Sequencing Knowledge for Construction Scheduling

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Abstract: This paper describes and formalizes knowledge utilized by skilled schedulers for sequencing construction activities. Although it is recognized that construction scheduling involves many tasks (activity identification, duration estimation, etc.), the focus here is limited to an understanding of a number of key activity sequencing principles. This paper provides a grammar or language that represents governing factors for construction activity sequencing. Four basic factors are identified and described in detail. The physical relationships that exist among the different building components is one of the factors. Another is the interaction of construction trades. Sequencing is also affected by the requirement of an interference-free path for all the objects to be displaced around the job site at construction time. Code regulations are also relevant for determining the order of execution of certain activities. A discussion of the flexibility of these four different sequencing constraints and of their relation to time is also presented. Finally, a brief overview of a knowledge-based prototype system that incorporates a few of the identified sequencing governing factors is provided.

Introduction

A vital part of construction planning is the appropriate scheduling of the different activities necessary to deliver the constructed facility. This is a task that demands experience and knowledge of construction issues. Good construction planners gain considerable scheduling knowledge by participating in the planning and control of actual projects.

The generation of a construction schedule involves varied processes, like producing a meaningful breakdown of a project into activities, allocating resources (manpower, equipment, etc.) and attempting to optimize their use, and others. One of the crucial problems faced when generating a construction schedule is to produce an adequate sequencing of the activities involved. The scope of this paper is limited to an understanding of a number of key factors that dictate activity precedence relationships. In that sense this paper is discussing only one of the multiple aspects that pertain to construction scheduling.

As mentioned, considerable knowledge utilized in the sequencing process is acquired through experience. There is little treatment of the topic of construction activity sequencing in the literature. Our intention is to contribute to fill this void by starting a formalized body of knowledge for activity sequencing.

The research described here is part of a broader effort that utilizes a knowledge-based systems (KBS) approach for generating construction

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schedules. The purpose of this paper is to provide the results of the research that the writers have performed for understanding and formalizing the fundamentals of construction activity sequencing. These results provide a grammar or language that represents the factors and relationships from which activity sequences are derived. An extensive interaction program with schedulers of five different construction firms has provided the basis for the present report.

This work has focused on midrise building construction. However, the discussion is such that it can be extended to other facility types.

Background

Some researchers have addressed the problem of understanding the factors that dictate the sequencing of construction activities. A brief description is provided here of the contribution of their work to this area.

One of the most relevant previous studies was performed by Gray and his assistants (Gray 1986). Their approach consisted of examining schedules produced by different contractors for construction of a laboratory building. Their main contribution is the identification of some basic relationships among building components that govern the sequencing of the activities that install these components. Among others, Gray identified relationships like building components "covered by" or "weather protected by other components" as those dictating sequencing.

A recent paper by Simons et al. (1988) describes the work at Bechtel, Inc. in the area of power-plant construction scheduling. The result is a construction simulation system that incorporates sequencing constraints derived from the relative position of the different physical components being assembled. In addition, the system accurately simulates the geometry of the construction site and the components being handled, and detects spatial interferences that result from a given activity sequence.

Recent work performed by Kartam and Levitt (1989) also deals with activity sequencing. Their approach is to assume the existence of only two activity-sequencing governing factors (or "general principles," as they label them): (1) Gravity support, like a column supporting a beam; and (2) items enclosed by other items, like the exterior walls enclosing interior components.

Zozaya-Gorostiza and Hendrickson (1988) at Carnegie Mellon University have also produced a system to schedule construction activities. Their approach is limited to the scheduling of activities to erect the structural members. Activity sequencing is performed by identifying and installing members connected to other members already in place. Identification of connecting members is tied to a Master format classification of the members.

Research work has been performed at Massachusetts Institute of Technology (MIT) related to this area (Navinchandra et al. 1988; Cherneff 1988). Their approach to represent the constraints that dictate activity sequencing is focused on the identification of elements "supported by" or "connected to" those already in place.

The reader can observe that a common core exists among the cited papers. All of them utilize some physical relationships among building components to produce an activity sequence. The work described here complements and extends the understanding of activity sequencing reached by the mentioned authors. To our knowledge, it is the first comprehensive attempt to formalize the basic factors that govern the sequencing of construction operations.

Methodology

The overall research work follows a KBS approach and consists of three main phases: (1) Knowledge acquisition from expert schedulers; (2) formalization of the acquired knowledge; and (3) prototype system generation. This paper focuses specifically on activity sequencing knowledge and its formalization. Other aspects of this work are described in (Echeverry et al. 1989), and in forthcoming publications.

Several experienced construction schedulers from different construction firms have contributed to this work. The scheduling knowledge elicitation was performed by: (1) Going through the process of generating a schedule for a midrise building; and (2) discussing schedules produced by the experts for different construction jobs.

Factors that Govern the Sequencing of Activities

Facility construction is accomplished by assembling components in a particular order or sequence. The notion of an activity is associated with the installation operations related to each of those components. In this paper it is assumed that an activity either installs, removes, modifies, or tests a particular component of the facility. 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 present work should be considered as an initial step in the formalization of sequencing knowledge.

As mentioned, the objective of this paper is to examine the different constraints that govern the sequencing of activities required to construct a facility. These constraints have been grouped into four major factors, described in the next few sections, and summarized in Table 1.

TABLE 1. Identified Factors that Govern Activity Sequencing

Governing factor (1)	General description (2)
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 intercomponent relationships
Trade interaction	Activity sequencing also responds to different ways in which trades affect each other during construction phase
Path interference	Building components have to be moved around jobsite in order to be installed. Activity sequence has to guarantee an interference-free path for installation of any component
Code regulations	Activity sequencing is also responsive to construction-phase safety considerations

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Physical Relationships Among Building Components

Activity sequencing logic in part responds to the way building components are physically related to each other. Building components can be permanent, like a column or a floor deck; and 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 herein. Examples of each are provided in Fig. 1.

Supported By

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.

Covered By

An analogous situation occurs for an activity that deals with a component that covers another component. Examples of this relationship are necessary to help in determining its applicability. A wall is covered by paint. Similarly, mass excavation material may be covered by an existing parking-lot pavement.

Embedded In, Contributing to Structural Function

This relationship among components occurs when one of the components has to be inside the other so that both cooperate for a structural function. An example is reinforcement inside a cast in place concrete element. The reinforcement should be placed before the concrete is cast. Another example, described in Fig. 1, deals with a situation in which the first-tier steel columns are embedded in the concrete foundation wall.

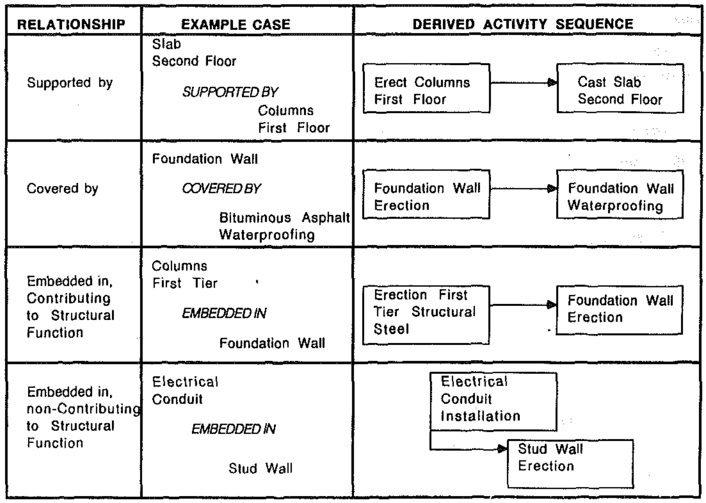
An exception to this rule is the installation of posttensioning reinforcement. However, even in this case, the reinforcement should be installed prior to the embedding matrix (grout).

Embedded In, Noncontributing to Structural Function

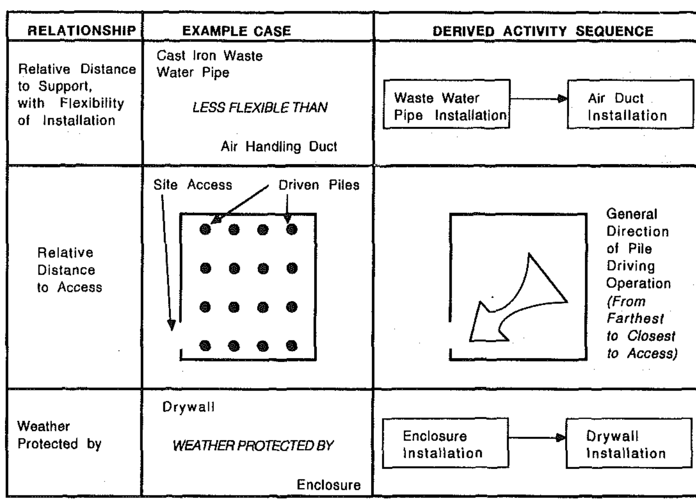
There are situations in which a component is embedded into another, but there is no structural function that depends on the components being together. Electrical conduit embedded into a masonry wall is a common case that exemplifies this situation. Typically, the embedded component is either installed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

Relative Distance to Support, with Flexibility of Installation

When two components are supported by a common third component, the



(a)



(b)

FIG. 1. Selected Examples of Activity Sequencing Derived from Building-Component Physical Relationships

installation order is affected by their distance to the support and by the flexibility of their installation. 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 former 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. The flexibility of installation is related to two aspects: (1) The flexi-

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bility of the component's material (PVC conduit is very flexible, cast-iron pipes are not); and (2) the importance of position for the component's function (a wastewater drainage pipe for instance has a strict slope constraint).

Relative Distance to Access

This relationship among building components applies in the case in which there are several identical components that have to be installed in a work 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 room painting.

Weather Protected By

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 Fig. 1, drywall installation should follow enclosure installation completion.

There are different kinds of weather sensitivity. Building components can be weather sensitive because of their composition. For example, water is frozen in freezing temperatures. Another possible reason for weather sensitivity is the installer's (crew or equipment) inability to operate under certain weather circumstances.

The most common weather factors are: (1) Precipitation, humidity, or moisture sensitivity (like drywall or paint); (2) cold-temperatures sensitivity (water-filled pipes prone to freeze are an example); (3) hot-temperatures sensitivity (e.g., cast-in-place concrete); and (4) high-winds sensitivity (like structural steel).

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. If no particular action is taken to prevent or control this negative effect, this situation is not relevant for activity sequencing. Risk can be reduced however, by planning to avoid the execution of nonprotected activities during the season(s) when the affecting weather conditions occur.

Trade Interaction

Construction involves a complex interaction of people, equipment, and materials (here defined as trade interaction). At a given point in time, dozens of crews may be operating on the site, with many of them constrained in their actions due to the presence and actions of others.

This means interaction among trades is a primary governing factor for activity sequencing. Activities represent the actions of the different crews, and therefore sequencing is 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 Fig. 2.

INTERACTION TYPE	EXAMPLE CASE	DERIVED ACTIVITY SEQUENCE
Space Competition	Concrete Slab Shoring *OCCUPIES SPACE REQUIRED BY* Interior Wall Layout Crew	Slab Shoring Removal → Interior Wall Layout
Resource Limitation	Enclosure Precast Panels Installation Crew *COMPETES FOR CRANE WITH* Box Culvert Installation Crew	Enclosure Installation ***Cannot be Concurrent With*** Box Culvert Installation
Unsafe Environment Effects	Rough Plumbing Crew *IS SENSITIVE TO* Steel Fireproofing Spray	Structural Steel Fireproofing → Rough Plumbing

(a)

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 → Elevator Installation

(b)

FIG. 2. Selected Examples of Activity Sequencing Derived from Trade Interaction

Space Competition

The space that a crew and its corresponding equipment occupy can be viewed as a special type of resource in the sense that the availability of the space 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 desirable. For example, the crews that operate on a recently finished concrete floor slab may have to wait until the formwork shoring of 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. It is clear that under this circumstance the operation of the different crews involved may be far less than optimal, but it is still possible. This indicates that the space-limitation constraint is not rigid.

Resource Limitations

If two activities operate simultaneously but compete for the same limited resource, a linear (nonparallel) sequencing of these activities is mandatory. Typically, activities using a crane or vertical lift are scheduled serially.

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Unsafe Environment Effects

Environment effects are defined here as the modifications in air quality, temperature, humidity, brightness, noise level, etc., that are produced on a work area by a crew and its equipment. Almost any construction activity has environment effects as a by-product 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 with the application of substances that produce volatile and flammable fumes, like some paints.

An interesting situation occurs, beyond the scope of this paper but relevant enough to be pointed out, when the environment effect caused by the progress of one activity disturbs the performance of other crews. Although there is no reflection on the activity sequencing, the productivity of the disturbed crew can be substantially affected.

Damaging of Installed Building Components

If a certain activity damages the finished work of another activity, then the damageable work should be performed afterwards. This is a very 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.

Requirement of Service

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

A very special case of service is the test, inspection, or approval by a supervisor or management crew of work in place, 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 later discussed in more detail.

Path Interference

This sequencing constraint relates to the effect of path interferences occurring at installation time. When a building component is ready to be installed it has to be transported from its temporary site storage location to its designed and permanent place (refer to Fig. 3). This necessarily requires the existence of an interference free path. It is important to note that 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.

The requirement of an interference free path tends not to be a dominant constraint for building construction activity sequencing. Most of the systems are installed in such a way that the preassembled parts or building components to be transported within the construction site are small.

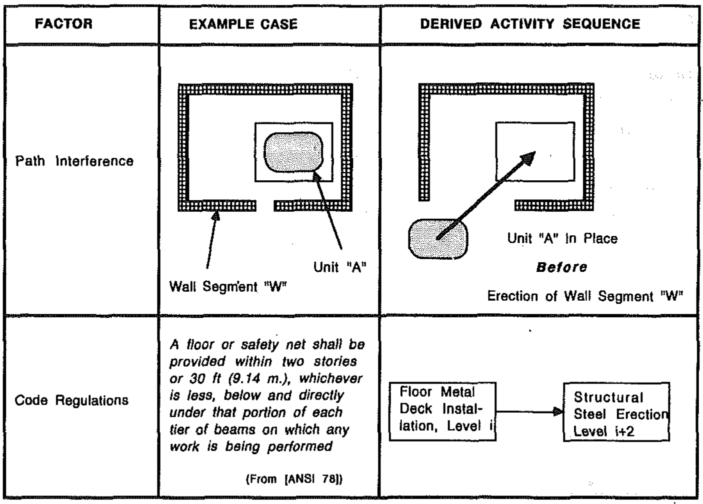

FIG. 3. Selected Examples of Activity Sequencing Derived from Interference-Free Path Requirements and Code Regulations

However, this constraint is extremely relevant for industrial construction. This type of construction usually involves the installation of large preassembled units that have to fit into their final position.

Code Regulations

Code regulations that contribute to govern activity sequencing are mainly related to: (1) The safety of workers and the general public during the construction stage; and (2) the inspection of the quality of work in place.

An example of this situation consists of the erection of steel frames (see Fig. 3). Today the Occupational Safety and Health Administration (OSHA) requires the installation of a temporary or permanent floor not more than two stories or 30 ft (9.14 m) below the actual frame erection operation ("American National" 1978; "Construction Industry" 1987). 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.

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.

Inflexible Constraints

An inflexible constraint is such that the activity sequencing imposed by this constraint is not practically modifiable with existing construction methods. A clear 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

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beams), the installation of the latter has to precede the installation of the former.

The constraints falling in this category can be easily 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 in the sense that it is unlawful to disobey them. Code regulations do change with time, though.

Flexible Constraints

Other constraints can be classified as flexible constraints. The critical question is how to quantify the degree of flexibility. It is difficult to determine with accuracy for any of the constraints described here. This is because the degree of flexibility is project- and contractor-dependent. For example, a contractor may decide to utilize 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. All the constraints not classified here as inflexible, are considered flexible.

The flexibility of sequencing constraints is a valuable tool that a contractor can utilize for the benefit of the project in diverse negative 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 by-passed, an increase in risk, time effort, or cost should be expected.

Time Dependence of Scheduling Logic

This section focuses on the relevance of time to the different scheduling constraints. Certain sequencing constraints can be applied independently of the timing of the affected activities. This is seen in the steel beams and metal deck installation example mentioned previously. Independently of the start and finish times of these two activities, the steel-beams installation has to precede the metal-deck installation.

However, some sequencing constraints require an overlap in the execution times of the affected activities to become valid. This is the case of an activity affecting the environment. Only those activities that coincide in time with this activity and that are sensitive to the effect should be resequenced. The constraints that fall into this category are here called time dependent:

- Space competition.
- Resource limitations.
- Unsafe environment effects.

Time 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).

Overview of a Knowledge-Based Approach to Support Activity Sequencing

It was mentioned that the research results presented here are part of a larger research effort to produce a knowledge-based schedule generation system. The intention in this paper is to describe only the part of the prototype system that deals with the sequence determination for a given set of activities. The suggestion by an anonymous reviewer of expanding the prototype implementation discussion is not appropriate here due to space limitations. However, this will be covered in detail in forthcoming papers.

The environment used for the implementation work offers the possibility of storing information both in rule-based and frame-based form. Frame representation is utilized to describe different objects (or frames), such as building components, activities, and construction spaces, and the different relationships among them. The constraints that govern activity sequencing are represented as relationships among the objects involved. For example, the initial level of columns is supported by pile caps (refer to Fig. 4). The resulting activity sequences (pile-cap installation precedes column erection in the example case) are deduced by utilizing rules similar to the one shown in Fig. 4.

Practical Applications

An important contribution of this work is formalization of knowledge employed by industry experts for sequencing construction activities. Multiple benefits can be derived from a formal understanding of the reasons that determine the sequence of construction activities. One important benefit is to

EXAMPLE OF RULE

IF Component "BC2" is supported by Component "BC1"
Activity "A2" installs Component "BC2"
Activity "A1" installs Component "BC1"

THEN

Activity "A1" precedes Activity "A2"

EXAMPLE OF OBJECTS (selected attributes shown only)

Activity Object PILE CAP INSTALLATION
PRECEDED BY: Activity Pile Driving
PRECEDES: Activity First tier Columns Erection
START TIME: t1
FINISH TIME: t2
ASSOCIATED CREW: PC-10
DURATION: Y days

Building Component Object PILE CAP
INSTALLED BY: Activity Pile Cap Installation
SUPPORTED BY: Piles
SUPPORTS: First tier Column
QUANTITY: X cu.yd.

FIG. 4. Examples of Rules and Objects

serve as an aid for the scheduling of construction projects, both for determining activity sequences and for evaluating tentative schedules.

In addition, once the knowledge used to sequence activities is embedded into a KBS, this system can play the role of an intelligent assistant for producing schedule templates. It can alleviate the amount of time and effort that the production of a schedule demands from experienced and expensive personnel.

Another very important benefit of formalizing activity-sequencing knowledge is training of inexperienced personnel. The current approach to training construction personnel in scheduling is by participation in project schedule development. Their training period can be substantially reduced if the knowledge that field personnel are expected to acquire is at least partially formalized and made available to them.

Conclusions

Generating a construction schedule demands substantial experience and practical knowledge on the part of the scheduler. This paper formalizes relevant knowledge employed for logically sequencing operations for building construction. It presents a grammar or language to express and communicate the knowledge underlying construction activity sequencing.

We hope that it will serve as a platform for the development of intelligent construction planning systems, like the one the writers are currently developing. It is also hoped that it will contribute to faster training and better performance for construction planners.

Future development of this work will tackle the representational difficulties associated with space and resource competition as they affect sequencing constraints. In this respect, particular attention is being given to the concept of fuzzy logic (Chang et al. 1990). Also, suggestions by anonymous reviewers to examine overall scheduling strategy (i.e., search of an optimal schedule satisfying given constraints) are also considered for further research.

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