Space Planning Method for Multistory Building Construction

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Abstract: This paper presents a space planning method for multistory building construction. Current formal space planning in practice is limited to site layout and logistics, where space is needed for activities for extended periods of time. The space planning needed to sequence activities inside a building under construction is often neglected. The proposed space planning method is a manual method that provides a logical order and priority for space planning decisions. This helps a construction planner to: (1) identify the specific spaces needed for activities; (2) define locations for these spaces on building floors; (3) develop a sequence of work that defines the order spaces are occupied; and (4) identify potential spatial conflicts. Detail is added to the plan as needed. Through evaluation of 74 activities on four case study projects, the proposed method was found to be an accurate representation of the planning needed in multistory building construction. Two applications of the planning method identified interference problems before they occurred in the field. This space planning method offers construction managers a useful technique to develop efficient interior sequences that minimize interference and work space congestion.

INTRODUCTION

Construction crews require space to move, store, and fabricate materials; and to perform work. Crews typically occupy space for short intervals of time and move through the building in different patterns depending on the nature of the work and materials used. Space often becomes scarce when multiple activities occur at the same time in close proximity. Numerous material handling paths and storage spaces also contribute to the challenge of finding adequate space to execute tasks. Space planning is needed to prevent interference between crews, equipment, and stored material.

This paper presents a planning method to include spatial considerations in the development of a construction sequence for enclosure and finish trades in three- to 10-story buildings. The method is represented by a process model that defines a logical order and priority for decisions necessary to produce construction space plans in a graphical format.

Industry Practice

Site logistic plans are the most common form of space management found in the industry. Plans are typically developed by a construction manager at the beginning of a project as a tool for allocating and managing space on the site for material deliveries, staging areas, and crane locations. Some site managers develop different plans for each phase of construction, which can be updated weekly. In rare cases, space is allocated directly on floors with painted markings or signs indicating material paths and storage areas. In most cases, however, detailed space allocation decisions are left to site personnel to be performed in a reactive manner. Variable productivity and the high uncertainty of spatially dependent relationships cause managers to ignore detailed space planning and provide buffers in the form of extra labor allowances or liberal (realistic) schedules.

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Recent Research

Previous research in the area of space planning in construction can be divided into two categories: (1) techniques for reducing work space congestion; and (2) scheduling techniques based on space constraints.

The time-space scheduling technique (Stradal and Cacha 1982) addresses the reduction of space congestion on a large scale and is best applied to linear projects, such as piping or paving operations, with large distinguishable work areas that can be parceled into smaller sections. This approach is most useful as a method for making preliminary estimates of congestion. Two possible solutions to high density work spaces are offered. The use of multicraft crews allows a single crew to perform several different inter-related activities at the same time. Also, altering design and construction methods to create on-the-job prefabrication allows separation of work crews by fabrication area.

Griffith (1984) also considers the impact of a structure's design on work space congestion. This study recognizes that complicated designs can contribute to congestion and recommends rationalizing awkward design details and designing so that maximum work can be undertaken in one operation by one crew.

Several techniques attempt to quantify space need and set square-foot-per-person limits on the number of workers allocated to an area at the same time. Parvis (1980) considers other resources as well through a conversion to "equivalent workers." Previous research has consistently shown that reductions in productivity result when the limit of one worker/300 sq ft is exceeded (Thomas 1990).

Recent research has focused on scheduling based on space constraints and the use of computers to allocate spaces to activities and tie spatial attributes to construction schedules. Smith (1987) presents an algorithm for computing a space-based project schedule based on a space demand profile. This method introduced the concept of an individual characterization of different types of activity space requirements.

The MovePlan system (Tommelein et al. 1992) allows space resources to be attached to each activity in a construction schedule and assigned positions by a user on the site for the duration of each activity. A conflict resolution module attempts to eliminate space conflicts on the site by adjusting the construction schedule (Tommelein et al. 1993). The MovePlan tool demonstrates the utility of a time-based layout of space. This form of space representation illustrates the impact of space requirements over time to a construction planner. Zouein (1995) developed MoveSchedule, an extension to MovePlan,

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which alleviates space conflicts by adjusting the construction schedule.

The SCaRC System (Thabet 1992) formally introduces space constraints into the construction scheduling process for multistory buildings. Space demand and space availability are compared for three classes of activities with variable spatial needs. A computer model decides whether or not to schedule an activity based on a space capacity factor that considers the impact of limited work space on productivity. Activity continuity status recognizes that some activities can be split into segments along typical floors or must progress continuously with no interruptions or work stoppages. A schedule is generated by considering space constraints before allowing an activity to start based on hard construction constraints (construction logic). Possible scheduling actions to resolve interference problems include: (1) decreasing the production rate of the activity according to the space capacity factor; (2) interrupting the flow of an activity based on the work continuity status; or (3) delaying the activity.

Previous research has identified key factors to consider during space planning and the need for time-based space planning. Current methods to address space planning focus on automated scheduling techniques and often rely on simplified models of space need. The present paper defines a space planning method for multistory building construction based on a detailed model of construction space need and patterns of space use.

Methodology

Space planning techniques on 10 case study projects were investigated through site visits, interviews, and a review of documented case studies. Space planning was also performed on a case study project. The 10 case studies and trial planning identified necessary plans to avoid interferences. These plans were then decomposed into information elements. The processes required to produce these plans were identified and placed in a logical order to define a space planning method. This method is represented in the IDEF$_0$ modeling methodology (*Integrated*, unpublished U.S. Air Force document, 1983) and shows relationships to a theoretical model of space, the construction space model (Riley 1995).

The space planning method was tested to demonstrate that it represents the planning processes needed on multistory construction projects. Interviews with experienced project managers evaluated the content of the model. Four case study projects were then evaluated to show a relationship between the performance of planning steps in the model and the existence of avoidable interference problems.

The final step of the research was to apply the planning method to two construction projects. These applications were performed to assess the ability of the planning method to detect interference problems before they occur in the field.

SPACE PLANNING METHOD

The space planning method is a process to formally develop an activity sequence for a three- to 10-story construction project using the design, material information, and construction schedule (Riley 1994). The resulting plan describes the sequence of activities, the sequence that materials are brought onto building floors, and the dynamic use of space during the project.

For this research the method was used manually. An automated version will be developed in subsequent research to decrease the planning effort and increase the number of analyses in a given time. The planning method uses patterns of needed space defined by a construction space model. The individual spaces needed by activities are classified according to the task performed in each space, e.g., unloading material, storage, and work areas. Behavior patterns for each ''type'' of space define the occurrence of these spaces, either at building, floor, or room levels; and the order that spaces are occupied by crews. The construction space model identifies 12 ''space types'' and a collection of three to six ''space behavior patterns'' for each.

The planning method is presented in the IDEF$_0$ modeling methodology and consists of three levels of detail. Level 0 provides an overview of the model. Level 1 specifies the four stages of the planning process that produce the key outputs. Each stage of level 1 includes a detailed sequence of processes, decisions, and supporting information used to develop each output (level 2), but are not described in detail in the present paper.

Create Construction Sequence

The highest level of the planning process model, level 0, describes the inputs, outputs, controls, and mechanisms for the overall planning process. At this level, the planning process is referred to as ''create construction sequence'' (Fig. 1).

The inputs to the planning process model (arrows entering the left side of the boxes in Fig. 1) describe information needed to make planning decisions. Material information is required to identify delivery, handling, and storage methods; and to determine the availability of materials for delivery to the site. Design information describes the shape, orientation, and physical relationships of materials. This can be represented as a product model that describes the decomposition of the different building systems into building, floor, and room levels. A construction schedule describes a time frame, initial logic network, and activity durations required to complete one typical floor of work. This schedule may or may not include initial considerations made for limited space and represents a typical level of formal planning by a construction manager found on construction projects.

The output of the planning method (arrows exiting the right side of the boxes in Fig. 2) is a set of information tools for construction managers. A work sequence describes the order in which individual trades complete their work in the building, on individual floors, and the order of successive and concurrent activities. A layout sequence is a graphical representation of the use of space during a sequence of time intervals, indicating the positions of space needed by work elements on building floors. The delivery sequence describes the order and quantities of materials that are unloaded onto building floors. The sequence is represented by milestone activities in the construction schedule that depend on available material paths, storage space, and the need for materials to supply subactivities on each floor.

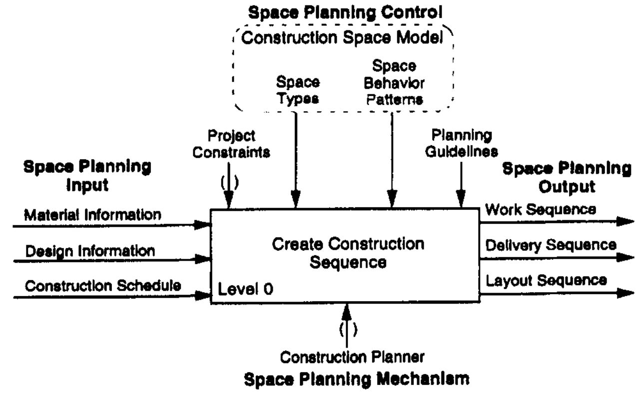

FIG. 1. Planning Process Model Level 0—Create Construction Sequence

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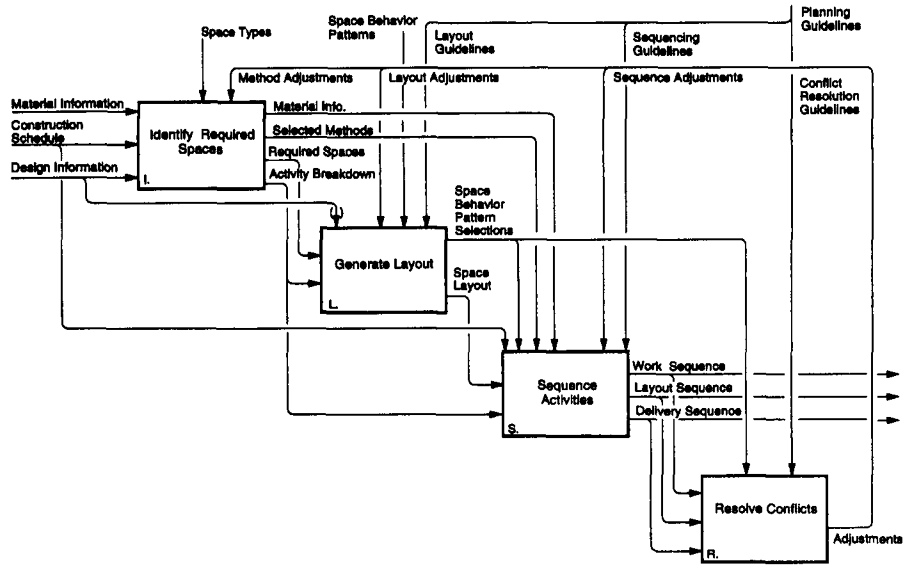

FIG. 2. Planning Process Model Level 2—Create Construction Sequence

Several items control or provide information for decisions in the planning process. These are represented as arrows entering the top of the boxes in Fig. 1. Project constraints consist of any outside factors that affect the decisions in the space planning process that are beyond the control of the planner. Space types represent the space occupied by, or available for, construction activity work elements. These are dictated by the methods selected to perform work. Space behavior patterns describe how activity work elements occupy space over time, e.g., spiral, linear, horizontal, or vertical. Patterns influence layout, sequencing, and conflict resolution decisions made during the planning process. Space planning guidelines collected through experience control layout, sequencing, and conflict resolution decisions in the planning method.

Each level-1 process is discussed in the following. Fig. 2 illustrates the four main processes in the planning process model and corresponding inputs, outputs, and controls in the $IDEF_0$ format. Table 1 lists the planning steps included in each stage of the process that support the detail behind Fig. 2. Fig. 3 illustrates the steps in the space planning processes for two sample activities, and will be referenced in the following text.

Identify (I) Required Spaces

In this function, the schedule of activities, specified materials, and design for the project are examined to determine what spaces will be needed for construction tasks. An initial construction schedule is used to identify which activities will be included in the space-based plan. Specified materials are examined to determine which materials are required for each activity and how much material will be needed on each floor. Design information is examined to determine the location and physical relationships among the materials.

Activities are decomposed into subactivities, which are completed on each floor; work units, which are completed in repetition; and work elements, which define the space types needed. The methods used for each work element determine how much space is required for each task. Fig. 3, step 1 illustrates how specific work spaces, material spaces, and paths required for each activity are identified based on selected construction methods and the types of spaces defined in the construction space model, e.g., activity 1 will require four work areas and an unloading area connecting an access point and two storage areas. The output of this process provides: (1) the breakdown of activities into work elements for layout and sequencing; (2) the specific activity spaces to be located in the building; (3) the method selections that determine the location of spaces; and (4) material information used to develop delivery sequences.

Generate Layout (L)

In this process, the locations for necessary spaces are assigned for each activity work element identified in the ''identify required spaces'' process. The activity breakdown and required spaces identified in step 1 are used to assign locations for the activity work elements. A specific space behavior pattern, as described in the construction space model, is selected for each activity work element, e.g., work is completed in a linear or spiral pattern, and stored material is distributed on floors or stacked in bulk. These patterns provide guidance to the location of individual spaces and the classification of spaces into building, floor, or room levels. Fig. 3, step 2 illustrates the layouts generated for two sample activities, e.g., locations of four work areas, an unloading area, and two distributed storage areas are defined for activity 1.

For each activity locations of spaces are identified on floor plans in the following order: (1) room-level spaces, dictated by the locations of work areas; (2) building-level spaces, which exist for extended durations and depend on building geometry; and (3) floor-level spaces, which connect or depend on locations of room- and building-level spaces. The output of this process is a space layout plan illustrating the position of spaces needed for subactivities on each floor and a set of space behavior patterns that describe how crews will move through space. It is important to note that this layout process is initially performed independently for each activity.

Sequence (S) Activities

In this process, a succession of consecutive and concurrent activities is generated, and a specific sequence to complete work units is defined. A material delivery and layout sequence are also developed.

Room-level sequences are identified based on the construction schedule and design information. A building-level sequence is then determined predominantly by project constraints that prioritize when floors are completed. Finally, floor sequences are selected (Fig. 3, step 3). These determine the order in which each activity will complete work units on individual floors.

Patterns and planning guidelines provide guidance in se-

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TABLE 1. Outline of Steps in Space Planning Method

Steps of planning method (1)	Description (2)
(a) Identify (I) required spaces	
I1 Identify material information	Determine physical characteristic, spatial attributes, and availability
I2 Select construction methods	Select means and methods needed for each work element
I3 Identify work activity spaces	Identify necessary work spaces depending on selected methods
I4 Identify material spaces and paths	Identify space needed to access and support work areas
(b) Generate layout (L)	
L1 Assign space behavior patterns	Select a pattern in construction space model to characterize space needs
L2 Layout room-level spaces	Determine position of work areas and other room level spaces
L3 Layout building-level spaces	Determine position of unloading areas, vertical paths, and other building space
L4 Layout floor-level spaces	Determine position of storage areas and other room-level spaces
L5 Create space layout	Develop a graphical plan illustrating locations of all needed spaces
(c) Sequence (S) activities	
S1 Identify room-level sequence	Determine work sequence based on hard logic and known dependencies
S2 Identify building sequence	Determine order each activity will work on floors, e.g., top-down/bottom-up
S3 Determine floor sequence	Determine work direction for activities to work on floors, e.g., left to right
S4 Identify material delivery sequence	Identify milestone schedule dates when materials will be placed on floors
(d) Resolve (R) conflicts	
R1 Identify interferencs and blockage	Evaluate layout sequence for overlapping spaces
R2 Determine activity to be modified	Identify which activity's space can be altered to prevent interference
R3 Determine conflict resolution method	Select plan to adjust, e.g., method, sequence, storage location, delivery date
R4 Determine conflict resolution action	Take specific action to adjust plan to avoid interference

quencing and layout decisions. For example, activities typically need space in one of three zones: in the building core, around the perimeter, or in floor areas (between the core and perimeter). Independent work sequence patterns are developed in each zone. Critical activities dictate the work pattern selected in each zone. This pattern should then be followed by successive activities, which require space in the same zone to minimize potential interference problems. Activities that must follow different patterns, yet still require work in the same zone, run a greater risk of interfering with each other, and require further consideration during planning. Once work patterns have been established, support areas such as unloading areas and storage spaces are identified and positioned in effective locations that do not interfere with direct work.

A key feature of the planning process is the generation of a layout sequence that graphically illustrates the use of space at selected time intervals. Fig. 3, step 3 illustrates how the layout of required spaces identified in step 2 is coupled with the sequence of activities to define how space is occupied at selected time intervals, e.g., activity 1 requires the unloading area U1 and storage area S1 on day one, and spaces W1, S1, U2, and S2 are needed on day two.

Following the development of a layout sequence, a sequence of material deliveries is identified, which designates the order in which materials are introduced onto each building floor. This is based on the selected floor and building sequence. The outputs of this process provide a work sequence, a delivery sequence, and a layout sequence, which graphically illustrates the use of space over time.

Resolve (R) Conflicts

In this process, the layout sequence is evaluated at selected time intervals to identify overlapping spaces for different activity work elements. Fig. 3, step 4 illustrates overlapping spaces during days two, three, and four in the layout sequence. A decision is made to adjust the sequence, layout, or method selection depending on the type of interference problem and the space behavior patterns of the activities in conflict. A specific action for resolving conflicts is then implemented, e.g., storage area S1 is relocated and the sequence of work for activity 1 is charged from clockwise to counterclockwise. The impact of these adjustments requires subsequent iterations of the space planning processes. If conflicts cannot be resolved by initial space planning, detail is added to the plan by evaluating more specific levels of space, from building to floor and room levels as necessary. Adjustments made by a planner to resolve conflicts are highly dependent on the types of interference problems, available space, and activity precedences. Explicit actions are therefore not provided to a planner; however, guidelines provide input to conflict resolution decisions.

The plan gains detail as a project progresses and more information is obtained about the actual sequence of work. It is necessary, however, to indicate a level of detail to which initial space planning should be performed. Space planning detail is classified into building, floor, and room levels, corresponding to the previously defined levels of space. Building-level space planning includes attributes of the entire building and does not cover specific spatial interactions on individual floors. Examples are the order in which floors will be completed by crews working on an activity, or the location of a material handling space that will serve multiple floors. Floor-level space planning refers to spatial interactions and sequences on individual floors. An example is the direction in which individual units of work will be completed on a floor or general locations of storage areas and paths on floors. Room-level space planning refers to direct sequential dependencies between activity work units and specific spatial interactions between individual crews and work elements. Examples are the order in which sequential activities will complete work in a room and specific locations of storage and work areas for individual work units.

The method presented includes basic space planning steps, such as identifying what spaces are needed, defining locations for these spaces, and identifying conflicts (overlapping spaces). Beyond these intuitive steps, the model proposes a logical order for decisions based on a classification of spaces and a level of planning detail for multistory construction projects. These concepts were evaluated on case study projects and through trial applications of the space planning method.

TESTING

The space planning method was evaluated on four case study projects (Table 2) with two objectives: (1) to determine if the content and detail of the process was accurate (test 1); and (2) to explore the relationship between the space planning deficiencies and resulting spatial interference problems (test 2). Case study sites were selected that were similar in nature (multistory buildings) and observable in similar phases of completion (enclosure and finish).

A key feature to note about each project is the project progress rate. This is the average amount of work completed each month, (measured in earned contract value in dollars), divided

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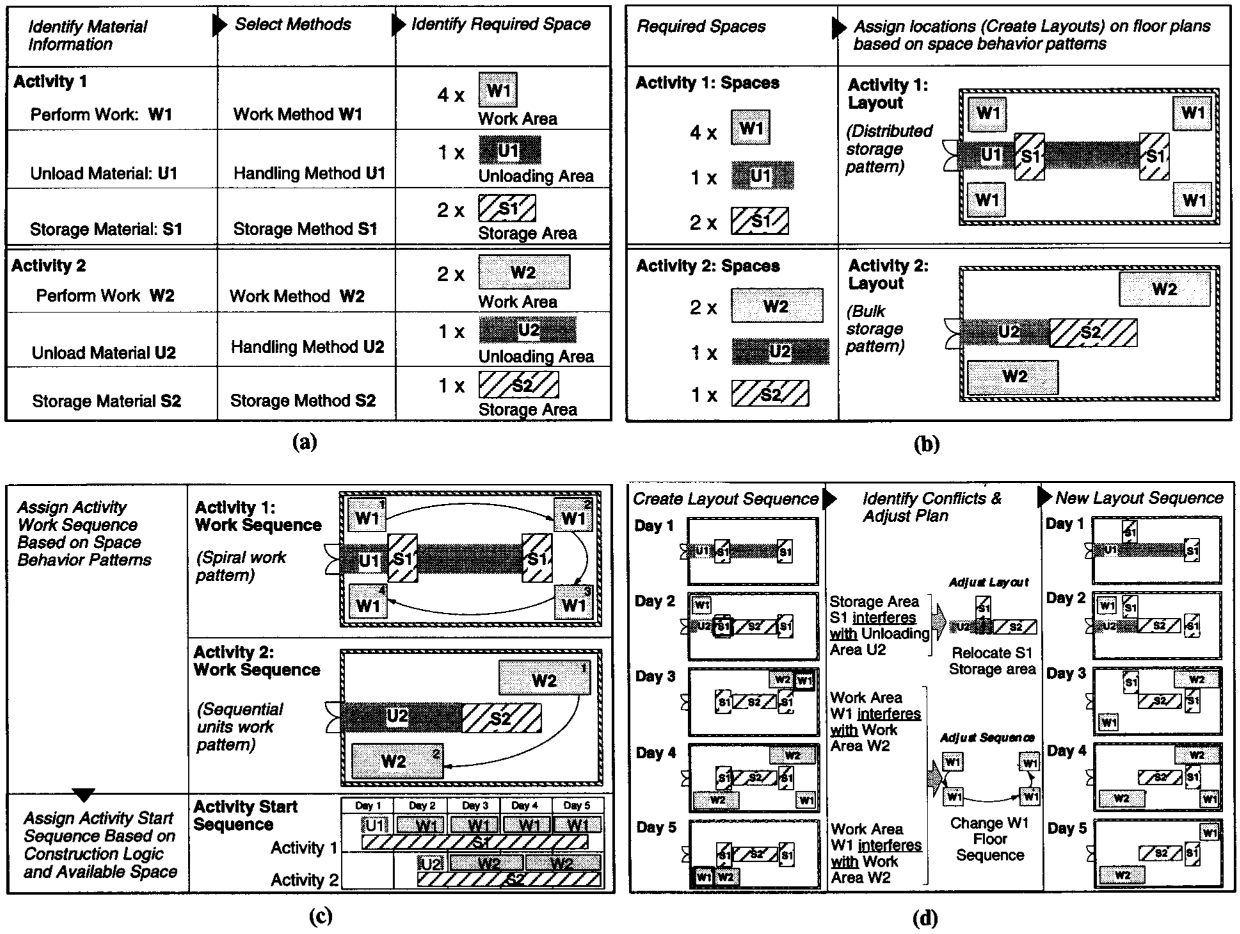

FIG. 3. Graphical Illustration of Planning Method: (a) Step 1—Identify Required Spaces; (b) Step 2—Generate Layout; (c) Step 3—Sequence Activities; (d) Step 4—Resolve Conflicts

TABLE 2. Case Study Project Information

		Facility Size			Work Rate		Design Description		
Project (1)	Facility type (2)	Typical floors (3)	Total floor area (m^2) (4)	Average sq ft/floor (5)	Average work-in-place per month (6)	Project progress rate[a] (7)	Structure (8)	Envelope (9)	Interior (10)
A	Office building shell	4	24,237	6,059	1,600,000	66	Concrete	Curtain wall	Shell space
B	Biomedical research	5	24,615	4,923	2,100,000	85	Concrete	Curtain wall	Laboratory
C	Medical	9	19,172	2,130	2,700,000	141	Concrete	Masonry	Hospital
D	Concert hall music building	3	3,367	1,122	250,000	74	Concrete	Masonry	Office music hall

[a]Average work-in-place in earned contract value ($)/month/total floor area.

by the gross square footage of the project. This figure provides an assessment of the comparative quantity of work taking place on a project in the amount of space available. At comparable phases of completion, larger values indicate a higher level of activity and greater demands for space. This can often be equated to a higher probability of interference problems and a greater need for space planning. A description of each test follows.

Evaluating Planning Content

Interviews with eight experienced project managers were used to evaluate the content of the space planning method. To be considered experienced, respondents needed a minimum of 10 years of field experience and had to be responsible for developing and maintaining a sequence of work on a current or recently completed multistory building project. The planning method was evaluated using the detailed steps in the space planning model (see Table 1). A detailed description of the planning method and examples of a plan were presented to each respondent. Interview questions were asked to determine if the space planning steps are considered necessary to project managers and superintendents, and to assess the level of detail in which planning should be performed (building, floor, or room level).

The planning processes in the model were developed through a detailed analysis of the space planning needed on actual construction projects. For this reason it was expected that most of the space planning recommended in the model would be considered necessary by experienced project managers. The results of the interviews supported this. All but one of the 50 space planning steps in the model were identified as necessary at some level of detail. Interviews also provided useful feedback and criticism about the method. Key points are addressed in the following.

Several space planning processes were identified by respondents as more critical than others. For example, the develop-

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ment of a defined work direction on each floor was more critical than defining the specific locations for every staging area. In cases such as this, the detail of planning was dependent on the relative ease of making planning decisions. In other cases, the potential positive or negative impacts on sequencing might make a particular space planning step more critical. For example, the location of a common unloading area can affect the productivity of many trades. Assessment of the relative importance of a particular planning step was not in the scope of this study, due to the high variability of actual impacts of particular problems on a project. In future versions of the space planning model, critical planning steps may be emphasized to reflect their potential to impact project costs.

All of the respondents felt that the space planning described by the model was important; however, current methods are informal and less detailed than the model purposes. As described, the level of effort to perform the plan is substantial and varies highly depending on available information and the knowledge of the planner. Many of the steps in the model, however, could be automated, making the method more easy to perform.

Several specific comments by respondents represent common arguments against detailed planning. The second respondent felt that "too many unknowns affect sequences," making planning futile. The space planning method is intended to increase the communication of information and decrease the unknown variables in planning. Furthermore, the construction space model has formalized general patterns of space behavior so that spatial needs can be predicted, which also reduces the unknowns involved with space planning.

Another manager felt that "detailed (space) planning is not a priority in the early phases of a project and should be left to a site superintendent to manage." The writers acknowledge that space planning on simple projects may, in most cases, be within the capabilities of experienced superintendents. However, other interview responses and case studies illustrate that a need exists to address spatial issues early in the project due to their impact on cost and the selection of construction methods. The space planning model may thus be considered most useful on complex multistory projects with compressed schedules on projects with less experienced planners.

One respondent indicated that "planning is hard to perform in detail because of (complications and labor intensity) in making plans." It can be argued that the space planning model is intended to simplify the planning process and provide a structure for creating plans that can be adjusted as construction progresses. In addition, many steps in the space planning model could be automated now that they have been formalized.

Another construction planner points out that "developing plans that are handed to subcontractors is risky because if things change, the subcontractor can hold it against you later." This is a highly valid point; however, the space planning method can be used to generate plans and identify key sequencing events without communicating all details of the plan directly to subcontractors. Also, the input of subcontractors can be invaluable to the development and communication of a productive sequence plan. In a graphical format, a plan developed with the model can be easily discussed. Suggestions can be received from subcontractors and incorporated to improve the plan and allow them to share "ownership" of the plan.

Comparing Project Space Planning and Interferences

To test the relationship between the space planning method and interference problems, a comparison was made between the space planning on case study projects and the interference problems found in the field. The premise of this study was that if avoidable interferences are observed on a project, the space planning on the project is deficient in comparison to the planning process model. For the purposes of this study, a space planning "deficiency" is defined as project planning that was not performed, or performed to less detail than described in the space planning method. In fairness to industry practitioners, it should be noted that established criteria for planning in the construction industry do not exist. It is perhaps more appropriate to refer to planning "deficiencies" as "areas for potential improvement."

Space Planning Assessment

Each case study project was evaluated to determine if and to what level of detail the planning steps in the method had been performed. Interviews were conducted with the individuals responsible for developing an initial sequence of activities for the project. Contract documents and schedules were examined to define the initial planned sequence of work and any space planning performed during preconstruction. Short-term spatial planning was assessed by interacting with site superintendents, who provided specific direction to contractors in the field. The actual implementation of planning was assessed through confidential and direct surveys with site contractors. A "score" for the space planning on the project for each step in the space planning method was assigned based on the following criteria: (1) all space planning efforts had to be implemented to be included as part of the plan; (2) all planning efforts had to be observable as a direct action taken by the construction managers or site manager; and (3) an observed example for each planning measurement had to be included to justify the measurement. The closeness of each project's planning effort to the space planning procedures recommended in the model was rated.

Interference Detection

A collection of typical spatial interferences was developed from prior site observations and literature (Table 3). Observable interference problems are listed (Table 3, column 1). For each of these problems a set of possible causes was identified (Table 3, column 2). The corresponding steps in the planning method that addressed each cause are also identified (Table 3, column 3). Several causes of interference are not predictable with the planning process and are considered unavoidable. These causes are the result of poor practice or changes and delays, and are noted in the cells of Table 3, column 3. The expected interference problems listed in Table 3 provide a "map" for relating observed spatial interference problems to specific planning deficiencies.

Multiple methods were used to detect interference problems on case study sites. Direct observation detected the majority of spatial conflicts. Additional problems were identified through surveys of site contractors and an analysis of the minutes of a foreperson's meetings. Out-of-sequence work and double handling of material were detected by four site observations at regular two-week intervals. Problems were recorded on each project as follows. If one problem resulted in multiple interferences on one floor, it was only recorded once. If one problem created an interference for two or more trades, an interference for each trade was recorded. If one problem created similar interferences on multiple floors, an interference was counted once for each floor. Only interferences that were avoidable through some form of planning were counted. If no amount or an unreasonable amount of planning was needed to detect and avoid an interference (more than recommended by this model), it was recorded but noted as unavoidable. Observed interferences were classified according to the associated planning processes that should have prevented the problem from occurring (Table 3, column 3).

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TABLE 3. Typical Causes of and Solutions to Interference Problems

Type of interference (1)	Causes (2)	Preventive planning process (3)
Double handling materials	Material brought to site too early	S4 Identify delivery constraints
	No storage location identified	L4 Layout floor-level storage
Blocked personnel/material path	Material stored in path	L3/L4 Layout building/floor spaces
	Work going on in path	S3 Identify floor sequence
	Work-in-place blocks path	S1 Identify room-level sequence
	Debris buildup in path[a]	Waste management[a]
Crowded work space	Crews working out of sequence	S3/S2 Identify floor or building sequence
	Crews pushed close together	I3 Identify work space constraints
	Material stored in work area	L4 Layout floor-level spaces
	Work-in-place crowds work area[a]	Insufficient work space[a]
	Crews pushing delayed activity[a]	Activity delay[a]
Work in hazardous area	Hazard not avoided with sequence	I3 Identify hazards; S3 identify floor sequence
	Hazard not protected adequately[a]	Safety practice[a]
Work out of sequence	Material blocking planned sequence	L4 Layout floor-level spaces, storage
	Trade not assigned sequence	S3/S2 Identify floor or building sequence
	Debris blocking planned sequence	I4 Identify debris paths
	Activities forced out of sequence[a]	Sequence problem[a]
Damage to stored materials	Stored for extended time	S4 Identify delivery constraints
	Stored in wrong area	L4 Identify floor-level spaces, storage
Debris buildup on floors	No path to remove	I4 Identify debris paths
	No removal procedure enforced[a]	Waste management[a]
Damaged/removed work in place	Work out of sequence	S3/S2 Identify floor/building sequence
	Work not protected	I3 Identify protected spaces
	No path left open	I4 Identify debris paths
	Work area too small[a]	Design sequence[a]
Material far from work area	Other materials in storage space	L4 Identify floor-level spaces, storage
	Other activity in storage area	S3/S2 Identify floor or building sequence
	No path to work area	I4 Identify horizontal material path
	Insufficient space available[a]	Must store in remote area[a]
Accidents from falling objects	Work under overhead hazard	I3 Identify work spaces, hazard areas
	Area not protected[a]	Work practice[a]
Injury from hazardous	Work near room hazard	I3 Identify work spaces, hazard areas
	Area not protected[a]	Work practice[a]
Path not provided	Hoist not provided	I4 Identify vertical material path
	Access opening not provided	I4 Identify horizontal material path
	Stair not provided	I4 Identify vertical personnel path
	Inefficient method	I2 Select methods
	Poor location	L3 Layout building-level spaces
	Deliveries not scheduled	S4 Identify delivery constraints

[a]Problems unavoidable through planning.

Results

Table 4 summarizes the planning evaluation and related occurrences of interferences for each case study project. The number of interference problems detected on the projects are listed by the planning process that could have identified them. (Note that some interference problems were detected by site management and are indicated as "resolve conflicts" planning steps. These are not included in the total count of interferences.)

The premise of this test was if avoidable interferences are observed on a project, then the planning on the project is deficient in comparison to the planning process model. An initial analysis of the data indicated this to be true, as planning steps rated as "0" or "—" have notably more corresponding interference problems observed.

An attempt was made to identify a relationship between the number of interferences observed and the relative importance of a particular planning step. For example, in Table 4 a low score (—) for process L4 on project A was associated with 26 interference problems, and the same low score for other processes resulted in 2, 4, 1, and 6 related interference problems. The relative impact, however, of each problem on the projects was highly variable. Also, had projects been observed at a different time, the interferences identified may have been different.

Failure to plan material paths (process I4) caused a high number of interference problems (33). Path planning decisions affect all of the trades working in the building that need to unload materials or remove debris; thus this could be considered a key planning step. Some planning processes may be considered more useful than others in avoiding occurrences of interference problems. However, with no measure of the actual cost of each problem, a weighting system to emphasize one step over another may misrepresent which planning processes are critical in terms of minimizing the cost of interference problems.

It is apparent that project A had significantly more interference problems (70) than the other projects. Possible explanations are that more work was taking place, or the sequence of work on the project was highly complex. Neither apply in this case. Project A (Table 2) had the lowest work rate during the observation period (6.25 \$/SF/month) and the least complex sequence of work, an office building shell. This strongly supports the conclusion that interference problems observed were most likely the result of planning deficiencies.

Project C also had a substantially higher number of interference problems (54) but also had the highest work rate (9.00 \$/SF/month) and most complex sequence of work, a medical facility. The sequence on this project was also disrupted by a major material specification error. While these circumstances partially explain the high number of interferences, the majority of problems in the project resulted from inadequate material and debris paths and a lack of assigned storage locations.

PLANNING APPLICATIONS

The space planning method was used to develop sequence plans on two construction projects. Observation of the actual

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TABLE 4. Summary of Project Planning and Related Interference

Model checklist (1)	Project A Planning evaluation (2)	Project A Related interference (3)	Project B Planning evaluation (4)	Project B Related interference (5)	Project C Planning evaluation (6)	Project C Related interference (7)	Project D Planning evaluation (8)	Project D Related interference (9)
(*a*) Identify (I) required spaces								
I2 Select methods	—[c]	2	+[a]	0	0[b]	1	0[b]	0
I3 Identify work activity spaces	0[b]	0	+[a]	0	0[b]	5	—[c]	0
I4 Identify material spaces	—[c]	4	+[a]	0	—[c]	0	0[b]	1
Identify paths spaces	0[b]	12	+[a]	1	0[b]	19	0[b]	1
(*b*) Generate layouts (L)								
L2 Layout room-level spaces	—[c]	1	0[b]	0	0[b]	0	+[a]	0
L3 Layout building-level spaces	0[b]	3	+[a]	0	+[a]	0	0[b]	0
L4 Layout floor-level spaces	—[c]	26	0[b]	3	—[c]	11	0[b]	7
(*c*) Sequence (S) activities								
S1 Identify room-level sequence	0[b]	1	+[a]	1	0[b]	4	+[a]	0
S2 Identify building sequence	0[b]	10	+[a]	0	+[a]	4	0[b]	1
S3 Determine floor sequence	0[b]	5	+[a]	0	0[b]	6	0[b]	1
S4 Identify delivery sequence	—[c]	6	+[a]	0	0[b]	4	0[b]	0
[Total number of avoidable interferences]		[70]		[5]		[54]		[11]
(*d*) Resolve (R) conflicts								
R1 Evaluate sequence for problems	0[b]	2	+[a]	0	0[b]	0	0[b]	0
Identify interferences	0[b]	4	0[b]	2	0[b]	1	0[b]	2
R2 Identify activity to be modified	0[b]	4	+[a]	0	+[a]	1	+[a]	2

[a]Performed at same detail as model.
[b]Performed, but at lower detail than the model.
[c]Not performed or implemented.

sequences identified interference problems that occurred. The sequence developed using the model was then compared to the actual sequence observed on-site. The observed interferences were then compared to those detected by the planning model to test the use of the model in identifying interferences before they occurred.

Single Room Project

The first test was performed on a single room (Fig. 4). By limiting the size of the application, the factors affecting the sequence were confined to physical constraints between activities and spatial limitations. The application focused on work areas, work patterns, and specific planning decisions related to work areas for 16 finish activities. The steps in the space planning method were carried out to identify needed work spaces, locate these spaces in the room, define work directions (floor sequence) for each trade (Fig. 4), and evaluate the layout sequence for possible interference problems based on time intervals in the early start schedule (Fig. 5). Layout sequences were generated with a space-scheduling tool, MovePlan (Tommelein and Zouein 1993).

The initial early start schedule required several work activities to occur at the same place at the same time. The planning process identified this, allowing for work sequences to be adjusted to eliminate potential problems. In some cases, this meant increasing the duration of the project slightly to allow work to progress in a reasonable sequence. An evaluation of

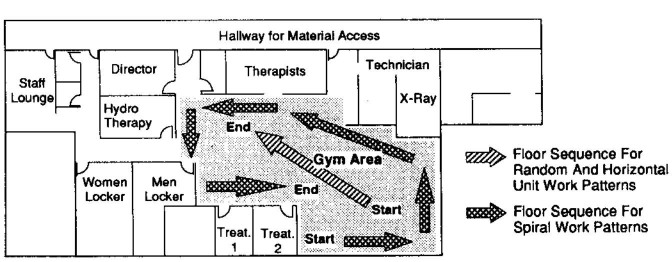

FIG. 4. Design of Gym Area and Surrounding Rooms

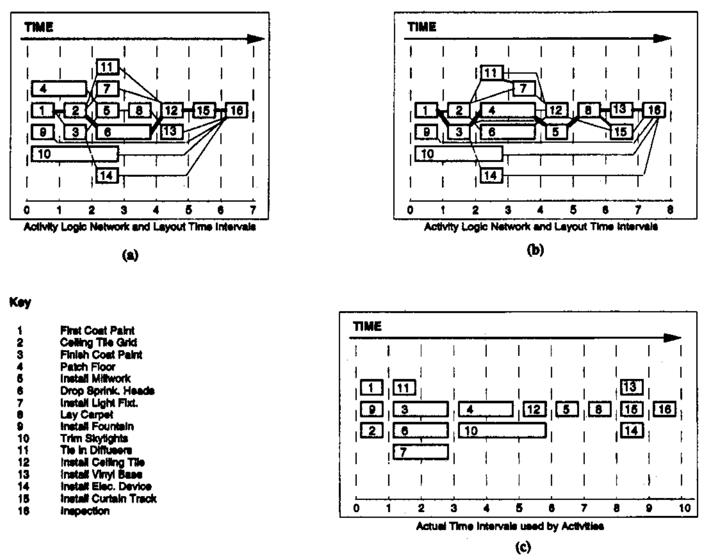

FIG. 5. Layout Time Intervals for Activities: (a) Early Start Schedule—Disregarding Spatial Impacts (Seven-Day Duration); (b) Final Sequence Plan Using Planning Method (Eight-Day Duration); (c) Observed Sequence (10-Day Duration)

each time interval in the seven-day schedule identified five spatial interferences. Work sequences and the schedule were then adjusted to resolve conflicts (activity 4 is made a successor of activity 3, and activity 7 is made a successor of activity 11). The resulting work plan required the duration of the project to be extended by one day (Fig. 6).

The construction manager instructed all trades to begin work as soon as possible, relying upon the crews to work out the sequence. The crews did make adjustments, but without the guidance of the construction manager or the benefit of a plan. This lack of close control of the sequence resulted in out of sequence work and unnecessary delays. The planned sequence had a longer duration (eight days) than the "early start" schedule defined by physical constraints only (six days).

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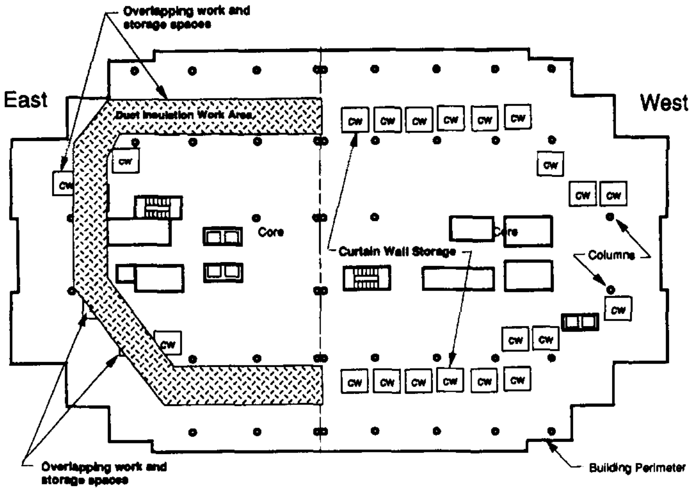

FIG. 6. Floor Layout Plan—Interference between Duct Insulation and Curtain Wall Storage (cw)

The actual sequence observed, however, took 10 days to complete because several crews left the area when space became congested. Although the work did take place without spatial interferences, the duration was longer than necessary. The ability of crews to adjust the sequence to avoid interferences was apparent; however, their ability to do so without affecting the duration of work was limited.

Planning a Four-Story Project

A building sequence plan was also developed for a four-story project. The scope of this plan included major work areas and material handling spaces for activities on multiple floors. This application was intended to detect interferences on individual floors of the building during two-month time intervals. It simulated preconstruction planning, for which the space planning method is intended.

The steps in the space planning method were carried out for 12 activities. Planning considered unloading areas, material paths, storage areas, and work areas. Needed spaces were identified for each activity based on work methods chosen for the project. Locations for needed space were defined on floor plans. These were maintained on separate layers of computer-aided design (CAD) drawings for each activity. Building, floor, and delivery sequences were defined according to the plan implemented by the general contractor. To evaluate floors for interference problems at a specified time interval, selected CAD layers were displayed according to Table 5.

Floor plans were evaluated at four intervals in the schedule, which corresponded to observations during site visits. Potential interference problems were indicated by overlapping spaces on the floor plan drawings.

Nine interferences were identified at the four intervals evaluated. These were compared to problems observed during site visits. Of the nine interferences detected through planning, eight were actually observed on the site. In each case, a simple planning adjustment could have avoided the problems found in the field. For example, the sequence used on the project called for the preloading of all curtain wall material. No assigned storage locations were identified. By evaluating the sequence with the planning method, it was determined that duct insulation work areas were potentially in conflict with stored curtain wall material (Fig. 6), indicating that assigned storage areas should have been imposed for this material. Had planning been performed prior to making the sequencing decisions used on the projects, spatial interference problems such as this would have been detected and adjustments could have been made to avoid them.

TABLE 5. Selected CAD Layers

Event occurring in interval (1)	Layers displayed (2)
Delivery of materials	Display: "unloading area" layer; "material path" layer; "storage space" layer
Between delivery and start date	Display: "storage space" layer
Activity in progress	Display: "work space" layer; "storage space" layer
Activity complete	Display: "work in place" layer

This application also demonstrated the value of evaluating several intervals in the middle of a project to identify key events in a sequence. For example, what materials need to be preloaded while access to floors is available, what locations this material should be stored, and what locations and durations should material-handling equipment (hoists and trash chutes) be provided.

OBSERVATIONS

Current site practice motivates crews to complete as much work as possible. A general tendency exists to perform any work currently available. This practice was observed on non-critical path activities. Trades often have sufficient float in their schedule to be performed later, but are directed to begin early to "get them out of the way." If the spatial impacts of performing work early are not evaluated, this tendency can lead to congestion. Work performed early can end up getting in the way of other, more critical work later in the sequence. The space planning model provides a tool to evaluate the impact of work on available space of successive activities to help make this an informed decision.

It is highly desirable to provide each trade with as much work space as possible. During testing, several trades were observed working in an open space that allowed them to use more efficient methods. Under these conditions, work was performed better than "normal" or expected productivity rates when compared to other trades performing similar tasks in more confined spaces. The need for "buffers" between activities has been identified through recent research (Howell et al. 1993). The research presented in this paper helps to further define why these buffers are needed and provides a method for determining their size.

The planning process allows frequently occupied work areas and the corresponding reciprocal dependencies between activities to be identified. If performed early, planning may indicate the need to adjust a design detail to create a more efficient sequence and therefore alleviate work space congestion (Griffith 1984).

Contrary to manufacturing applications where it is desirable to minimize inventories of stored materials and have the right amount of material arrive at the right time, it is often advantageous to bring as much material to the jobsite as possible. While many benefits result from "just-in-time" delivery, many motivating factors found for maintaining a large inventory of materials were observed on-site. A construction manager is challenged to balance the materials made available on a job and the available space for work. For enclosure and interior activities, just-in-time delivery means that materials arrive when sufficient space is available, not necessarily when they are needed for use. With a better plan of what space is available, a more informed decision can be made about which materials should be delivered to the project.

Two hurdles must be overcome before industry practitioners can be expected to implement the space planning method. First, detailed space planning must be accepted as a useful, cost-saving practice. Interviews with practitioners revealed general skepticism towards detailed planning. Until a cost-ben-

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efit analysis of detailed planning is performed, it is expected that this view will persist. This research attempts to demonstrate the potential value of such planning and provide a usable method to create detailed space plans. Next, support tools to assist with space planning must be developed to minimize planning effort and potential downstream costs of detailed planning. Trial applications of the method demonstrated the value of a simple tool that links CAD and critical path method data to generate layout sequences. Several researchers have developed prototype space planning tools (Thabet 1992; Tommelein and Zouein 1993).

CONCLUSION

The space planning method provides an approach to develop a construction sequence that is responsive to the space needs of enclosure and finish grades. Through interviews with experienced project managers and four case study projects, the method was found to be an accurate representation of the planning necessary to manage space on multistory building projects. Trial applications on two construction projects found the method to be useful in identifying interference problems before they occurred in the field.

The use of the method yields practical information for planning decisions in the form of a defined work flow through the building, schedule of material delivery, and assigned storage and work areas that will prevent interference problems. Detailed space planning should be recognized by industry practitioners as a technique for creating efficient construction sequences. With the development of support tools, the space planning method offers a usable process to create space plans for multistory building construction.

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