Patterns of Construction-Space Use in Multistory Buildings

By David R. Riley[1] and Victor E. Sanvido,[2] Associate Members, ASCE

Abstract: This research presents a construction-space model that defines a collection of descriptive space types and typical patterns of space use in multistory building construction. Recent space-planning research describes characteristics of space and provides simple models of space demand for construction work to support automated space-planning methods. These simplified models cannot accurately represent the space needed for complex networks of work and material-handling activities in multistory buildings. The construction-space model identifies 12 construction-activity space uses, and their typical patterns. Repeatable patterns of space needs are recognizable and often occur independently in core, floor area, and perimeter work zones. The construction-space model characterizes these space needs to predict space demand, and thus supports the logical planning of productive work sequences. Through case-study research and site observation, the space model was found to accurately represent the use of space by construction activities in multistory building construction. If applied on site, this research helps construction managers plan and manage space.

INTRODUCTION

Building construction requires space to move, store, and fabricate materials, and to perform work. The work space needs of construction activities in multistory buildings change as work progresses. Often multiple activities occur simultaneously in close proximity and space becomes scarce. Complex networks of material-handling paths and storage spaces also contribute to the challenge of finding adequate space to execute tasks. These space requirements must be predicted and accounted for by construction managers to minimize workspace congestion and interference. If this space is not provided, it could result in reduced productivity, safety hazards, and poor-quality work. A clear understanding of why space is needed for construction work would help to better predict space demand.

This research defines repeatable patterns that describe how typical activities use space over time. These space-behavior patterns support the development of a smooth flow of work—a sequence that helps prevent crews from interfering with each other. The focus of this research is on the use of space inside a building for interior work, including mechanical trades, drywall, and finishes and for enclosure trades, such as masonry and curtain wall. The scope is limited to multistory (three to 10 story) buildings, where these trades can often select from multiple sequences to perform work.

Industry Practice

The most common form of representing space found in the industry is through site plans. These plans are most necessary for high-rise buildings that are normally situated in congested urban locations. Plans are typically developed by a construction manager at the beginning of a project as a tool to allocate and manage space for material deliveries, staging areas, crane locations, and material hoists. Some site managers develop different plans for each phase of construction and update these weekly. In rare cases, space is allocated directly on individual floors for material storage and paths.

[1]Asst. Prof., Dept. of Build. Constr., Univ. of Washington, 116 Arch. Hall, AL-115, Seattle, WA 98105; formerly, Postdoctoral Scholar, CIC Res. Lab., Dept. of Arch. Engrg., Pennsylvania State Univ., 104 Engrg. Unit A, University Park, PA 16802.

[2]Assoc. Prof., CIC Res. Lab., Dept. of Arch. Engrg., Pennsylvania State Univ., 104 Engrg. Unit A, University Park, PA.

Note. Discussion open until May 1, 1996. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 9, 1995. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 121, No. 4, December, 1995. ©ASCE, ISSN 0733-9364/95/0004-0464–0473/$2.00 + $.25 per page. Paper No. 10086.

Construction Work-Space Planning Literature

Construction work-space planning research falls into three categories: site-layout techniques, spatial characteristics of construction work, and methods to quantify space need. First, site-layout research recognizes that space is needed, for some length of time, to store materials, prefabricate assemblies of materials, and perform work. These needs also apply to the use of space inside the building; however, they become more complex since the spaces used are smaller, and are occupied for shorter periods of time. For example, one area on a building floor may be used as storage space, a work area, and a debris path in the span of one week, while a pile of topsoil or a reinforcing-bar laydown area may exist for months at a time outside the building (Riley 1994).

Tommelein et al. (1992) consider three characteristics of space: need, timing, and location, to material-handling activities. Space need is the physical, three-dimensional space required to accommodate a resource and is specified by shape and volume and governed by material dimensions, quantities, stacking ability, overlap, and shape. The timing in which space is needed must be considered when planning the space on the site. Factors that affect this timing include the grain size of duration (period of planning interval), start and finish times, material-handling activities, equipment operation, equipment movement (footprint size and maneuvering space), and available resources. The location where space is needed must also be considered, and can be characterized by remoteness, access, space reuse, grouping, and environmental impact.

Howell et al. (1994) identified the need for buffers between activities that share resources by examining several cases of the interaction between activities. When activities share resources, such as space, one activity generally cannot proceed efficiently until the other has finished and moved to another location. If crews are forced to share space, they may interfere with each other's work and should, therefore, be provided with sufficient free space to work. When activities are sequenced in close succession, or with disregard for space need, the potential for interferences increases (Riley 1994). Variable productivity and work rates of crews often demands that loose (realistic) schedules be incorporated into construction sequences, with buffers between sequential activities.

There have been several attempts to quantify the space required for construction activities. Parvis (1980) sets a sq-ft per person limit on the number of workers allocated to an area at the same time. This method also considers other resources that occupy space through a conversion to "equivalent workers." Research has consistently shown that there are reductions in productivity when the limit of one worker per 300 sq ft (28 m^2) is exceeded (Thomas 1989).

J. Constr. Eng. Manage., 1995, 121(4): 464-473

Smith (1987) defines the space required by a worker, an object, or an activity (work space) as the sum of the physical space a body carves out naturally (S_{fixed}), the space immediately peripheral to S_{fixed} (S_{imd}), and the shared space peripheral to S_{imd} and within the work enclosure in question (S_{shared}). Thabet (1992) defines two primary parameters to compare the demand and availability for space in different work areas. Space demand is the space needed for manpower, equipment, and handling of material. Space availability is the space of work area minus the space demand for concurrent activities. Thabet further defines three classes of space demands: Class A requires an entire work area and does not share space with other activities; class B requires space for workforce and equipment, but no space for materials; and class C requires space for workforce, equipment, and materials. Material-storage-space requirements diminish as activity progresses, making room for other activities.

Recent research successfully identifies the characteristics of space need. Current space models describe characteristics of space and provide simple models of space demand for construction work to support automated space-planning methods.

This paper aims to define a detailed, site-tested description of construction-work-space needs to help construction managers better plan and manage the space on multistory construction projects.

Methodology

This research was performed in three phases. During the first phase, construction work was documented on 10 case-study projects of variable size and geometry. A combination of site visits, interviews, and review of documented case studies (Table 1) were utilized. Construction work on a multifacility project was also observed in detail for two years. This prestudy helped to narrow the scope of further research on the enclosure and interior trades in three–10 story facilities, where common patterns of work are most recognizable and variable sequencing solutions exist. Observations on the initial case-study projects indicate that different activities need space in different locations to perform and support work, and that they flow through the building in various directions. Unique work elements, which require space and a collection of space patterns, are identified as the construction-space model. The patterns graphically represent the effect of space use on the area of a floor of a building.

The second phase of the research identifies examples of activities that followed the patterns in the model. Although intuitive to experienced construction planners, observation shows that crews performing the same activity on different projects often complete work in similar sequences. Typical patterns of space used by common activities are thus recognizable. For example, masonry crews prefer to complete one face of a building at a time, while other trades complete work on an entire floor before moving on to the next. Examples of identifiable patterns are found for common construction activities.

The final step in the research was to compare the descriptions of space use in the model to the space use on four test projects. This was performed by observing the use of space at four two-week intervals during the enclosure and finish phases of construction.

TABLE 1. Summary of Case-Study Projects and Investigation Methods

Site (1)	Building function (2)	Project size (3)	Investigation methods (4)
A	Speculative office	26 stories, 47,300 m²	Interview, case study
B	Commercial office	Multibuilding, 600,000 m²	Interview, case study
C	Commercial office	Multibuilding, 199,000 m²	Site visit, interview
D	Speculative office	42 stories, 95,000 m²	Site visit, interview, case study
E	Speculative office	55 stories, 11,400 m²	Site visit, interview, case study
F	Speculative office	72 stories, 17,000 m²	Interview, case study
G	Shopping mall	Two stories, 42,600 m²	Site visit, interview, case study
H	Hospital expansion	Nine stories, 75,700 m²	Site visit, interview, case study
I	Hospital expansion	14 stories, 66,000 m²	Site visit, interview
J	Speculative office	38 stories, 85,000 m²	Site visit, interview, case study

Construction-Space Decomposition

Construction space is hierarchically classified to illustrate its physical relationship to typical construction work. Space is required to perform construction work. As construction work is decomposed into activities, a corresponding hierarchy of necessary space is defined. Fig. 1 illustrates three relationships between construction work, work in place, and space: (1) Construction space is occupied by construction processes; (2) processes produce work in place or the product; and (3) this product occupies space.

A construction process results in a construction product. A process can be decomposed into activities. A construction activity is defined as a set of tasks performed by a crew to shape and place a material into its final position (work in place). Crews are made up of workers performing a specific task. A construction activity is a portion of construction work in a building performed by different trades and defined by materials, e.g., build walls. Activities are composed of subactivities (e.g., frame walls or hang drywall on floor 2 in Fig. 1). A construction subactivity is a component of a construction activity, which is completed independently of other subactivities on each floor, in individual units of work. A construction activity work unit is a component of a subactivity, e.g., frame room 101 walls or frame room 102 walls. It is repetitive, performed in a specified sequence, and consists of a series of activity work elements. A construction activity work element is a component of a work unit, including direct and indirect work, which is required to complete the work unit; e.g., unload metal studs, store metal studs, cut metal studs, install metal studs, or remove debris. The decomposition of a construction activity defines a hierarchy of construction space. Activities, subactivities, and work units complete work at building, floor, and room levels, respectively.

CONSTRUCTION-SPACE MODEL

The construction-space model describes the types of construction spaces needed for construction work elements, and the spaces occupied by completed work units. It further defines typical patterns in which these spaces occur and move over time.

Construction-Space Types

The construction-space model defines two types of space. "Areas" are spaces occupied by activity work elements for a period of time. "Paths" are spaces required for the movement of materials, people, and other resources. The construction-space model defines the following 12 "process space types" that are required to execute activity work elements (see Fig. 1):

1. Layout area: The space required to determine the position of a material to be placed by an activity.
2. Unloading area: The space occupied or required by

J. Constr. Eng. Manage., 1995, 121(4): 464-473

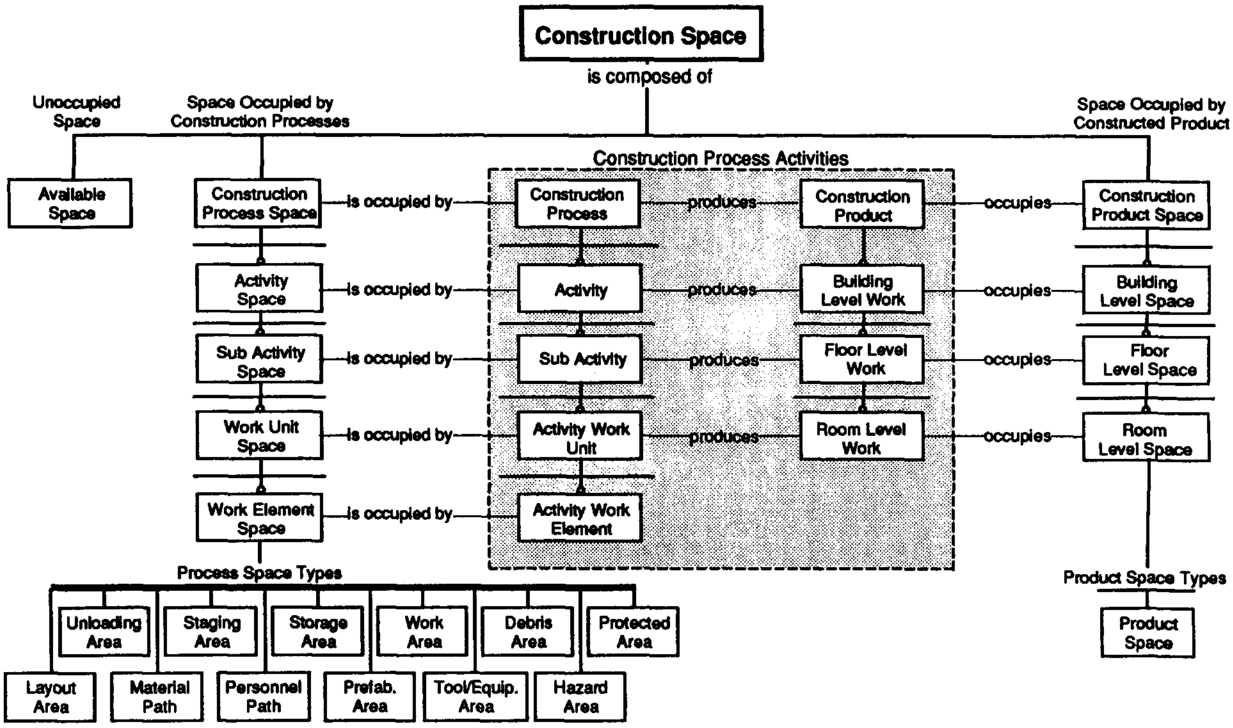

FIG. 1. Construction-Space Decomposition

material-handling resources to place materials onto floors at access points.

3. Material path: The space required to move a particular material from unloading areas to storage areas and work areas.
4. Staging area: The space required to temporarily arrange materials near work areas for short intervals of time.
5. Personnel path: The path required for workers to travel between access points, material storage areas, and work areas.
6. Storage area: The space required to keep material or tools from the time delivered to site to the time of use.
7. Prefabrication area: The space used to prepare, shape, prefabricate, or assemble materials.
8. Work area: The space required for crews to install materials.
9. Tool and equipment area: Space occupied by a resource or temporary facility, which is used to support other activity work elements.
10. Debris path: The space needed for the disposal of scrap material and packaging.
11. Hazard area: Space that is unusable due to health hazards or other dangers created by construction activities.
12. Protected area: Spaces that are used to protect material in place.

Although the decomposition space for activities is defined at building, floor, and room levels, work-element spaces do not necessarily exist at one classified "level" of space. For example, a staging area for a particular material type needed on every floor of the building is a "floor-level" space. Another material that requires a single staging area to serve the entire building uses "building-level" space. Therefore, the classification of work-element spaces varies according to the nature of construction work elements and materials.

The model also recognizes that a portion of work in place is completed by construction activities (see Fig. 1). The constructed product is defined as the materials that are put into their final position by direct work, and which occupy space. The space occupied by the finished product (work in place) can often affect a work sequence and is also decomposed.

To support the space-planning process, patterns are classified into a hierarchy according to the level of detail each had on the space on a typical building floor. Three levels of construction-product space are identified in Fig. 1. Building-level spaces occur on multiple floors and the surrounding spaces of a building. Floor-level spaces occur in one location on each floor of a facility. Room-level spaces occur in multiple locations or repeating units on a floor on a building. This hierarchy helps define a logical sequence and the priority of space during planning.

Space Behavior Patterns

The second element of the construction-space model is a defined set of space-behavior patterns. In many cases, a pattern can be used to describe which space is needed by an activity work element under ideal conditions. For example, heavy materials are immediately distributed in appropriate quantities to storage locations near points of use, making them easily accessible to crews and minimizing double handling. Other materials, which require protection from weather or theft, are ideally stored in bulk at one location and distributed in small quantities as needed. Patterns also represent the use of space based on selected methods of work, one of which may be no more ideal than another.

For each "process-space type," a subset of "process-space patterns" describes how crews typically use space over time to perform work elements. "Product-space-type" patterns describe the effects of completed work on space. The purpose of modeling this behavior is to define relationships between activities with different patterns and to predict the space needed for activity work elements.

Process-Space Patterns

Three to six patterns are identified for each of the 12 process-space types. Three representative examples are: work-area, prefabrication-area, and storage-area patterns. Work

J. Constr. Eng. Manage., 1995, 121(4): 464-473

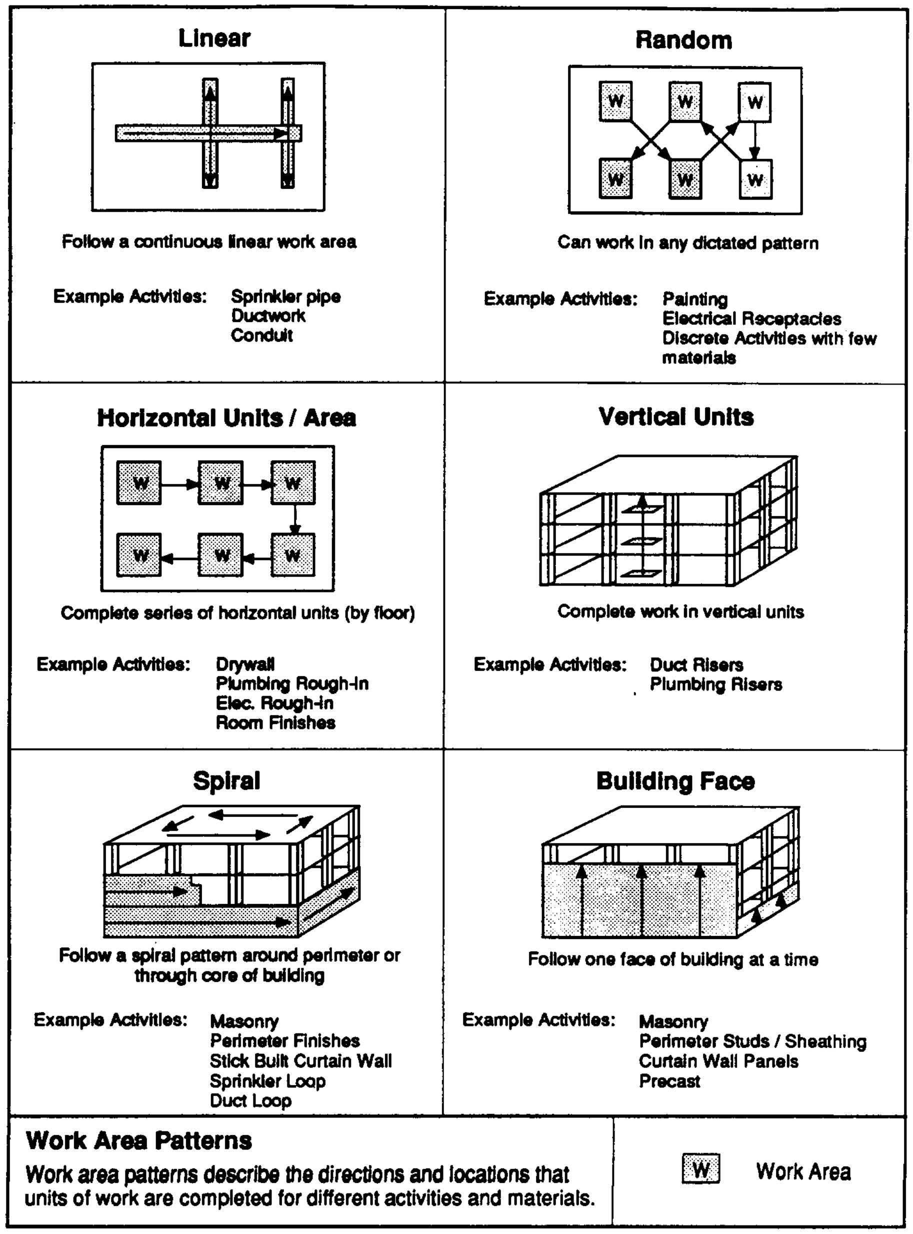

FIG. 2. Work-Area Patterns

areas needed for a particular activity may be required in one of several patterns. Although some crews complete work in units and move from one room to the next in a random or dictated order (e.g., drywall or painting), other crews must follow a vertical or linear path to install materials such as pipe risers and duct loops. Other crews, such as masonry and curtain-wall crews, complete work on one face of a building at a time. A spiral-type pattern is typically followed by crews completing interior perimeter finish work. These work-area patterns are illustrated in Fig. 2.

Various trades require space to prefabricate or preassemble materials prior to final installation. The location and size of these spaces may vary. Space for conduit bending and drywall cutting is often needed in each room or at multiple work locations on a floor. Other materials are prefabricated at one location on each floor, such as electrical assemblies and plumbing fixture spools. Masonry units are typically cut at one location for an entire building. These prefabrication patterns are illustrated in Fig. 3.

Storage patterns depend highly on the nature of materials. Some materials are stored in bulk at one location on each floor, such as hardware and electrical fittings. Heavy or voluminous materials, such as drywall, are immediately distributed around the floor to each work area. Other materials are placed in proximity to several work areas. When space on building floors is limited, materials can be stored at a remote location and brought onto floors as needed. These storage patterns are illustrated in Fig. 4.

Product-Space Patterns

Once materials are placed in their final position they affect the available space for ensuing activities. For example, certain activities create available work space for other activities, such as slab construction or formwork/shoring removal. Other activities remove or eliminate available space, e.g., equipment installation or the completion of floor finishes. Perimeter activities enclose space, and subsequently reduce access or offer weather protection. The erection of interior wall studs partitions available space, dividing it into smaller units, and often reduces travel paths for materials. Certain bulky or inflexible materials such as ductwork are often installed prior to others (conduit and piping), which can inhibit the work space of duct

J. Constr. Eng. Manage., 1995, 121(4): 464-473

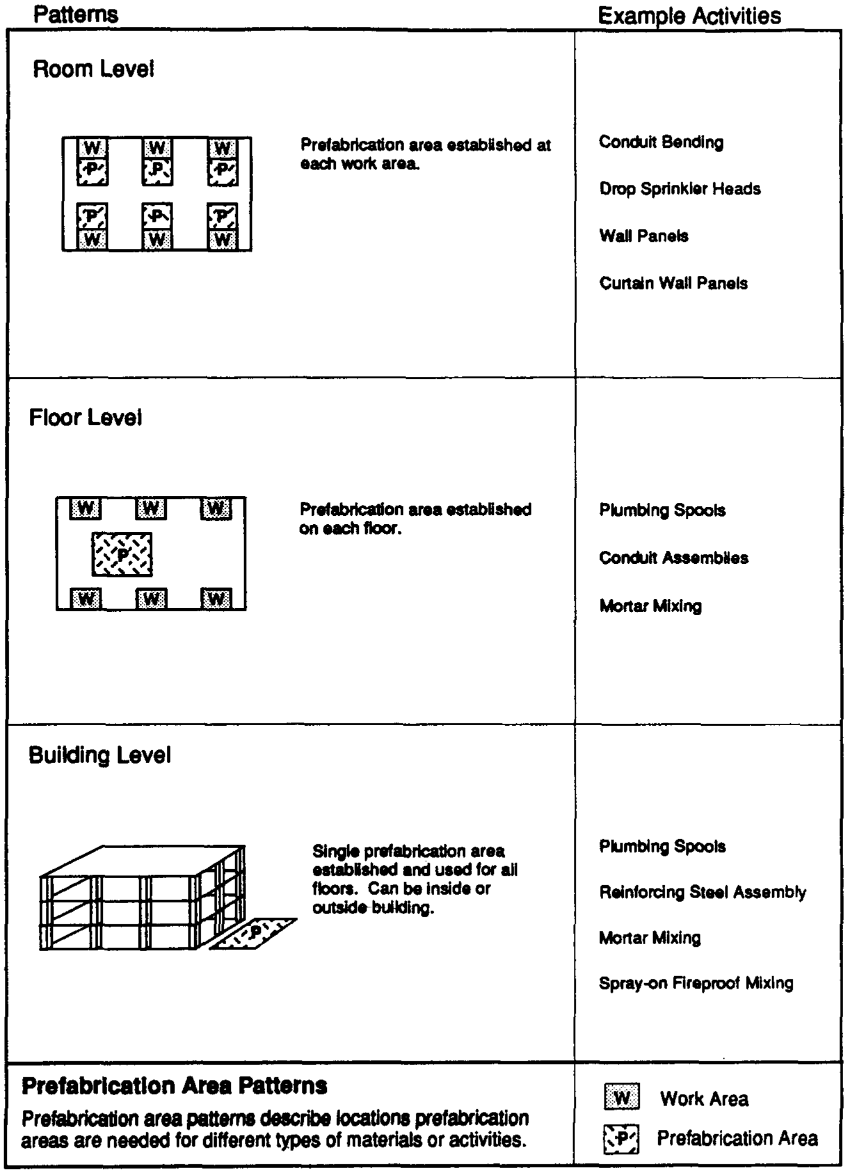

FIG. 3. Prefabrication-Area Patterns

crews. In these cases, a direct impact on the sequence results from work-space needs. Finally, certain activities complete work with no impact on available space, such as the installation of wall conduit or overhead work. These product-space patterns are illustrated in Fig. 5.

Product-space patterns help to define how the available space on building floors changes as a result of completed work. In many cases, the sequence of work depends on these patterns. Typical sequence relationships can be identified between common activities and product-space patterns. For example, it is desirable to perform material-loading activities prior to enclosing space, while activities with weather-sensitive materials are delayed until spaces are enclosed. Other activities, which are preferably performed prior to partitions being built, are material distribution and overhead work.

Although the space types define the reasons why space might be needed for a particular activity, the space-behavior patterns describe how space need and availability will occur over the life of an activity. Together, the defined space types and behavior patterns provide a method to characterize the space needed for individual construction activities.

MODEL TESTING

The construction-space model was tested by comparing the use of space on four case-study sites (see Table 2) with the definitions and patterns in the model. The sites selected were similar in nature (multistory buildings) and observed in similar phases of completion (enclosure and finish). A key feature of 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 by the gross square footage of the project. This figure provides an assessment of the comparative quantity of work 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.

On each case-study site, activities in progress were identified with their corresponding materials and equipment needs. Each activity was observed from the initial placement of material onto building floors to the final removal of debris. The methods used to perform work elements were noted. The spaces required for each work element were tabulated by activity, based on the definitions in the model. On each floor

J. Constr. Eng. Manage., 1995, 121(4): 464-473

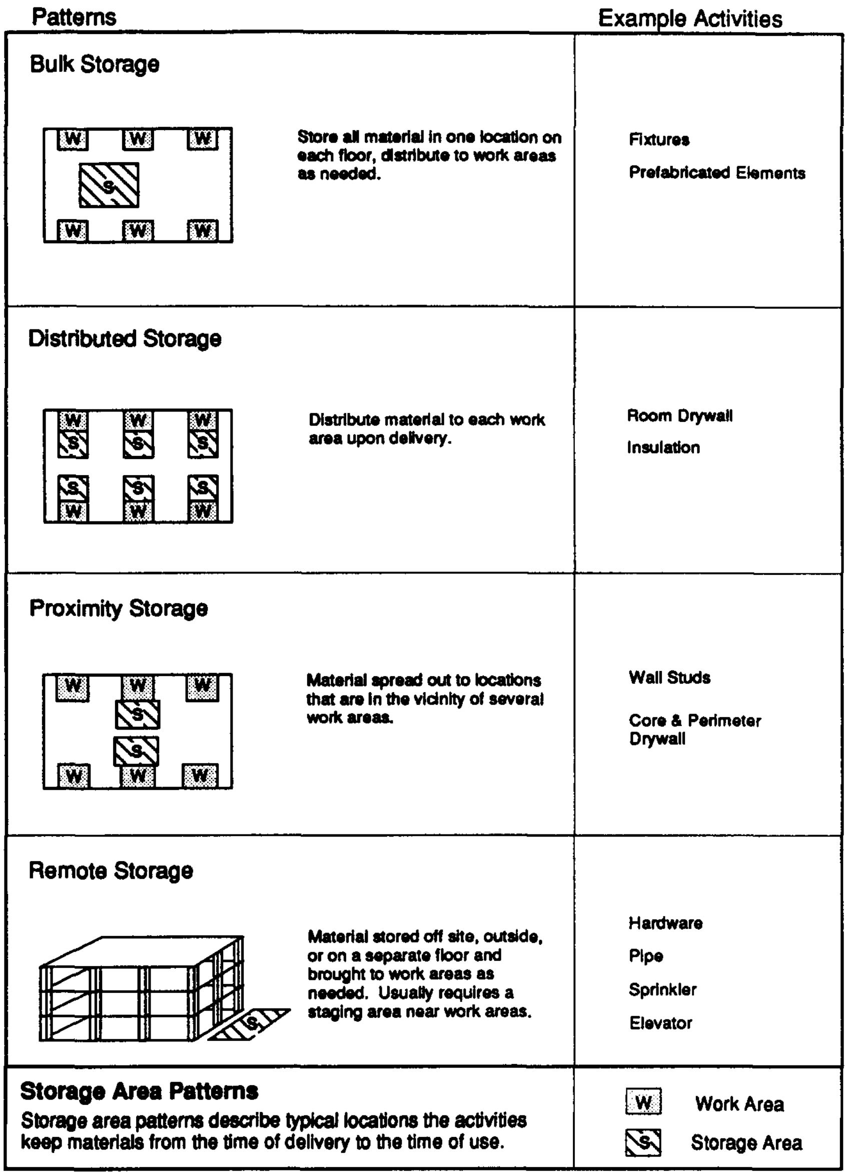

FIG. 4. Storage-Area Patterns

of test-site buildings, the space usage was recorded on a floor layout sketch at two-week intervals. An example is shown in Fig. 6. The locations and approximate sizes of occupied spaces were noted. An analysis of how space use changed over these intervals defined the pattern of space usage for each work element. Digital images of types and patterns of space use were also captured to record the site-visit observations. These are maintained in a database for reference.

When possible, four observations of each work element were made at regular time intervals of two weeks. In a few cases, it was not possible to observe each work element over four weeks, because some activities did not occur for the entire duration of the test or at the time of observations. In these cases, the space use for activities was determined by interviewing key personnel of the contractors and construction managers.

Space Definition Evaluation

Testing of the model included evaluating the accuracy and completeness of both the space-type definitions and the space-behavior patterns. Testing was performed to show that spaces found on each case-study site could be described by the definitions in the model, and to show that similar activities had the same space needs on different projects. For the first part of the test, a representative sample of the typical enclosure and interior activities that occur in a multistory building were observed. These included: enclosure trades (masonry, brick veneer, perimeter studs and sheathing, curtain wall, glazing) and interior trades (mechanical, electrical, and plumbing rough in, wall framing, drywall, wall insulation, pipe insulation, duct insulation, wall finishes, and floor finishes). Seventy four activities were observed on four sites. Activities were observed until no new undefined types of space were identified. At least one occurrence of each type of space in the model was observed and photographed. The model was revised when space usage that was not defined in the model was observed. The results were then evaluated for the frequency of occurrence and similarities between different activities.

Table 3 illustrates the types of spaces observed on projects and the total number of occurrences of each type. Examples of each type of space defined in the model were observed. Occurrences of space types ranged from a high of 74, for work in place and work areas, to a low of six, for protected areas. There were no spaces occupied by activities that were not defined by one of the types of space in the model. Several types of space were identified frequently, indicating that these spaces should be considered most frequently during planning.

J. Constr. Eng. Manage., 1995, 121(4): 464-473

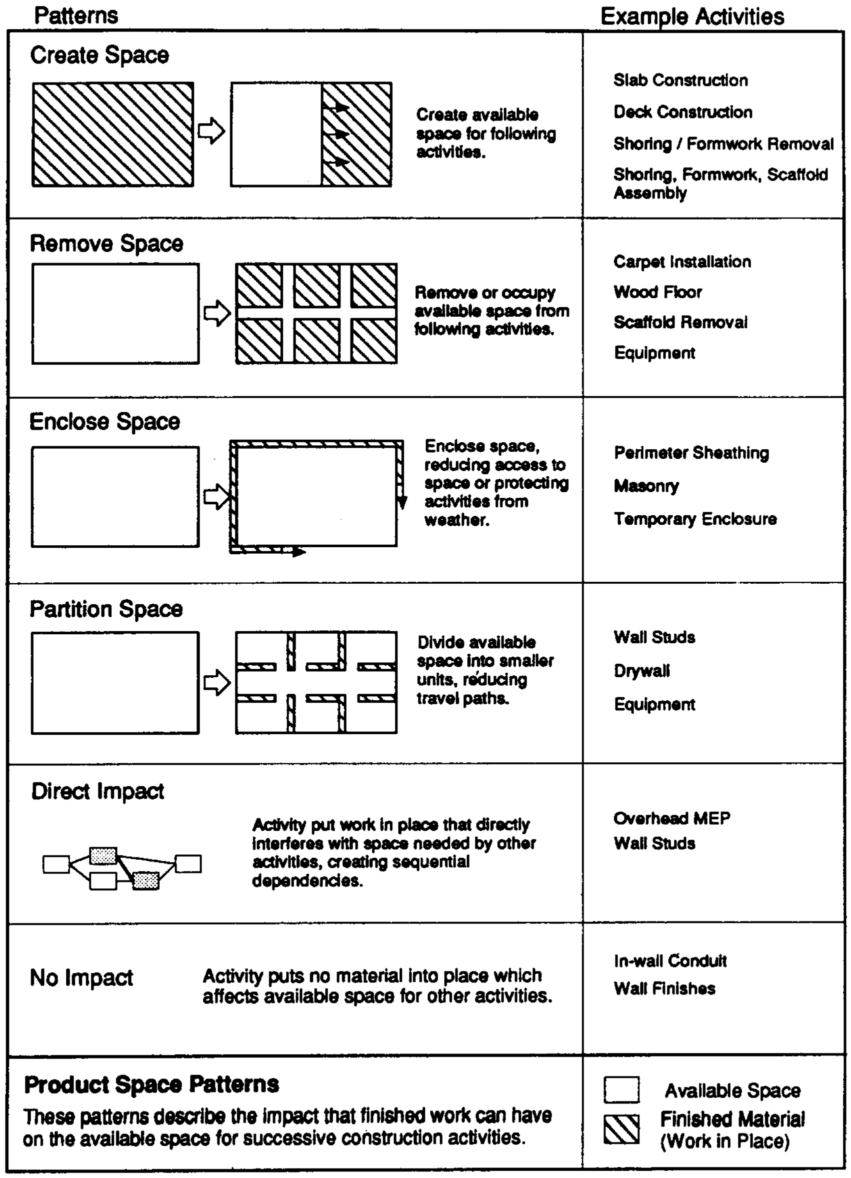

FIG. 5. Product-Space Patterns

TABLE 2. Case-Study-Project Information

		Facility Size			Work Rate		Design Description		
Project (1)	Facility type (2)	Typical floors (3)	Total floor area (m²) (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/month/total floor area.

These are unloading areas, material paths, storage areas, work areas, and product space.

Examination of the activities on different sites showed that similar activities have similar spatial needs, supporting the theory that the space needs of particular activities can be generalized. In all but one case, each activity needed the same set of spaces on each project.

Space-Behavior Pattern Evaluation

To test the second part of the construction-space model, the patterns in the model were evaluated by observing construction activities and corresponding work elements over time. Locations of work elements were mapped on floor plans at regular time intervals to show patterns of movement. Layout

J. Constr. Eng. Manage., 1995, 121(4): 464-473

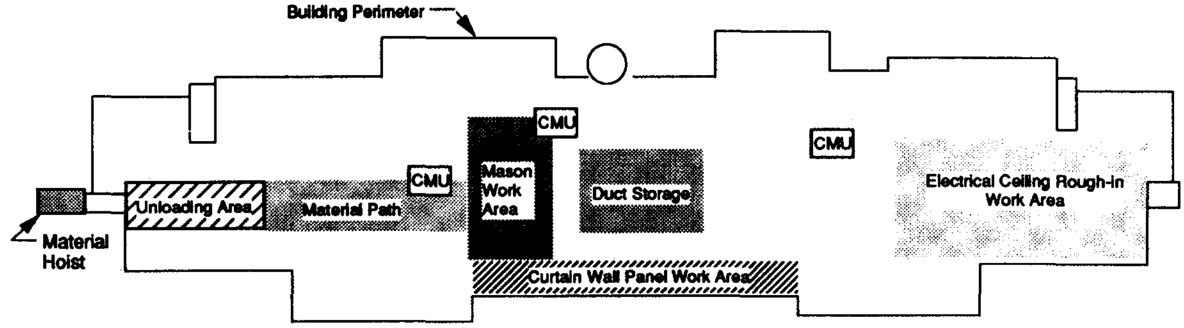

FIG. 6. Examples of Space-Behavior Pattern Data

TABLE 3. Summary of Space-Type Testing Data

	Space Types												
Sites (1)	Work in place (2)	Layout area (3)	Unloading area (4)	Material path (5)	Storage area (6)	Personnel path (7)	Staging area (8)	Prefabrication area (9)	Work area (10)	Tool/equipment (11)	Debris path (12)	Hazard area (13)	Protected area (14)
A	16	13	16	15	14	15	8	6	16	8	9	4	1
B	19	16	18	17	18	19	10	10	20	12	12	6	1
C	25	18	24	24	24	24	7	14	24	9	21	5	2
D	14	11	14	14	14	8	5	5	14	6	13	1	2
Total	74	58	72	70	70	66	30	35	74	35	55	16	6
Percentage of 74 activities	100.0	78.4	97.3	94.6	94.6	89.2	40.5	47.3	100.0	47.3	74.3	21.6	8.1

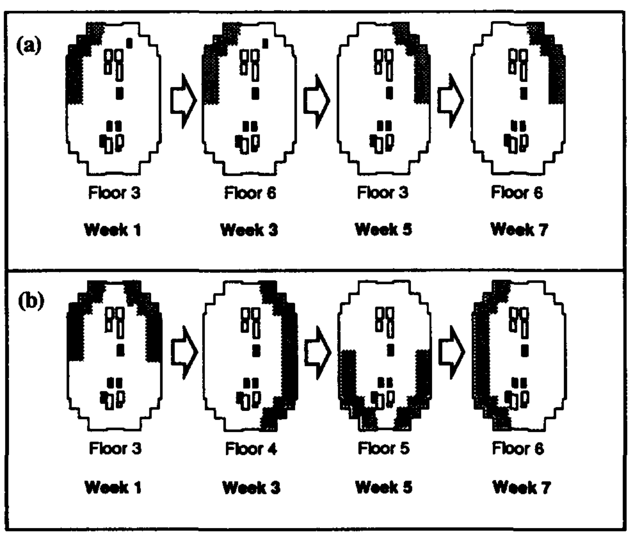

FIG. 7. Examples of Space-Behavior Patterns on Floor Layout Plans: (a) Building-Face Work Pattern; (b) Spiral Work Pattern

sketches included all major spaces that could be identified on each building floor, e.g., stacked material, work areas, piles of debris, access points, and recognizable paths. Locations of miscellaneous items such as loose debris, small piles of material scraps, and small tools were not recorded. An example of how patterns were identified on floor layout plans is illustrated in Fig. 7. Shaded regions indicate the location of an activity work element at each observation period, resulting in a pattern.

Table 4 illustrates the distribution of up to six types of patterns for each space type observed on projects. An example of all but two of the 49 patterns was observed on the case-study projects. Each space observed could be described by a pattern in the model. Vertical path patterns were eliminated from the original model because they represented the same spatial information on a floor as unloading areas.

In cases where comparable construction methods were selected and similar materials were used, activities followed similar patterns. An example of this is shown in Table 5, which illustrates the space behavior patterns observed for curtain-wall and wall-framing activities on multiple projects. Patterns for similar activities on different projects were very similar, supporting the theory that the space use of particular activities can be generalized, and that the use of space over time can be predicted.

Two further observations were made during the evaluation of space patterns. First, activities were observed performing work in one of three independent zones, i.e., perimeter, floor, or core. Site analyses indicated that activities in the same zone often followed the same pattern, permitting crews to follow each other in succession without interfering with each other's work areas. The relevance of this was observed by contrasting work sequences on project A and project B. On project A, activities in the same zones completed work in different patterns, often resulting in observed interference problems. In contrast, on project B, which had a measurably larger amount of work taking place (as indicated by the project progress rate), all activities in core, floor, and perimeter zones followed the same pattern respectively, and virtually no interference problems were observed.

The second observation was made about the nature of work performed by the crews. The breakdown of an activity into subactivities and work units was often summarized for planning and scheduling purposes. For example, a single activity might appear in a construction plan as "install sprinkler pipe," when, in reality, the installation of a sprinkler pipe involves several steps or subactivities: install pipe hangers, hang main pipe loop, hang branch pipe, and install sprinkler heads. These subactivities were typically performed sequentially by a crew, rather than concurrently, to increase efficiency. This results in an impact on the space used by a crew. Instead of the crew occupying a space one time and permanently vacating the space, the crew actually passes through the same space several times as it completes each subactivity. This increases the complexity of determining the rate at which a crew occupies and vacates space, which is a critical factor in the sequencing of successive activities.

J. Constr. Eng. Manage., 1995, 121(4): 464-473

TABLE 4. Summary of Space-Behavior Patterns Observed

Patterns (1)	Work in place (2)	Layout area (3)	Unloading area (4)	Material path (5)	Storage area (6)	Personnel path (7)	Staging area (8)	Prefabrication area (9)	Work area (10)	Tool/equipment (11)	Debris path (12)	Hazard area (13)	Protected area (14)
	Space Types												
1													
Name	Create	Room	Core	Work access	Bulk	Core	Room	Room	Linear	Room	Direct perimeter	Room	Temperature
Occurrences	1	19	8	15	35	11	12	13	22	23	22	4	5
Popularity[a]	1.4	25.7	10.8	20.3	47.3	14.9	16.2	17.6	29.7	31.1	29.7	5.4	6.8
2													
Name	Remove	Floor	Floor penetration	Storage access	Distribution	Floor	Floor	Floor	Random	Floor	Stock perimeter	Overhead	Perimeter
Occurrences	3	34	0	55	13	22	11	14	5	5	24	3	1
Popularity[a]	4.1	45.9	0.0	74.3	17.6	29.7	14.9	18.9	6.8	6.8	32.4	4.1	1.4
3													
Name	Enclose	Building	Single point perimeter	—	Proximity	Perimeter	Building	Building	Horizontal units	Building	Direct core	Building perimeter	Activity specific
Occurrences	8	5	61	—	17	12	7	8	26	7	0	9	—
Popularity[a]	10.8	6.8	82.4	—	23.0	16.2	9.5	10.8	35.1	9.5	0.0	12.2	0.0
4													
Name	Partition	—	Multipoint perimeter	—	Remote	Perimeter	—	—	Vertical units	—	Stock core	—	—
Occurrences	9	—	3	—	5	2	—	—	8	—	9	—	—
Popularity[a]	12.2	—	4.1	—	6.8	2.7	—	—	10.8	—	12.2	—	—
5													
Name	Direct impact	—	—	—	—	Core	—	—	Spiral	—	—	—	—
Occurrences	24	—	—	—	—	19	—	—	3	—	—	—	—
Popularity[a]	32.4	—	—	—	—	25.7	—	—	4.1	—	—	—	—
6													
Name	No impact	—	—	—	—	—	—	—	Face	—	—	—	—
Occurrences	29	—	—	—	—	—	—	—	10	—	—	—	—
Popularity[a]	39.2	—	—	—	—	—	—	—	13.5	—	—	—	—
Total occurrences	74	58	72	70	70	66	30	35	74	35	55	16	6
Percent representation of 74 activities	100.0	78.4	97.3	94.6	94.6	89.2	40.5	47.3	100.0	47.3	74.3	21.6	8.1

[a]Number of occurrences/74 observed activities.

TABLE 5. Examples of Similar Activities on Different Projects with Similar Patterns

Activities (1)	Work in place (2)	Layout area (3)	Unloading area (4)	Material path (5)	Storage area (6)	Personnel path (7)	Staging area (8)	Prefabrication area (9)	Work area (10)	Tool/equipment (11)	Debris path (12)	Hazard area (13)	Protected area (14)
	Space Types												
						(a) Curtain Wall							
Project B													
Description	—	—	Crane	—	—	—	—	—	—	—	Packing hoist	—	—
Pattern	Enclose	Building	Single point perimeter	Storage access	Semidistribution	Perimeter	Room	Room	Face	—	Stock perimeter	Perimeter	—
Project A													
Description	—	—	Crane	—	—	—	—	—	—	—	Packing chute	—	—
Pattern	Enclose	Building	Single point perimeter	Storage access	Semidistribution	Perimeter	Room	Room	Face	—	Direct perimeter	Perimeter	—
						(b) Wall Framing							
Project B													
Description	—	—	Hoist	—	—	—	—	Saw	—	Saw	Scrap hoist	—	—
Pattern	Partition	Floor	Single point perimeter	Work access	Distribution	Floor/core	—	Room	Horizontal units	Room	Stock perimeter	—	—
Project C													
Description	—	—	Hoist	—	—	—	—	Saw	—	—	Scrap hoist	—	—
Pattern	Partition	Floor	Single point core	Work access	Distribution	Floor/core	—	Room	Horizontal units	—	Stock perimeter	—	—
Project D													
Description	—	—	Forklift	—	—	—	—	Saw	—	—	Scrap forklift	—	—
Pattern	Partition	Floor	Single point perimeter	Work access	Distribution	Floor/core	—	Room	Horizontal units	—	Direct perimeter	—	—

Extensions to Model

The goal of this research was to define the reasons space is needed for construction work and to identify typical patterns of space use. Evaluation of the construction-space model found it to accurately represent space use in multistory building construction. The detail of this representation, however, is limited to defining the existence of needed spaces and the patterns in which they occur over time. Further data is needed to define typical sizes and locations of needed spaces for individual types of activities and their subactivities.

The model also provides a generic framework to describe construction-space decomposition. This decomposition varies among different activities depending on the nature of their materials and preferred work methods. As illustrated in the aforementioned sprinkler case, more detailed descriptions are needed of the typical breakdown of activities into subactivities and work units. This would provide a more accurate repre-

J. Constr. Eng. Manage., 1995, 121(4): 464-473

sentation of how crews decompose tasks into subcycles to work most efficiently, and how this decomposition affects their work-space needs.

Potential areas for further research are to define the sizes and locations of space, and the typical work breakdown needed for collections of commonly occurring activities. Another is to define adjacency requirements for spaces needed by common activities to support layout decisions. A multimedia database could illustrate examples of space patterns for planning and training.

PRACTICAL IMPLICATIONS

This research has several practical implications. Typically, a construction activity is represented in a schedule as a single event on a building floor and must be assumed to occupy and move through space as a single unit. The decomposition of activities into individual work elements in the construction-space model provides additional detail to this characterization. As a result, the space needs for portions of an activity should be considered separately (e.g., placing materials onto floors, storing materials for some time period, and construction work).

On several of the case-study projects, the analysis of activities using this model resulted in contributions to project planning. On project A, the preloading of raised floor material took place prior to the completion of overhead work. This preloading required several crews to move the material out of their way on a daily basis. To eliminate this problem, predicted patterns of work were determined to identify future work areas on building floors. Available storage locations for the floor material were then identified in the remaining unused spaces. Use of this storage space was mandated by the construction manager, greatly reducing the interferences. If this analysis had been performed earlier, the need to define storage areas or perhaps delay the loading of the raised floor material would have been evident.

On project B, planning predicted that a crew installing a specialized curtain wall on one side of the building would complete work in a different pattern (by face) than other trades working by floor. As a result, the material storage and work sequence of the wall framing was altered to keep the work area open around the critical enclosure activity. With ample work space provided, the curtain-wall crew finished enclosing the building ahead of schedule.

The analysis and development of space patterns resulted in several observations about construction sequences. Activities in multistory buildings generally fall into different zones: core activities, floor activities, and perimeter activities. Activities that take place in different zones can typically occupy the same floor with minimal interference. However, activities in the same zone should follow similar patterns to help keep them from interfering with each other. On projects A and C, when activities in the same zone followed the same pattern, fewer interferences were encountered.

Testing of the model showed that the space needs of activities can be predicted in an appropriate level of detail for construction sequence planning. In many cases, where space and logistics management on building floors is left to superintendents, to perform work in a reactive manner, the predicted patterns of space need in the model can help define a productive flow of work and supporting material-handling paths before work on site begins.

CONCLUSION

There are recognizable patterns of space use, and these were found to be repeatable and predictable on multiple projects. The construction-space model defines space types and space-behavior patterns as generic representations of how activities need space over time. These patterns can help to define a productive flow of work in the core, floor, and perimeter zones of a building. Testing of the model showed that different materials and activities have repeating (predictable) space needs from one project to the next.

When applied to site conditions on test projects, it was found that the model can be used to predict space need and identify the existence of potential interference problems between stored material and crews. This facilitated the development of a work sequence in which crews flow through the building in planned patterns, reducing the chance of blocked paths and spatial conflicts. When activities in the same work zone follow similar patterns, it is possible for large quantities of work to take place with minimal interference problems. These patterns may be considered as one key element to efficient multistory building construction.

The construction-space model helps increase awareness of the spatial relationships between activities. This may contribute to a shift away from the paradigm that space planning should be left to the last minute and performed only when interferences have already occurred. In particular, the characterization of common activities by their individual space needs will help to elevate and communicate these needs to inexperienced planners and students.

APPENDIX. REFERENCES

Howell, G., Laufer, A., and Ballard, G. (1993). "Interaction between subcycles: one key to improved methods." *J. Constr. Engrg. and Mgmt.*, ASCE, 119(4), 714–728.

Parvis, R. F. (1980). "Analysis of workspace congestion from scheduling data." *Trans. AACE*, F4.

Riley, D. R. (1994). "Modeling the space behavior of construction activities," PhD thesis, Penn State Univ., Univ. Park, Pa.

Smith, D. M. (1987). "An investigation of the space constraint problem in construction planning," MSc thesis, Dept. of Civ. Engrg., Virginia Polytech. Inst. & State Univ., Blacksburg, Va.

Thabet, W. (1992). "A space constrained resource constrained schedule system for multi-story buildings," PhD thesis, Virginia Polytech. Inst. & State Univ., Blacksburg, Va.

Thomas, H. R. (1990). "Loss of construction labor productivity due to inefficiencies and disruptions: the weight of an expert opinion," *Rep.*, Pennsylvania Transp. Inst., Penn State Univ., Univ. Park, Pa., 91–98.

Tommelein, I. D., Castillo, J. G., and Zouein, P. P. (1992). "Space-time characterization for resource management on construction sites." *Proc., 8th Conf. on Computing in Civ. Engrg.*, 623–630.

Tommelein, I. D., and Zouein, P. P. (1992). "Activity-level space scheduling." *Proc., 9th Int. Symp. on Automation and Robotics in Constr.*, 947–954.

Zouein, P. P., and Tommelein, I. D. (1993). "Space schedule construction." *Computing in civil and building engineering*, ASCE, New York, N.Y., 1770–1777.

J. Constr. Eng. Manage., 1995, 121(4): 464-473