-IN-PLACE-FOOTPRINT) (ALL-XPT-F (ONE-TO-PAST LEVEL))
COVERED-BY:	(ALL (ONE-TO-MANY STEEL-SPRYD-FIREPROOFING))
EMBEDDED-IN:	(FIRST CONCR-FOUND-WALL)
INSTALLED-BY:	(ALL (SAME STEEL-ERECTION))
OPER-SPACE:	(FIRST FOUNDATION-IN-PLACE-FOOTPRINT) (ALL-XPT-F (ONE-TO-PAST LEVEL))
SUPPORTED-BY:	(FIRST CONCR-PILE-CAP) (FIRST CONCR-FOOTING) (ALL-XPT-F (PREV STRUCTURAL-TEEL-TIER))
SUPPORTS:	(ALL-XPT-L (ONE-TO-MANY METAL-FLOOR-DECK)) (ALL-XPT-L (NEXT STRUCTURAL-STEEL-TIER)) (LAST STEEL-ROOF-BEAM/JOIST)

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COMPONENT:	STEEL-SPRYD-FIREPROOFING
APPROX-LOCATION:	(ALL (SAME LEVEL))
COVERS:	(ALL (MANY-TO-ONE STRUCTURAL-STEEL)) (ALL-XPT-L (NEXT METAL-FLOOR-DECK)) (LAST STEEL-ROOF-BEAM/JOIST) (LAST METAL-ROOF-DECK)
DAMAGED-BY-INST:	(ALL-XPT-L (NEXT CONCR-DECK))
INSTAL-DAMAGES:	(ALL (SAME PLUMBING-RISER/MAIN)) (ALL (SAME AIR-HANDLING-RISER/MAIN)) (ALL (SAME HVAC-TERMINAL-UNIT)) (ALL (SAME ELEC-RISER/MAIN)) (ALL (SAME EXTERIOR-MASONRY-WALL)) (ALL (SAME CURTAIN-WALL-PANEL)) (ALL (SAME WALL-STUDS))
INSTALLED-BY:	(ALL (SAME FIREPROOFING-SPRAYING))
OPER-SPACE:	(ALL (SAME LEVEL))

COMPONENT:	METAL-FLOOR-DECK
APPROX-LOCATION:	(ALL (SAME LEVEL))
COVERED-BY:	(ALL (SAME CONCR-DECK)) (ALL (PREV STEEL-SPRYD-FIREPROOFING))
INSTALLED-BY:	(ALL (SAME METAL-DECK-INSTALLATION))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(ALL (MANY-TO-ONE STRUCTURAL STEEL))
SUPPORTS:	(ALL (SAME CONCR-DECK)) (ALL (SAME CURTAIN-WALL-FRAME)) (ALL (PREV PLUMB-ING-RISER/MAIN)) (ALL (PREV AIR-HANDLING-RISER/MAIN)) (ALL (PREV AIR-HANDLING-LOCAL-UNIT)) (ALL (PREV FIRE-PROT-RISER/MAIN)) (ALL (PREV ELEC-RISER/MAIN))
YIELDS-CONSTR-SPACE:	(ALL (SAME LEVEL))

COMPONENT:	CONCR-DECK
APPROX-LOCATION:	(ALL (SAME LEVEL))
COVERS:	(ALL (SAME METAL-FLOOR-DECK))
INSTAL-DAMAGES:	(ALL (PREV PLUMBING-RISER/MAIN)) (ALL (PREV AIR-HANDLING-RISER/MAIN)) (ALL (PREV HVAC-TERMINAL-UNIT)) (ALL (PREV ELEC-RISER/MAIN)) (ALL (PREV EXTERIOR-MASONRY-WALL)) (ALL (PREV CURTAIN-WALL-PANEL)) (ALL (PREV WALL-STUDS))
INSTALLED-BY:	(ALL (SAME CAST-CONCR-DECK))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(ALL (SAME METAL-FLOOR-DECK))
SUPPORTS:	(ALL (SAME EXTERIOR-MASONRY-WALL)) (FIRST BACKFILL-MATERIAL) (LAST ELEVATOR) (ALL (SAME INTERIOR-FINISHES-COMPONENT)) (ALL (SAME WALL-STUDS)) (ALL (PREV WALL-STUDS))

COMPONENT:	STEEL-ROOF-BEAM/JOIST
APPROX-LOCATION:	ROOF
COVERED-BY:	(TERMINAL LEVEL STEEL-SPRYD-FIREPROOFING)
INSTALLED-BY:	ROOF-FRAME-INSTALLATION
OPER-SPACE:	(TERMINAL LEVEL LEVEL)
SUPPORTED-BY:	(TERMINAL TIER STRUCTURAL-STEEL)
SUPPORTS:	METAL-ROOF-DECK

COMPONENT:	METAL-ROOF-DECK
APPROX-LOCATION:	ROOF
COVERED-BY:	BUILT-UP-ROOF ROOF-MEMBRANE (TERMINAL LEVEL STEEL-SPRYD-FIREPROOFING)
INSTALLED-BY:	METAL-ROOF-DECK-INSTALLATION
OPER-SPACE:	(TERMINAL LEVEL LEVEL)
SUPPORTED-BY:	STEEL-ROOF-BEAM/JOIST
SUPPORTS:	(DEF COOLING-EQUIP-PIPING) BUILT-UP-ROOF ROOF-MEMBRANE (TERMINAL LEVEL PLUMBING-RISER/MAIN) (TERMINAL LEVEL AIR-HANDLING-RISER/MAIN) (TERMINAL LEVEL ELEC-RISER/MAIN) (TERMINAL LEVEL FIRE-PROT-RISER/MAIN) (TERMINAL LEVEL AIR-HANDLING-LOCAL-UNIT)
YIELDS-CONSTR-SPACE:	ROOF

ROOFING

ROOF-COVERING:
      ALTERNATIVES: **BUILT-UP-ROOF**
                    ROOF-MEMBRANE

COMPONENT:	BUILT-UP-ROOF
APPROX-LOCATION:	ROOF
COVERED-BY:	(DEF COOLING-EQUIP)
COVERS:	METAL-ROOF-DECK
INSTALLED-BY:	ROOF-INSTALLATION
OPER-SPACE:	ROOF
SUPPORTED-BY:	METAL-ROOF-DECK
WEATHER-PROTS:	HEATING-EQUIP/PIPING ELEVATOR SWITCHGEAR/DIST-SWITCHBOARD POWER-GENERATION-EQUIPMENT HEATING-EQUIPMENT/PIPING ENERGY-SUPPLY-EQUIP/PIPING

COMPONENT:	ROOF-MEMBRANE
APPROX-LOCATION:	ROOF
COVERED-BY:	(DEF COOLING-EQUIP)
COVERS:	METAL-ROOF-DECK
INSTALLED-BY:	ROOF-INSTALLATION
OPER-SPACE:	ROOF
SUPPORTED-BY:	METAL-ROOF-DECK
WEATHER-PROTS:	HEATING-EQUIP/PIPING ELEVATOR SWITCHGEAR/DIST-SWITCHBOARD POWER-GENERATION-EQUIPMENT HEATING-EQUIPMENT/PIPING ENERGY-SUPPLY-EQUIP/PIPING

EXTERIOR-CLOSURE

EXTERIOR-SKIN:
      ALTERNATIVES: **MASONRY-WALL/WINDOWS: EXTERIOR-MASONRY-WALL WINDOWS**

      CURTAIN-WALL: CURTAIN-WALL-FRAME-SEGMT CURTAIN-WALL-PANEL

COMPONENT:	EXTERIOR-MASONRY-WALL
APPROX-LOCATION:	(ALL (SAME LEVEL))
DAMAGED-BY-INST:	(ALL (SAME STEEL-SPRYD-FIREPROOFING)
INSTAL-DAMAGES:	(ALL (PREV WINDOW)) (ALL (PREV PREV WINDOW)) (ALL (PREV PREV PREV WINDOW))
INSTALLED-BY:	(ALL (SAME EXTERIOR-MASONRY-INSTALLATION))
OPER-SPACE:	(ALL-XPT-F (SAME LEVEL)) (FIRST BACKFILLED-PERIMETER)
SUPPORTED-BY:	(ALL (SAME CONCR-DECK)) (ALL (SAME CONCR-SLAB))
SUPPORTS:	(ALL (SAME WINDOW))

COMPONENT:	WINDOW
APPROX-LOCATION:	(ALL (SAME LEVEL))
DAMAGED-BY-INST:	(ALL (NEXT EXTERIOR-MASONRY-WALL)) (ALL (NEXT NEXT EXTERIOR-MASONRY-WALL)) (ALL (NEXT NEXT NEXT EXTERIOR-MASONRY-WALL))
INSTALLED-BY:	(ALL (SAME WINDOW-INSTALLATION))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(ALL (SAME EXTERIOR-MASONRY-WALL))
WEATHER-PROTECTS:	(ALL (SAME INTERIOR-FINISHES-COMPONENT))

COMPONENT:	CURTAIN-WALL-FRAME-SGMT
APPROX-LOCATION:	(ALL (SAME LEVEL))
INSTAL-DAMAGES:	(ALL (PREV CURTAIN-WALL-PANEL)) (ALL (PREV PREV CURTAIN-WALL-PANEL)) (ALL (PREV PREV PREV CURTAIN-WALL-PANEL))
INSTALLED-BY:	(ALL (SAME CURTAIN-WALL-FRAME ERECTION))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(ALL (SAME CONCR-SLAB)) (ALL (SAME METAL-FLOOR-DECK))
SUPPORTS:	(ALL (SAME CURTAIN-WALL-PANEL))

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COMPONENT:	CURTAIN-WALL-PANEL
APPROX-LOCATION:	(ALL (SAME LEVEL))
DAMAGED-BY-INST:	(ALL (NEXT CURTAIN-WALL-FRAME)) (ALL (NEXT NEXT CURTAIN-WALL-FRAME)) (ALL (NEXT NEXT NEXT CURTAIN-WALL-FRAME)) (ALL (SAME STEEL-SPRYD-FIREPROOF-ING))
INSTALLED-BY:	(ALL (SAME CURTAIN-WALL-PANEL-INSTALLATION))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(ALL (SAME CURTAIN-WALL-FRAME))
WEATHER-PROTECTS:	(ALL (SAME INTERIOR-FINISHES-COMPONENT))

PLUMBING

SUPPLY/DRAINAGE: PLUMBING-RISER/MAIN

COMPONENT:	PLUMBING-RISER/MAIN
APPROX-LOCATION:	(ALL (SAME LEVEL))
COVERED-BY:	(ALL (SAME INTERIOR-FINISHES-COMPONENT))
DAMAGED-BY-INST:	(ALL-XPT-L (NEXT CONCR-DECK)) (ALL (SAME STEEL-SPRYD-FIREPROOFING))
INSTALLED-BY:	(ALL (SAME PLUMBING-RISER/MAIN-INSTALLATION))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(ALL-XPT-L (NEXT METAL-FLOOR-DECK)) (ALL-XPT-L (NEXT CONCR-SLAB)) (LAST METAL-ROOF-DECK)

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ENERGY-SUPPLY: ENERGY-SUPPLY-EQUIP/PIPING
HEATING-GENERATION: HEATING-EQUIP/PIPING
COOLING-GENERATION: COOLING-EQUIP/PIPING
AIR-HANDLING: AIR-HANDLING-RISER/MAIN
       OPTIONAL: **AIR-HANDLING-LOCAL-UNIT**

COMPONENT:	ENERGY-SUPPLY-EQUIP/PIPING
APPROX-LOCATION:	(DEF TERMINAL LEVEL)
INSTALLED-BY:	ENERGY-SUPPLY-EQUIP-INSTALLATION
OPER-SPACE:	(DEF TERMINAL LEVEL)
SUPPORTED-BY:	(DEF TERMINAL CONCR-SLAB) (DEF TERMINAL CONCR-DECK)
WEATHER-PROT-BY:	ROOF-MEMBRANE BUILT-UP-ROOF

COMPONENT:	HEATING-EQUIP/PIPING
APPROX-LOCATION:	(DEF TERMINAL LEVEL)
INSTALLED-BY:	HEATING-EQUIP-INSTALLATION
OPER-SPACE:	(DEF TERMINAL LEVEL)
SUPPORTED-BY:	(DEF TERMINAL CONCR-DECK) (DEF TERMINAL CONCR-SLAB)
WEATHER-PROT-BY:	ROOF-MEMBRANE BUILT-UP-ROOF

COMPONENT:	COOLING-EQUIP/PIPING
APPROX-LOCATION:	(DEF ROOF)
COVERS:	(DEF ROOF-MEMBRANE) (DEF BUILT-UP-ROOF)
INSTALLED-BY:	COOLING-EQUIP-INSTALLATION
OPER-SPACE:	(DEF ROOF)
SUPPORTED-BY:	(DEF STEEL-ROOF-BEAM/JOIST)

COMPONENT:	AIR-HANDLING-RISER/MAIN
APPROX-LOCATION:	(ALL (SAME LEVEL))
COVERED-BY:	(ALL (SAME INTERIOR-FINISHES-COMPONENT))
DAMAGED-BY-INST:	(ALL-XPT-L (NEXT CONCR-DECK)) (ALL (SAME STEEL-SPRYD-FIREPROOF:NG))
INSTALLED-BY:	(ALL (SAME AIR-HANDLING-RISER/MAIN-INSTALLATION))
OPER-SPACE:	(ALL (SAME LEVEL))
SUPPORTED-BY:	(ALL-XPT-L (NEXT CONCR-SLAB)) (ALL-XPT-L (NEXT CONCR-DECK)) (LAST METAL-ROOF-DECK)

```
COMPONENT:              AIR-HANDLING-LOCAL-UNIT
APPROX-LOCATION:        (ALL (SAME LEVEL))
COVERED-BY:             (ALL (SAME INTERIOR-FINISHES-COMPONENT))
DAMAGED-BY-INST:        (ALL-XPT-L (NEXT CONCR-DECK)) (ALL (SAME STEEL-SPRY-FIREPROOFING))
INSTALLED-BY:           (ALL (SAME AIR-HANDLING-LOCAL-UNIT-INSTALLATION))
OPER-SPACE:             (ALL (SAME LEVEL))
SUPPORTED-BY:           (ALL-XPT-L (NEXT CONCR-SLAB)) (ALL-XPT-L (NEXT CONCR-DECK)) (LAST METAL-
                        ROOF-DECK)
```

SPECIAL-MECHANICAL-SYSTEMS

FIRE-PROTECTION: FIRE-PROT-RISER/MAIN

```
COMPONENT:              FIRE-PROT-RISER/MAIN
APPROX-LOCATION:        (ALL (SAME LEVEL))
COVERED-BY:             (ALL (SAME INTERIOR-FINISHES-COMPONENT))
DAMAGED-BY-INST:        (ALL-XPT-L (NEXT CONCR-DECK)) (ALL (SAME STEEL-SPRD-FIREPROOFING))
INSTALLED-BY:           (ALL (SAME FIRE-PROT-RISER/MAIN-INSTALLATION))
OPER-SPACE:             (ALL (SAME LEVEL))
SUPPORTED-BY:           (ALL-XPT-L (NEXT CONCR-SLAB)) (ALL-XPT-L (NEXT CONCR-DECK)) (LAST METAL
                        ROOF-DECK)
```

INTERIOR-ELECTRICAL

POWER-GENERATION: POWER-GENERATION-EQUIP
DISTRIBUTION: SWITCHGEAR/DIST-SWITCHBOARD
ELEC-RISER/MAIN

```
COMPONENT:              POWER-GENERATION-EQUIP
APPROX-LOCATION:        (DEF LEVEL-0)
INSTALLED-BY:           POWER-GENERATION-EQUIP-INSTALLATION
OPER-SPACE:             (DEF LEVEL-0)
SUPPORTED-BY:           (DEF CONCR-SLAB-ON-GRADE)
WEATHER-PROT-BY:        ROOF-MEMBRANE BUILT-UP-ROOF


COMPONENT:              SWITCHGEAR/DIST-SWITCHBOARD
APPROX-LOCATION:        LEVEL-0
INSTALLED-BY:           SWITCHGEAR/DIST-SWITCHBOARD-INSTALLATION
OPER-SPACE:             LEVEL-0
SUPPORTED-BY:           CONCR-SLAB-ON-GRADE
WEATHER-PROT-BY:        ROOF-MEMBRANE BUILT-UP-ROOF


COMPONENT:              ELEC-RISER/MAIN
APPROX-LOCATION:        (ALL (SAME LEVEL))
COVERED-BY:             (ALL (SAME INTERIOR-FINISHES-COMPONENT))
DAMAGED-BY-INST:        (ALL-XPT-L (NEXT CONCR-DECK)) (ALL (SAME STEEL-SPRYD-FIREPROOFING))
INSTALLED-BY:           (ALL (SAME ELEC-RISER/MAIN-INSTALLATION))
OPER-SPACE:             (ALL (SAME LEVEL))
SUPPORTED-BY:           (ALL-XPT-L (NEXT CONCR-SLAB)) (ALL-XPT-L (NEXT METAL-FLOOR-DECK)) (LAST
                        METAL-ROOF-DECK)
```

INTERIOR-CONSTRUCTION

INTERIOR-PARTITIONS: STUD/DRYWALL-PARTITIONS: WALL-STUDS
```
COMPONENT:              WALL-STUDS
APPROX-LOCATION:        (ALL (SAME LEVEL))
COVERED-BY:             (ALL (SAME INTERIOR-FINISHES-COMPONENT))
DEMAGED-BY-INST:        (ALL (SAME STEEL-SPRYD-FIREPROOFING))
INSTALLED-BY:           (ALL (SAME WALL-STUD-INSTALLATION))
OPER-SPACE:             (ALL (SAME LEVEL))
SUPPORTED-BY:           (ALL-XPT-F (SAME CONCR-SLAB)) (ALL-XPT-F (SAME CONCR-DECK)) (ALL-XPT-L (NEXT
```

```
                              CONCR-SLAB)) (ALL-XPT-L (NEXT CONCR-DECK)) (LAST METAL-ROOF-DECK) (FIRST
                              CONCR-SLAB-ON-GRADE)
SUPPORTS:                     (ALL (SAME INTERIOR-FINISHES-COMPONENT))
```

INTERIOR-FINISHES

INTERIOR-FINISHES-COMPONENT

```
COMPONENT:                    INTERIOR-FINISHES-COMPONENT
APPROX-LOCATION:              (ALL (SAME LEVEL))
COVERS:                       (ALL (SAME WALL-STUDS)) (ALL (SAME CONCR-DECK)) (ALL (SAME CONCR-SLAB)) (ALL
                              (SAME FIRE-PROT-RISER/MAIN)) (ALL (SAME AIR-HANDLING-RISER/MAIN)) (ALL (SAME
                              PLUMBING-RISER/MAIN)) (ALL (SAME ELEC-RISER/MAIN))
INSTALLED-BY:                 (ALL (SAME INTERIOR-FINISHES-INSTALLATION))
OPER-SPACE:                   (ALL (SAME LEVEL))
SUPPORTED-BY:                 (ALL-XPT-F (SAME CONCR-SLAB)) (ALL-XPT-F (SAME CONCR-DECK)) (ALL (SAME WALL-
                              STUDS)) (FIRST CONCR-SLAB-ON-GRADE))
WEATHER-PROT-BY:              (ALL (SAME CURTAIN-WALL-PANEL)) (ALL (SAME WINDOW))
```

CONVEYING
ELEVATOR

```
COMPONENT:                    ELEVATOR
APPROX-LOCATION:              (TERMINAL LEVEL)
INSTALLED-BY:                 ELEVATOR-INSTALLATION
OPER-SPACE:                   (TERMINAL LEVEL)
SUPPORTED-BY:                 (TERMINAL LEVEL CONCR-SLAB) (TERMINAL LEVEL CONCR-DECK)
WEATHER-PROT-BY:              BUILT-UP-ROOF ROOF-MEMBRANE
```

PART 2:   Prototype Rules for Activity Sequencing.

The rules here listed are used by the prototype to establish precedence links between activities. As discussed in Section 5.3, there are sequencing constraints that are independent of the relative timing, or overlap, of the activities. The rules here presented address this particular situation.

This appendix is extracted from the prototype code. Each rule is identified by KEE™ using a label, "INST-ACTIV-DAM-PRED-RULE," for instance. The rule body is stored into the "EXTERNAL.FORM" field. It is represented in the form "IF <premise> THEN <consequence>." The <premise> is composed of several conditions joined by an implicit "AND." Similarly, the <consequence> consists of several actions also joined by an implicit "AND." KEE™ supports the use of variables within the conditions and the actions, identified with a question mark "?" at the beginning of their label. For example, the variable "?ACTIVITY" is used to match all possible activities within the Context.

(INST-ACTIV-WEATHER-PROT-RULE
   ("diego" "6-4-90 15:54:44" "diego" "6-20-90 10:46:07")
   NIL
   (TIME-INDEP-PRIM-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?ACTIVITY IS ?COMPONENT) (THE
WEATHER-PROT-BY OF ?COMPONENT IS ?PROTECTING-COMPONENT) (NOT (?PROTECTING-COMPONENT =
EARTH-COMPONENT)) (?PRECEDING-ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?PRECEDING-ACTIVITY
IS ?PROTECTING-COMPONENT) THEN (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (WEATHER-PROTE-
CTS ?PROTECTING-COMPONENT ?COMPONENT)) (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (WEATHER-PRO-
TECTED-BY ?COMPONENT ?PROTECTING-COMPONENT)) (THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(INST-ACTIV-YLD-SP-PRED-RULE
   ("diego" "9-7-89 10:02:42" "diego" "6-20-90 9:55:30")
   NIL
   (TIME-INDEP-SEC-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (LISP (EQUAL (GET.VALUES ?ACTIVITY (QUOTE
PRECEDED-BY)) NIL)) (THE INSTALLS OF ?ACTIVITY IS ?COMPONENT) (THE OPER-SPACE OF ?COMPONENT IS ?SPACE)
(THE YIELDS-CONSTR-SPACE OF ?SPACE-PROV-COMP IS ?SPACE) (THE REMOVES OF ?PRECEDING-ACTIVITY IS
?SPACE-PROV-COMP) (?PRECEDING-ACTIVITY IS IN CLASS REMOV-ACTIVITY) THEN (THE PRECEDES-JUSTIFICATION OF
?PRECEDING-ACTIVITY IS (YIELDS-CONSTR-SPACE ?SPACE-PROV-COMP ?COMPONENT)) (THE PRECEDED-BY-JUSTIFIC-
ATION OF ?ACTIVITY IS (YIELDED-CONSTR-SPACE-BY ?COMPONENT ?SPACE-PROV-COMP)) (THE PRECEDED-BY OF
?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(INST-ACTIV-SERV-PRED-RULE
   ("diego" "8-24-89 10:57:15" "diego" "6-20-90 10:00:08")
   NIL
   (TIME-INDEP-PRIM-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?ACTIVITY IS ?COMPONENT) (THE
PROV-SERVICE-BY OF ?COMPONENT IS ?SERVICING-COMPONENT) (NOT (?SERVICING-COMPONENT = VOID-COMPONE-
NT)) (?PRECEDING-ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?PRECEDING-ACTIVITY IS ?SERVICING-C-
OMPONENT) THEN (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (PROVIDES-SERVICE-TO ?SERVICING-
COMPONENT ?COMPONENT)) (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (PROVIDED-SERVICE-BY
?COMPONENT ?SERVICING-COMPONENT)) (THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(INST-ACTIV-DAM-PRED-RULE
   ("diego" "8-24-89 10:48:41" "diego" "6-20-90 10:03:38")
   NIL
   (TIME-INDEP-PRIM-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?ACTIVITY IS ?COMPONENT) (THE
DAMAGED-BY-INST OF ?COMPONENT IS ?DAMAGING-COMPONENT) (NOT (?DAMAGING-COMPONENT = VOID-COMPONE-
NT)) (?PRECEDING-ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?PRECEDING-ACTIVITY IS ?DAMAGING-C-
OMPONENT) THEN (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (INSTALLATION-DAMAGES
?DAMAGING-COMPONENT ?COMPONENT)) (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (DAMAGED-BY-INSTALL-
ATION ?COMPONENT ?DAMAGING-COMPONENT)) (THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))

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```
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(INST-ACTIV-EMBD-PRED-RULE
   ("diego" "8-24-89 10:37:35" "diego" "6-20-90 10:08:30")
   NIL
   (TIME-INDEP-PRIM-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?ACTIVITY IS ?COMPONENT) (THE
EMBEDS OF ?COMPONENT IS ?EMBEDED-COMPONENT) (NOT (?EMBEDED-COMPONENT = VOID-COMPONENT))
(?PRECEDING-ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?PRECEDING-ACTIVITY IS ?EMBEDED-COMPO-
NENT) THEN (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (EMBEDED-IN ?EMBEDED-COMPONENT
?COMPONENT)) (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (EMBEDS ?COMPONENT ?EMBEDED-COMPONENT))
(THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(INST-ACTIV-SUPP-PRED-RULE
   ("diego" "8-24-89 10:33:30" "diego" "6-20-90 10:14:44")
   NIL
   (TIME-INDEP-PRIM-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?ACTIVITY IS ?COMPONENT) (THE
SUPPORTED-BY OF ?COMPONENT IS ?SUPPORTING-COMPONENT) (NOT (?SUPPORTING-COMPONENT = EARTH-COMPO-
NENT)) (?PRECEDING-ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?PRECEDING-ACTIVITY IS
?SUPPORTING-COMPONENT) THEN (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (SUPPORTS
?SUPPORTING-COMPONENT ?COMPONENT)) (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (SUPPORTED-BY
?COMPONENT ?SUPPORTING-COMPONENT)) (THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(INST-ACTIV-COVER-PRED-RULE
   ("diego" "8-24-89 10:24:36" "diego" "6-20-90 10:20:48")
   NIL
   (TIME-INDEP-PRIM-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?ACTIVITY IS ?COMPONENT) (THE
COVERS OF ?COMPONENT IS ?COVERED-COMPONENT) (NOT (?COVERED-COMPONENT = VOID-COMPONENT))
(?PRECEDING-ACTIVITY IS IN CLASS INSTAL-ACTIVITY) (THE INSTALLS OF ?PRECEDING-ACTIVITY IS ?COVERED-COMPO-
NENT) THEN (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (COVERED-BY ?COVERED-COMPONENT
?COMPONENT)) (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (COVERS ?COMPONENT ?COVERED-COMPONENT))
(THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(REM-ACTIV-COVER-PRED-RULE
   ("diego" "8-24-89 10:09:43" "diego" "6-20-90 10:39:15")
   NIL
   (TIME-INDEP-PRIM-LOGIC-RULES)
   NIL
   ()
   ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS REMOV-ACTIVITY) (THE REMOVES OF ?ACTIVITY IS ?COMPONENT) (THE
COVERED-BY OF ?COMPONENT IS ?COVERING-COMPONENT) (NOT (?COVERING-COMPONENT = VOID-COMPONENT))
(?PRECEDING-ACTIVITY IS IN CLASS REMOV-ACTIVITY) (THE REMOVES OF ?PRECEDING-ACTIVITY IS ?COVERING-COMP-
```

ONENT) THEN (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (COVERED-BY ?COMPONENT ?COVERING-COMPON-
ENT)) (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (COVERS ?COVERING-COMPONENT ?COMPONENT))
(THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(PARSE.ERRORS)
(RULE.TYPE (SAME.WORLD.ACTION))
))

(REM-ACTIV-SUPP-PRED-RULE
  ("diego" "8-24-89 10:05:12" "diego" "6-20-90 10:42:41")
  NIL
  (TIME-INDEP-PRIM-LOGIC-RULES)
  NIL
  ()
  ((ASSERTION)
(EXTERNAL.FORM ((IF (?ACTIVITY IS IN CLASS REMOV-ACTIVITY) (THE REMOVES OF ?ACTIVITY IS ?COMPONENT) (THE
SUPPORTS OF ?COMPONENT IS ?SUPPORTED-COMPONENT) (NOT (?SUPPORTED-COMPONENT = VOID-COMPONENT))
(?PRECEDING-ACTIVITY IS IN CLASS REMOV-ACTIVITY) (THE REMOVES OF ?PRECEDING-ACTIVITY IS ?SUPPORTED-CO-
MPONENT) THEN (THE PRECEDED-BY-JUSTIFICATION OF ?ACTIVITY IS (SUPPORTS ?COMPONENT ?SUPPORTED-COMP-
ONENT)) (THE PRECEDES-JUSTIFICATION OF ?PRECEDING-ACTIVITY IS (SUPPORTED-BY ?SUPPORTED-COMPONENT
?COMPONENT)) (THE PRECEDED-BY OF ?ACTIVITY IS ?PRECEDING-ACTIVITY))))
(MAKE.AND.WORLD? (NIL))
(NONMONOTONIC.PREMISES)
(RULE.TYPE (SAME.WORLD.ACTION))
))

APPENDIX D: Overview of Building Systems

In several sections of this dissertation there is reference to the systems that compose a building. The objective of this appendix is to provide a summary of those building systems considered in the prototype. As mentioned, the Building Systems Index (BSI) is followed. Also, a rather extensive BSI listing of the different systems and their subsystems is here used as a basis to indicate those systems covered in the prototype.

It is important to restate the fact that the prototype does not include all the formalized knowledge (described in Chapters 4 and 5 mainly). The prototype's main use was as an aid to produce a better knowledge formalization. The level of detail addressed in the prototype is not targeting the precise description about systems and their components. It is rather focused on a macro-level view of buildings and their systems.

This appendix provides a BSI listing of systems obtained from [Army 85]. Those systems addressed in the prototype are indicated with an asterisk "*". The position of the asterisk within a division describes the level of detail at which a particular system is implemented in the prototype. Normally the level of detail of the BSI listing is larger than that of the prototype. However, those few cases in which the prototype is more detailed are marked with "1". In these cases the reader is referred to Figure 6.3 (p. 76).

It is recognized that parts of the Mechanical, Electrical, and other systems are placed prior to or concurrently with systems such as Substructure and Structural Frame. BSI is systems oriented and therefore does not reflect this fact. However, the rules that were formalized in Chapter 5 contribute to an adequate sequencing of the installation of these systems and their components.

The level of detail addressed by the represented systems includes the major systems considered by experienced schedulers to develop an initial schedule.

01 SUBSTRUCTURE

011	Standard Foundations	
* 011/1000		Column Foundations²
011/2000		Continuous Foundations
* 011/3000		Foundation Walls¹
011/4000		Column Piers

012	Special Foundations	
012/1000		Special Foundations

* 013	Slab on Grade	
013/1000		Slab on Grade
013/2000		Steps on Grade

014	Basement Excavation	
014/1000		Basement Excavation

015	Basement Walls	
015/1000		Basement Walls

02 STRUCTURAL FRAME

* 021	Floor Construction	
021/1000		Floor Construction¹

* 022	Roof Construction	
022/1000		Structural Framing
022/2000		Roof Deck
022/3000		Concrete Topping

023	Stair Construction	
023/1000		Stair Construction

03 ROOFING

* 031	Roofing	
031/1000		Roof Covering
031/2000		Roof Insulation
031/3000		Roof Flashing
031/4000		Roof Openings

04 EXTERIOR CLOSURE

041	Exterior Walls	
* 041/1000		Exterior Wall Construction¹
041/2000		Interior Skin Construction
041/3000		Screen Walls
041/4000		Soffits & Fascia
041/5000		Exterior Finishes

* 042	Exterior Doors	
042/1000		Metal Doors
042/2000		Fully Glazed Doors
042/3000		Wood Doors
042/4000		Special Doors
042/5000		Gates

* 043	Exterior Windows	
043/1000		Operable Windows
043/2000		Fixed Windows
043/3000		Louvers

05 INTERIOR CONSTRUCTION

051	Interior Partitions - Fixed	
* 051/1000		Drywall
051/2000		Masonry

---

² Refer to Figure 6.3, p. 76, for additional levels of detail in the prototype.

```
051/3000                      Concrete

052    Interior Partitions - Moveable
       052/1000               Interior Partitions - Moveable

053    Interior Doors
       053/1000               Metal Doors
       053/2000               Fully Glazed Doors
       053/3000               Wood Doors
       053/4000               Special Doors

054    Interior Windows
       054/1000               Interior Windows
```

* 06 INTERIOR FINISHES[3]

```
061    Wall Finishes
       061/1000               Gypsum & Plaster Products
       061/2000               Masonry & Tile Products
       061/3000               Liquid Finishes
       061/4000               Paper, Plastic & Fabric
       061/5000               Woods
       061/6000               Metals
       061/7000               Glass
       061/8000               Finish Packages
       061/9000               Special Surfaces

062    Flooring & Floor Finishes
       062/1000               Gypsum & Plaster Products
       062/2000               Masonry & Tile Products
       062/3000               Liquid Finishes
       062/4000               Paper, Plastic & Fabric
       062/5000               Woods
       062/6000               Metals
       062/7000               Glass
       062/8000               Finish Packages
       062/9000               Special Surfaces

063    Ceilings & Ceiling Finishes
       063/1000               Gypsum & Plaster Products
       063/2000               Masonry & Tile Products
       063/3000               Liquid Finishes
       063/4000               Paper, Plastic & Fabric
       063/5000               Woods
       063/6000               Metals
       063/7000               Glass
       063/8000               Finish Packages
       063/9000               Special Surfaces
```

07 SPECIALTIES[2]

```
071    Toilet & Bath Specialties
       071/1000               Toilet & Bath Accessories

072    Cabinetry
       072/1000               Cabinetry

073    Shelving
       073/1000               Metal Shelving
       073/2000               Wood Shelving
       073/3000               Other Shelving

074    Other Specialties
       074/1000               Other Specialties
```

---

[3] "Interior Finishes" in the prototype includes a number of items: Specialties (07), Plumbing Fixtures (081/1000), HVAC Fixtures (092/2000, 093/200, 094/200), Fire Protection Systems Fixtures (101/1200, 101/3100), Electrical Receptacles & Plugs (112/7000), Lighting Fixtures (113/1000), and testing.

08 PLUMBING

- 081   Sanitary Systems
  - 081/1000   Fixtures[2]
  - 081/2000   Waste & Vent Systems
  - 081/3000   Cold Water Systems
  - 081/4000   Hot Water Systems

- 082   Rainwater Drainage
  - 082/1000   Fixtures
  - 082/2000   Drainage Systems

083   Special Plumbing Systems
- 083/1000   Compressed Air Systems
  - 083/1100   Equipment
  - 083/1200   Fixtures
  - 083/1300   Distribution Systems

- 083/2000   Industrial Gaseous Systems
  - 083/2100   Equipment
  - 083/2200   Fixtures
  - 083/2300   Distribution Systems

- 083/3000   Liquid Systems
  - 083/3100   Equipment
  - 083/3200   Fixtures
  - 083/3300   Distribution Systems

- 083/4000   Acid Waste System
  - 083/4100   Equipment
  - 083/4200   Fixtures
  - 083/43000   Distribution Systems

- 083/5000   Other Systems

084   Special Plumbing Fixtures
- 084/1000   Kitchen Systems
- 084/2000   Swimming Pools
- 084/3000   Hospitals
- 084/4000   Other

09 HEATING, VENTILATION, AND AIR CONDITIONING (H.V.A.C.)

- 091   Energy Supply System
  - 091/1000   Natural Gas System
    - 091/1100   Equipment/Meters/Regulators
    - 091/1200   Piping Systems

  - 091/2000   Fuel Oil Systems
    - 091/2100   Storage Systems
    - 091/2200   Transfer Systems
    - 091/2300   Distribution Systems

  - 091/3000   LPG Systems
    - 091/3100   Storage Systems
    - 091/3200   Transfer Systems
    - 091/3300   Distribution Systems

  - 091/4000   Steam (Supplied form Central)
    - 091/4100   Pressure Reducing/Regulations System
    - 091/4200   Distribution Systems

  - 091/5000   Chilled Water (Supplied from Central)

  - 091/6000   Solar Systems
    - 091/6100   Equipment
    - 091/6200   Piping

  - 091/7000   Other Generation Systems

- 092   Heating Generation Systems
  - 092/1000   Equipment

092/2000	Fixtures[2]
092/3000	Interconnecting Piping System
092/4000	Distribution Piping Systems

* 093	Cooling Generation Systems
093/1000	Equipment
093/2000	Fixtures[2]
093/3000	Interconnecting Piping System
093/4000	Distribution Piping Systems

* 094	Air Handling (Conditioned (Heated or Cooled)) Systems
094/1000	Equipment
094/2000	Fixtures[2]
094/3000	Distribution Systems

095	Ventilation Systems
095/1000	Equipment
095/2000	Fixtures
095/3000	Distribution Systems

096	Exhaust Systems
096/1000	Equipment/Fixtures
096/2000	Fixtures
096/3000	Distribution/Collection Systems

097	Special Systems
097/1000	Clean Rooms
097/2000	RF Shielding
097/3000	Paint Spray Booths
097/4000	Special Air Filtration
097/5000	Humidity Control Systems
097/6000	Other

098	Controls and Instrumentation
098/1000	Devices
098/2000	Transmission Media

099	Testing, Balance, etc.
099/1000	Test and Balance[2]
099/2000	Identification Systems
099/3000	O & M Data

10 SPECIAL MECHANICAL SYSTEMS

101	Fire Protection Systems
* 101/1000	Wet Sprinkler Systems
101/1100	Devices
101/1200	Fixtures[2]
101/1300	Equipment
101/1400	Distribution Systems
101/1500	Pumping Systems

101/2000	Dry Sprinkler Systems
101/2100	Devices
101/2200	Fixtures
101/2300	Equipment
101/2400	Distribution Systems
101/2500	Pumping Systems

* 101/3000	Standpipe Systems
101/3100	Fixtures[2]
101/3200	Equipment
101/3300	Distribution Systems

101/4000	Extinguishers
101/4100	Dry Chemical
101/4200	Carbon Dioxide
101/4300	Water
101/4400	Soda Acid

| 101/5000 | Halon Systems |

101/6000	Hood and Duct Systems
101/7000	Other Systems

102   Pool Systems
102/1000	Devices
102/2000	Fixtures
102/3000	Equipment
102/4000	Distribution Systems

103   POL Systems
103/1000	Devices
103/2000	Fixtures
103/3000	Equipment
103/4000	Distribution Systems

104   Refrigeration Systems
104/1000	Devices
104/2000	Fixtures
104/3000	Equipment
104/4000	Distribution Systems

105   Process Systems
105/1000	Devices
105/2000	Fixtures
105/3000	Equipment
105/4000	Distribution Systems

106   Water/Waste Treatment Systems
106/1000	Devices
106/2000	Fixtures
106/3000	Equipment
106/4000	Distribution Systems

107   Chimneys and Stacks
107/1000	Devices
107/2000	Fixtures
107/3000	Equipment
107/4000	Distribution Systems

108   Other Misc. Systems
108/1000	Devices
108/2000	Fixtures
108/3000	Equipment
108/4000	Distribution Systems

11 INTERIOR ELECTRICAL

* 111   Service and Distribution System
111/1000	Underground Empty Conduits (to 5' outside building)
111/2000	Overhead Service Feeder (and Weatherhead)
111/3000	Main Protection Equipment
111/4000	Primary Transformers
111/5000	Power Protection Equipment
111/6000	Secondary Transformers
111/7000	Lighting Protection Equipment
111/8000	Power and Lighting Distribution
111/9000	Special Equipment
111/9100	Metering
111/9200	Capacitors

* 112   Power Systems
112/1000	Electrical Equipment Connections
112/1100	Equipment by Electrical
112/1200	Equipment Furnished by Others (FBO)

112/2000	Safety Switches and Breakers
112/2100	Fusible Safety Switches
112/2200	Non-Fusible Safety Switches
112/2300	Circuit Breakers

112/3000	Motor Starters

112/3100	Manual Full Voltage Non-Reversing
112/3200	Magnetic FVNR
112/3300	Magnetic Reversing
112/3400	Reduced Voltage
112/4000	Contactors and Relays
112/4100	Magnetically Held Non-Reversing
112/4200	Mechanically Held Non-Reversing
112/4300	Magnetically Held Reversing
112/4400	Mechanically Held Reversing
112/4500	Time Delay Relays
112/5000	Time Switches
112/6000	Photoelectric Control
112/7000	Receptacles and Plugs[2]
112/7100	Wiring Devices
112/7200	Power Receptacles and Plugs
112/8000	Power Distribution

113   Lighting Systems

113/1000	Lighting Fixtures[2]
113/1100	Incandescent
113/1200	Quartz
113/1300	Fluorescent
113/1400	Mercury Vapor
113/1500	Multi Vapor
113/1600	High Pressure Sodium
113/1700	Low Pressure Sodium
113/1800	Emergency Lighting
113/1900	Special Lighting Fixtures
113/2000	Lighting Controls
113/3000	Lighting Distribution

114   Grounding Systems

114/1000	Electrical Service Ground
114/2000	Building Structure Ground
114/3000	Lightning Protection
114/3100	Air Terminals
114/3200	Mounting Devices
114/3300	Conductors
114/3400	Fastening Devices
114/3500	Ground Rods
114/3600	Connectors
114/3700	Exothermic Welds
114/4000	Computer System Ground
114/5000	Special Grounding Systems
114/6000	Trench and Backfill
114/7000	Raceways

12 SPECIAL INTERIOR ELECTRICAL SYSTEMS

121   Sound Systems

121/1000	Telephone Systems
121/1100	Telephone Systems
121/1200	Central Switchboard
121/1300	Telephone Sets
121/1400	Underground Ducts
121/1500	Manholes
121/2000	Intercommunication Systems
121/3000	Public Address Systems
121/4000	Radio Communication Systems
121/5000	Sound Distribution

122   Alarm Systems

| 122/1000 | Fire Alarm Systems |
| 122/2000 | Intruder Detection Systems |

| 122/3000 | Equipment Alarm Systems |
| 122/4000 | Alarm Distribution |

123   Television Systems
123/1000	Master Antenna Systems
123/2000	Closed Circuit TV Systems
123/3000	TV Distribution

124   Control Systems
124/1000	Energy Management and Control Systems
124/2000	Radio Control Systems
124/3000	Control Distribution

125   Hospital Systems
125/1000	Nurses Call Systems
125/2000	Doctors Paging Systems
125/3000	Doctors Register Systems
125/4000	Ground Detection Systems
125/5000	Narcotics Alarm Systems
125/6000	Oxygen Alarm Systems
125/7000	Distribution Systems

126   Time Systems
| 126/1000 | Clock and Program Systems |
| 126/2000 | Distribution Systems |

127   Electric Heating Systems
127/1000	Baseboard Heaters
127/2000	Wall and Ceiling Heaters
127/3000	Industrial Unit Heaters
127/4000	Duct Heaters
127/5000	Heating Cables
127/6000	Distribution Systems

128   Power Generation Systems
128/1000	Engine Generator Sets
128/1100	Gasoline Powered
128/1200	Diesel Powered
128/1300	Vapor Gas Powered
128/1400	Turbine Engine Powered
128/1500	Transfer Switches
128/1600	Accessories
128/1700	Power Distribution

128/2000	Uninterruptible Power Systems
128/2100	Static Charger-Battery
128/2200	Motor-Generator Battery
128/2300	Inertia Flywheel Motor Generator
128/2400	Power Distribution

128/3000	Emergency Battery System
128/4000	Wind Power System
128/5000	Solar Power System

* 13 EQUIPMENT & CONVEYING

131   Fixed and Moveable Equipment

132   Furnishings

133   Special Construction
| 133/1000 | Special Construction |

134   Conveying Systems
| 134/1000 | Conveying Systems |

14 SITE PREPARATION

141   Clearing
* 141/1000	Clearing & Grubbing
* 141/2000	Tree Removal
141/3000	Selective Thinning

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141/4000	Tree Pruning

142 Demolition
* 142/1000	Building Demolition

142/2000	Site Demolition
* 142/2100	Pavement Removal
142/2200	Fence Removal
142/2300	Wall Removal
142/2400	Curb Removal
142/2500	Catch Basin/Manhole Removal
142/2600	Cap Existing Utilities
142/2700	Miscellaneous Removals

142/3000	Relocations
142/3100	Building Relocation
142/3200	Shrub/Tree Relocation
142/3300	Utility Relocation

143 Site Earthwork
143/1000	Site Grading
143/1100	Site Grade-Cut/Fill
143/1200	Rough Grading

* 143/2000	Site Excavating
143/2100	Strip/Stockpile Topsoil
143/2200	Bulk Excavation (Stockpile)
143/2300	Waste Material Disposal

143/3000	Borrow Fill
143/3100	Borrow Excavation and Site Fill
143/3200	Borrow (Purchased) and Site Fill
143/3300	Fill Compaction

143/4000	Soil Stabilization
143/4100	Erosion Control to Slopes
143/4200	Pressure Grouting
143/4300	Lime Slurry Injection
143/4400	Soil Cement Treatment

143/5000	Soil Treatment
143/5100	Termite Control
143/5200	Vegetation Control

143/6000	Site Dewatering
143/6100	Pumping
143/6200	Well Points
143/6300	Gravity Drainage

143/7000	Site Shoring
143/7100	Sheeting/Shoring
143/7200	Tiebacks and Anchors

15 SITE IMPROVEMENTS[4]

151 Pavements
151/1000	Parking Lots
151/1100	Bituminous
151/1200	Concrete
151/1300	Other Surfaces
151/1400	Pavement Marking
151/1500	Curbs, Rails & Barriers
151/1700	Parking Lot Structures

151/2000	Roads
151/2100	Bituminous

---

[4] Site Improvements and Site Utilities were not considered in the prototype because they are outside the footprint of the building. Early on in the implementation phase it was decided to exclude all systems outside the building footprint.

151/2200	Concrete
151/2300	Other Surfaces
151/2400	Curbs & Gutters
151/2500	Rails & Barriers
151/2600	Pavement Markings

151/3000	Walks
151/3100	Bituminous
151/3200	Concrete
151/3300	Precast Pavers
151/3400	Brick Paving
151/3500	Limestone Paving
151/3600	Flagstone Paving
151/3700	Granite Paving
151/3800	Other Materials
151/3900	Edging

151/4000	Steps
151/4100	Concrete
151/4200	Wood
151/4300	Metal
151/4400	Step Treads & Risers

| 151/5000 | Terraces and Plazas |

152	Site Development
152/1000	Fence & Gates
152/1100	Chain Link Fences & Gates
152/1200	Mesh Fences & Gates
152/1300	Wood Fences & Gates
152/1400	Other Fences & Gates

152/2000	Walls
152/2100	Retaining Walls
152/2200	Terrace & Perimeter Walls

152/3000	Signs
152/3100	Directories
152/3200	Directional/Traffic Signs
152/3300	Building Identification Signs

152/4000	Site Furnishings
152/4100	Benches & Seats
152/4200	Trash Receptacles
152/4300	Drinking Fountains
152/4400	Mail Boxes
152/4500	Picnic Tables
152/4600	Bicycle Racks
152/4700	Telephone Booths
152/4800	Other Site Furniture

152/5000	Fountains & Pools
152/5100	Pools
152/5200	Fountains

152/6000	Playing Fields & Sports Facilities
152/6100	Baseball Fields
152/6200	Football Fields
152/6300	Tennis Courts
152/6400	Athletic Tracks
152/6500	Bleachers

| 152/7000 | Flagpoles |
| 152/8000 | Miscellaneous Structures |

153	Landscaping
153/1000	Fine Grading & Soil Preparation
153/1100	Fine Grading
153/1200	Fertilizer Application
153/1300	Limestone Application

| 153/2000 | Top Soil & Planting Beds |

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153/2100                    Spreading Topsoil
153/2200                    Plant Beds

153/3000                Seeding & Sodding
153/3100                    Seeding
153/3200                    Sodding

153/4000                Plantings
153/4100                    Groundcover
153/4200                    Deciduous Trees
153/4300                    Evergreen Trees
153/4400                    Flowering Trees
153/4500                    Evergreen Shrubs
153/4600                    Flowering Shrubs
153/4700                    Hedges
153/4800                    Flowers & Bulbs

153/5000                Planters
153/5100                    Built-in Planters
153/5200                    Prefabricated Planters
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16 SITE UTILITIES[5]

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161     Water Supply & Distribution
161/1000                Well Systems

161/2000                Potable Water Distribution
161/2100                    Utility Services Connection
161/2200                    Excavating & Backfilling
161/2300                    Pipe & Pipe Fittings
161/2400                    Valves
161/2500                    Valve Boxes
161/2600                    Thrust Blocks

161/3000                Potable Water Storage
161/3100                    Ground Water Storage Tank
161/3200                    Elevated Water Storage Tank
161/3300                    Water Reservoirs
161/3400                    Pumps

161/4000                Fire Protection System
161/4100                    Fire Hydrants
161/4200                    Excavation & Backfilling
161/4300                    Pipe & Pipe Fittings
161/4400                    Valves
161/4500                    Valve Boxes

161/5000                Irrigation Systems
161/5100                    Excavation & Backfilling
161/5200                    Pipe & Pipe Fittings
161/5300                    Sprinkler Heads
161/5400                    Valves
161/5500                    Controllers

162     Drainage & Sewage Systems
162/1000                Storm Drainage
162/1100                    Excavation & Backfilling
162/1200                    Pipe & Fittings
162/1300                    Manholes
162/1400                    Catch Basins
162/1500                    Curb Inlets
162/1600                    Dry Wells
162/1700                    Headwalls
162/1800                    Retention Ponds
162/1900                    Lift Stations

162/2000                Sanitary Sewer
162/2100                    Excavation & Backfilling
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[5] See footnote 3 on p. 144.

162/2200	Pipe & Pipe Fittings
162/2300	Manholes & Cleanouts
162/2400	Septic Tanks
162/2500	Title Fields
162/2600	Distribution Boxes
162/2700	Lift Stations
162/3000	Process & Acid Waste Systems

163   Heating Distribution Systems

163/1000	Hot Water & Steam Supply System
163/1100	Excavation & Backfilling
163/1200	Pipe & Fittings
163/1300	Valves
163/1400	Insulation
163/1500	Valve Pits
163/1600	Distribution Equipment

164   Cooling Distribution System

164/1000	Chilled Water Supply System
164/1100	Excavation & Backfilling
164/1200	Pipe & Fittings
164/1300	Valves
164/1400	Insulation
164/1500	Valve Pits
164/1600	Distribution Equipment

165 ·   Gas Distribution System

166   Exterior Electrical

166/1000	Substations
166/1100	Metering
166/1200	Steel Structure, Buses and Insulators
166/1300	Primary Switches
166/1400	Transformers
166/1500	Oil Circuit Breakers
166/1600	Voltage Regulators
166/1700	Capacitors
166/1800	Lightning Arrestors
166/1900	Grounding
166/2000	Overhead Power Distribution
166/2100	Poles & Conductor Supports
166/2200	Conductors
166/2300	Transformers
166/2400	Switches & Fuse Cutouts
166/2500	Lightning
166/2600	Capacitors
166/2700	Metering
166/3000	Underground Power Distribution
166/3100	Raceways
166/3200	Manholes
166/3300	Cables and Terminations
166/3400	Pad Mounted Transformers
166/3500	Switches and Fuse Cutouts
166/3600	Lightning Arrestors
166/3700	Capacitors
166/3800	Metering
166/4000	Overhead Communications & Alarm Systems
166/4100	Telephone Systems
166/4200	Sound Systems
166/4300	Fire Alarm Systems
166/4400	Intruder Detection Systems (IDS)
166/5000	Underground Communication & Alarm Systems
166/5100	Telephone Systems
166/5200	Sound Systems
166/5300	Fire Alarm Systems
166/5400	Intruder Detection Systems (IDS)

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