Representing Work Spaces Generically in Construction Method Models

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Abstract: Construction activities require a set of work spaces to be executed safely and productively. The locations and volumes of these spaces change in three dimensions and across time, according to project-specific design and schedule information. Previous research on construction space management requires users to specify the spatio-temporal data necessary to represent each project-specific space needed for construction. Since a construction schedule consists of hundreds of activities requiring multiple types of spaces, this approach is practically infeasible. There is a need for a generic (project-independent) representation of work spaces, from which the project-specific instances of spaces can be derived automatically based on project-specific design and construction schedule information. This paper formalizes such a generic space description as a computer-interpretable ontology. This ontology is general, reusable, and comprehensive. A prototype system developed uses this ontology to capture the spatial requirements associated with construction methods and to automate the generation of project-specific spaces represented in three dimensions and across time.

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Introduction

Construction activities need a set of work spaces to be executed in a safe and productive manner. Riley (1994) identified 13 types of spaces required by construction activities. These are building components, layout areas, unloading areas, material paths, personnel paths, storage areas, staging areas, prefabrication areas, crew areas, tool and equipment areas, debris paths, protected areas, and hazard areas. Superintendents need to represent and manage all of these space requirements of construction activities during planning and scheduling to enable a safe and productive environment and to minimize schedule delays caused by spatial conflicts between activities (Rad 1980; Sanvido 1984; Hetrick and Khayyal 1987; Oglesby et al. 1989; Tommelein and Zouein 1993; Riley 1994; Thabet and Beliveau 1994; Thomas and Sakarcan 1994; Akinci and Fischer 2000a).

We classify these 13 spaces into three categories, as follows:

1. Macrolevel spaces—the large-scale spaces located across sites; e.g., storage, staging, layout, unloading, and prefabrication areas.
2. Microlevel spaces—the spaces required within the proximity of the components being installed; e.g., crew, equipment, hazard, and protected areas. These spaces also include the building components to be installed.
3. Paths—the spaces required to be left clear for transporting people, material, and debris; e.g., material, personnel, and debris paths.

In this research, we focus on representing microlevel spaces to enable superintendents to plan for these spaces during planning and scheduling. Microlevel spaces constitute core activity space requirements associated with direct installation work. Therefore, any problem resulting from spatial conflicts between the microlevel spaces required by two different activities directly impacts the work flow at construction sites (Howell and Ballard 1995; O'Brien et al. 1997; Riley and Sanvido 1997; Akinci et al. 1998; Akinci and Fischer 2000b). In the rest of the paper, the terms ''microlevel spaces'' and ''work spaces'' will be used interchangeably.

During construction, microlevel spaces required by activities change in three dimensions (x, y, z) and along time according to design and schedule information. Hence, planning for these spaces requires them to be represented in four dimensions (x, y, z, and t). Fig. 1 shows a small schedule consisting of window installation activities on all four sides of a building and their corresponding space requirements. In this simple case, the window subcontractor was planning on installing the windows from the outside using a scissor lift. This method requires space for the labor crew to be productive and a space for the equipment supporting the labor crew. Fig. 1(a) shows the project-specific instances of the equipment space and the labor crew space required during the placement of each window. Fig. 1(b) shows the symbolic four-dimensional representation of these spaces, assuming that the spaces are rectangular prisms aligned with Cartesian directions. This symbolic representation of the spaces requires the specification of eight spatio-temporal data items for each space—(x, y, z) insertion points; the dimensions on the x-, y-, and z-axes; and the start and end times for the use of the space.

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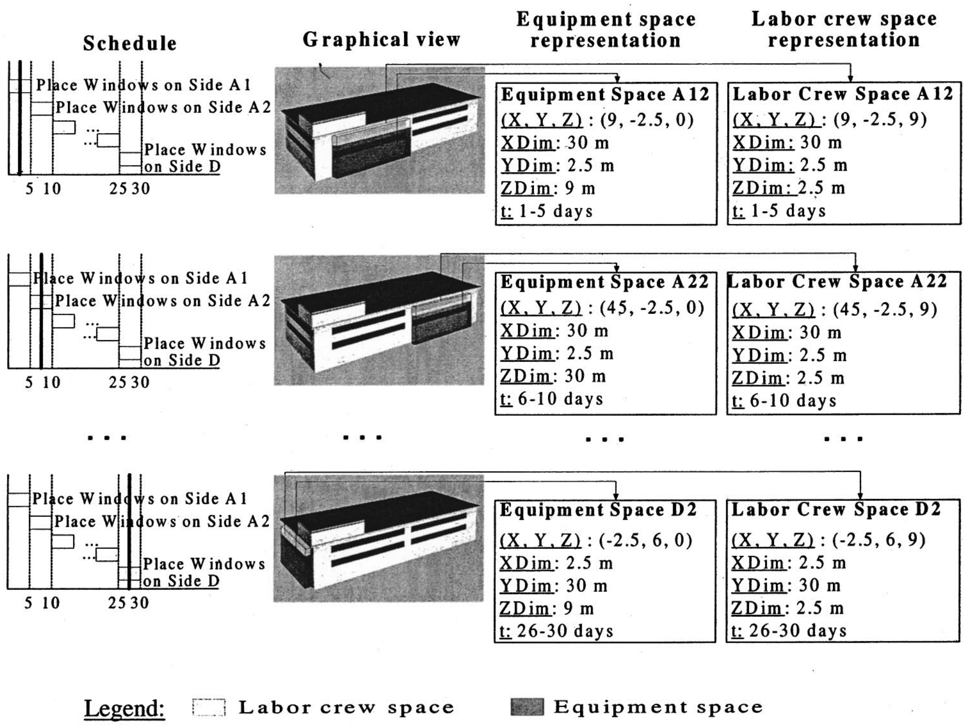

Fig. 1. Representation of spaces required by window installation activities occurring on all four sides of a building: (a) graphic; (b) symbolic

Current project management tools do not enable superintendents to manage microlevel activity space requirements during planning. 3D computer-aided design (CAD) software lacks the temporal information, and scheduling software lacks the 3D geometric information to represent the spaces in *x*, *y*, *z*, and *t*. 4D CAD tools include both the temporal and the 3D geometric information to display when and where the activities are going to occur. However, they typically show the spaces occupied by building components of the permanent facility, excluding the other types of spaces required by activities.

Consequently, currently superintendents explicitly or intuitively have to define eight spatio-temporal data items for representing each project-specific work space instance manually. These eight spatio-temporal data items include the *x*-coordinate, *y*-coordinate, *z*-coordinate, *x* dimension, *y* dimension, and *z* dimension for 3D spatial representation, and the start date and duration for temporal representation. This creates significant work for superintendents. For example, just to represent the four instances of spaces occupied by the six window installation activities shown in Fig. 1, a superintendent needs to define 196 spatio-temporal data items. This shows that it is practically prohibitive to expect superintendents to specify manually all of the spatio-temporal information to represent project-specific activity space requirements and to update this information manually as the design or the schedule changes. Hence, there is a need for an automated approach for the generation of project-specific activity space requirements. The first step in automating the generation of spaces is to formalize a generic representation of spaces in a computer-interpretable way such that users describe the spaces that they need only one time, and the system then automatically generates the project-specific instances of those spaces.

Subcontractors, when asked, can describe the different types of spaces needed during their operations generically in relation to the construction methods that they are going to use. For example, the window subcontractor in the case above described the space requirements shown in Fig. 1 as follows:

> ‘‘The installation of windows using the scissor lift method requires a labor crew space for the labor crew to be productive and an equipment space for the scissor lift supporting the labor crew. The labor crew space is located at the outside of the windows, and it is 2.5 m wide, 2.5 m high, and 3 m long, depending on the size of the window. The equipment space is located below the labor crew space. It occupies 3 m length, 2.5 m width, and its height extends from the ground to the location of the labor crew space.’’

This generic description applies to all project-specific labor crew space and equipment space instances shown in Fig. 1. In other words, this generic description of space requirements is reusable for representing the spaces occupied by the window installation activities to which the same ‘‘install windows using scissor lift’’ method is applied.

The goal of our research was to formalize these generic descriptions of spaces in a computer-interpretable way such that subcontractors can describe the spaces they need generically, and such that a computer system automatically interprets that knowledge according to project-specific design and schedule information to generate the project-specific work spaces represented in four dimensions. We implemented a prototype system, 4D WorkPlanner Space Generator (4D SpaceGen), which incorporates this ontology to automatically generate spaces. Akinci (2000) describes the mechanisms implemented in this system to transform the generic space representations to project-specific spaces.

Characteristics of Generic Space Representation

Three desirable characteristics of a generic space representation are as follows:

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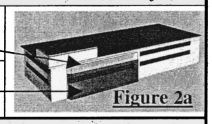
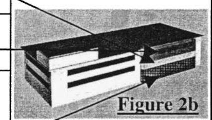
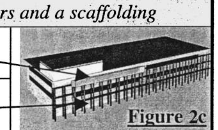
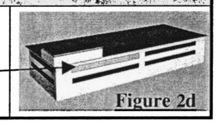
	Spatial Requirement	Description	Graphical Representation
(a)	*Method 1: Place windows from the outside using Crew W-1 consisting of three workers and one scissor lift*		
	Labor Crew Space	Located at the outside of the windows, requiring 2.5 m width, 3 m length, and 2.5 m height.	 Figure 2a
	Equipment Space	Supports the labor crew from below, requiring 2.5 m width and 3 m length, and it is located on the ground.	
(b)	*Method 2: Place windows from the outside using Crew W-2 consisting of three workers and a swing stage*		
	Labor Crew Space	Located at the outside of the windows, requiring 1.5 m width and 3 m length and 2.5 m height.	 Figure 2b
	Equipment Space	Supports the labor crew from above, requiring 1.5 m width and 3 m length, and it is located on the roof top.	
	Hazard Space	Located below the labor crew space due to the risk of falling objects. It requires an offset of 1 m from the length and width of the labor crew space. The hazard space goes all the way to the ground.	
(c)	*Method 3: Place windows from the outside using Crew W-3 consisting of three workers and a scaffolding*		
	Labor Crew Space	Located at the outside of the windows, requiring 3 m width, 3 m length, and 2 m height.	 Figure 2c
	Temporary Resource Space	Fixed space determined by the scaffolding around the building.	
(d)	*Method 4: Place windows from the inside using Crew W-4, consisting of three workers*		
	Labor Crew Space	Located at the inside of the windows, requiring 1.5 m width, 3 m length, and 2 m height.	 Figure 2d

Fig. 2. Different types of work spaces required by four construction methods of installing windows

1. Generality. A generic space representation should be able to model the different work space requirements of various construction methods used by subcontractors. In addition, a general space representation should also include all attributes necessary to represent different types of spaces required by activities. In developing an ontology of spaces, we abstracted the common attributes of representing microlevel construction spaces.
2. Reusability. A generic space description should apply to all of the corresponding project-specific work spaces. This reusability characteristic of a generic space representation significantly reduces the input requirements from the user. The case above showed that a space description related to a construction method applies to all project-specific instances. In addition, a generic space representation should be able to describe all of the project-specific work spaces regardless of the varying locations and sizes of the components within a project. For example, the same generic positional description should be used in describing the position of the window labor crew space on all sides of the building.
3. Comprehensiveness. A generic space representation should include all values necessary to model different types of spaces having different orientation and size requirements. Each type of space requires a different orientation vocabulary to describe the location of the space. For example, in the case described above, the labor crew space is located at the *outside* of the components, and the equipment space is located *below* the labor crew space. Similarly, each space type requires different volumetric parameters to describe the size of the space. For example, the labor crew space has a fixed size. A length, width, and height description is sufficient to represent it. On the other hand, the size of the equipment space changes according to the elevation of the labor crew space; instead of a fixed height representation, the location of the equipment space needs to be modeled explicitly, and the height should be derived from that representation. The generic space representation should be comprehensive enough to represent these different position and size descriptions of the spaces.

Relationship between Construction Methods and their Spatial Requirements

As discussed, subcontractors define the microlevel spatial requirements of activities generically according to the construction methods they plan to use. Fig. 2 provides an example of how the activity space requirements change in relation to the construction method being used. This example includes different types of spaces required by four alternative construction methods of installing windows.

Fig. 2 shows that the types of spaces required, their orientations with respect to the components being installed, and their size change with the construction method being used. Hence, the generic space representation should capture these relationships between the construction methods and space requirements.

Related Research Background

To represent activity space requirements generically within construction method models, this research combines and extends previous research in construction space management and construction method modeling.

Background Research on Construction Space Management

Many previous research studies focused on representing macrolevel spaces required by construction activities (Tommelein

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et al. 1992; Tommelein and Zouein 1993; Choi and Flemming 1996; Choo and Tommelein 1999; Hegazy and Elbeltagi 1999; Zouein and Tommelein 1999). A few investigated how to model microlevel spaces (Rad 1980; Riley 1994; Thabet and Beliveau 1994; Riley 1998).

All of the researchers who modeled microlevel spaces discuss the dynamic nature of activity space requirements. They identify the spatio-temporal attributes necessary to represent the project-specific work spaces (Rad 1980; Riley 1994; Thabet and Beliveau 1994; Zouein and Tommelein 1994; Riley 1998). These spatio-temporal attributes are similar to those shown in Fig. 1(b). Most of the previous research studies ask users to manually enter the project-specific three-dimensional and temporal data for each of the spaces required. As discussed above, it is not practically feasible for users to define the geometric and temporal information for all of the project-specific instances of spaces required by construction activities. Consequently, previous research does not adequately provide a representation that makes it practical for construction professionals to define the spaces that they need generically in relation to the construction method that they are going to use.

Background Research on Construction Method Modeling

Previous research on construction method modeling defines and represents construction methods as sets of generic activities required to install certain types of building components (Zozaya-Gorostiza et al. 1989; Tommelein et al. 1994; Aalami 1998). The main components of construction method models are components, actions, and resources (CAR) (Darwiche et al. 1988; Jägbeck 1994; Stumpf et al. 1996; Aalami 1998; Froese and Rankin 1998). As shown by previous research efforts, this representation enables the automated generation of project-specific construction plans and schedules.

For automated planning, construction method knowledge explains *why* certain groups of construction activities and sequences exist. However, it does not explain *how* activities are going to be executed; i.e., where the crew will be located with respect to the component, for what purpose the equipment will be used, and where it will be located with respect to the labor crew.

The CAR representation defines resources as *who* does the work, including human-power and equipment. This description of resources does not include the activity space requirements. Consequently, current construction method models lack a representation for the spatial requirements of activities, and the schedules generated using the CAR representation do not account for the space requirements of activities. We combine the previous research done in construction space management and construction method modeling by developing an ontology to represent spaces generically within method models.

In addition to the construction method modeling efforts, a number of researchers have focused on modeling construction operations using discrete event simulation (Tommelein et al. 1994; Martinez 1996; Shi and AbouRizk 1997; Shi 1999). In this approach, the space requirements of construction activities are modeled as any other resources requirement. Even though this approach provides a good approximation of activity space requirements, it does not provide an environment to differentiate the different types of spaces required by activities, which is necessary to identify different types of time-space conflicts between activities (Akinci 2000). In the project described, we extend the research done in this area by modeling in detail the different types of spaces required by construction activities.

Ontology for Generic Space Representation

An ontology for generic space representation provides the basis for an explicit representation of microlevel work space knowledge to enable professionals to include work spaces in schedules and 4D CAD models. In this research, we developed a construction work space ontology by abstracting the common attributes of the generic space descriptions (such as those given in Fig. 2) and by representing the work spaces and their relationships to construction methods. To develop this ontology, we performed case studies on three different construction sites, where we observed the different work spaces required by various activities associated with exterior enclosure works (e.g., window installation, wall panel installation, roof installation, and likewise). We also interviewed seven superintendents from four different trades to see how they describe the spaces they require for their activities generically.

Common Attributes of Generic Space Representations

By abstracting the observations made at various jobsites and summarizing the interviews conducted with superintendents, we realized that a space requirement can be described as oriented with respect to a reference object and requiring certain volumetric parameters. Hence, three common attributes for a generic representation of work spaces are as follows:

1. Reference object, in relation to which the space is located;
2. Orientation, describing the orientation of the space with respect to its reference object; and
3. Volumetric parameters, representing the size of the space (e.g., length, width, and height).

These generic space requirement descriptions apply to activities in a detailed schedule, such as three-week look-ahead schedules, in which the activities are decomposed according to their action types. We chose to represent this level of detail, since a schedule at this level starts to have meaningful representations about *how* the activities are going to be executed (Halpin and Riggs 1992; Ballard 1997). Given this assumption on the level of detail, we did not model generic temporal attributes and assumed that the microlevel spaces modeled will be required throughout the duration of each construction activity. These assumptions and the approximation worked well for the space requirements of all exterior enclosure activities that we modeled from three different jobsites. However, we realize that a more detailed temporal representation might be needed for highly mobile resources utilized in highly dynamic environments with many concurrent activities. In those cases, our approximation provides a conservative way to model the space requirements and enables the user to micromanage the activities that have possible spatial interferences between them.

Fig. 3 shows the formalized representation of the labor crew space, the equipment space, and the hazard space descriptions shown in Fig. 2 using these three common attributes. In this research, we did not model the temporary resource (such as scaffolding) space requirements of construction activities, since the space requirements of those resources are determined based on the way that specialty contractors design them. Generally, a drawing is generated for such components, and as a result they can be represented as part of the product model during construction. The Industry foundation classes (IFC) representation of the space re-

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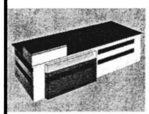
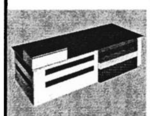
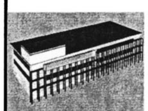
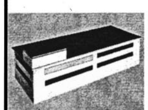
Graphic Representation	Labor Crew Space	Equipment Space	Hazard Space
1. Place windows using three workers and a scissor lift			
	Ref. Object: Window Orientation: Outside Parameters: Length: 3 m Width: 2.5 m Height: 2.5 m	Ref. Object: Labor Crew Space Orientation: Below Parameters: Length: 3 m Width: 2.5 m Height: from the ground to the labor crew space	
2. Place windows using three workers and a swing stage			
	Ref. Object: Window Orientation: Outside Parameters: Length: 3 m Width: 2.5 m Height: 2.5 m	Ref. Object: Labor Crew Space Orientation: Above Parameters: Length: 3 m Width: 2.5 m Height: from the roof to the labor crew space	Ref. Object: Labor Crew Space Orientation: Below Parameters: Length Offset: 0.5 m Width Offset: 0.5 m Height: from the ground to the labor crew space
3. Place windows using three workers and a scaffolding			
	Ref. Object: Window Orientation: Outside Parameters: Length: 3 m Width: 2.5 m Height: 2.5 m		
4. Place windows using three workers			
	Ref. Object: Window Orientation: Outside Parameters: Length: 3 m Width: 2.5 m Height: 2.5 m		

Fig. 3. Formal representations of the spaces required by four construction methods of installing windows

quirements of the temporary resources confirms this assertion (Industry 1998). As a result, we did not include the space requirement of the scaffolding used in the third method shown in Fig. 3.

These three sets of attributes identified for generic representations of microlevel spaces are similar to the attributes used for the qualitative representation of positional information in computer science (Hernandez 1994; Clementini et al. 1997; Freksa et al. 1998; Mukerjee 1998). Qualitative representation of positional information formalizes the spatial relationship between two objects by constraining the position of the *primary object* (the one located) with respect to the *reference frame*. The reference frame is defined as the *orientation* determining the direction of the primary object in relation to the *reference object*.

Previous research on qualitative representation of positional information identified the following three different ways of representing the reference frame (Clementini et al. 1997; Claus et al. 1998):

1. Egocentric—in which an observer is virtually positioned at a specific location and the positions of the primary objects around the observer are described in relation to the observer. This approach assigns the observer to be the reference object. The orientation descriptions associated with the observer, such as left_of, right_of, above, below, etc., represent the locations of objects around the observer. In egocentric representations, the orientation descriptions change as the observer moves from one point to another. The egocentric representation of work spaces would require allocating a fixed location for the observer and stating the orientation of each space with respect to that location. The description of the position of each space would be different for each project-specific space instance. Consequently, this representation does not meet the reusability criteria and cannot be used for the generic representation of spaces.
2. Geocentric—in which the primary objects are defined relative to a coordinate system of reference frames. Examples of geocentric descriptions are north, south, east, west, and so on. The geocentric representation of work spaces changes with the location and the orientation of the components being installed. Consequently, the geocentric reference frame does not meet the reusability criteria and cannot be used for the generic representation of spaces.
3. Allocentric—in which the primary objects are described relative to a distinguished reference structure. In allocentric representations, the relative position of the primary object does not change with respect to its related reference object, even though the location of the reference object might change. Therefore, if the reference objects are described as the components being installed, the positional relationship between the spaces and the reference object will be the same regardless of changes in location and orientation of the components. Consequently, we modeled the positional information of spaces using an allocentric representation.

Representing Space Requirements in Construction Method Models

We extended the representation of construction methods [Fig. 4(a)] by including labor crew, equipment, hazard, and protected spaces required by installation activities (Riley 1994).

As described in the previous section, these spaces have three common attributes (reference object, orientation, and a set of parameters describing the size). In addition, each space has a func-

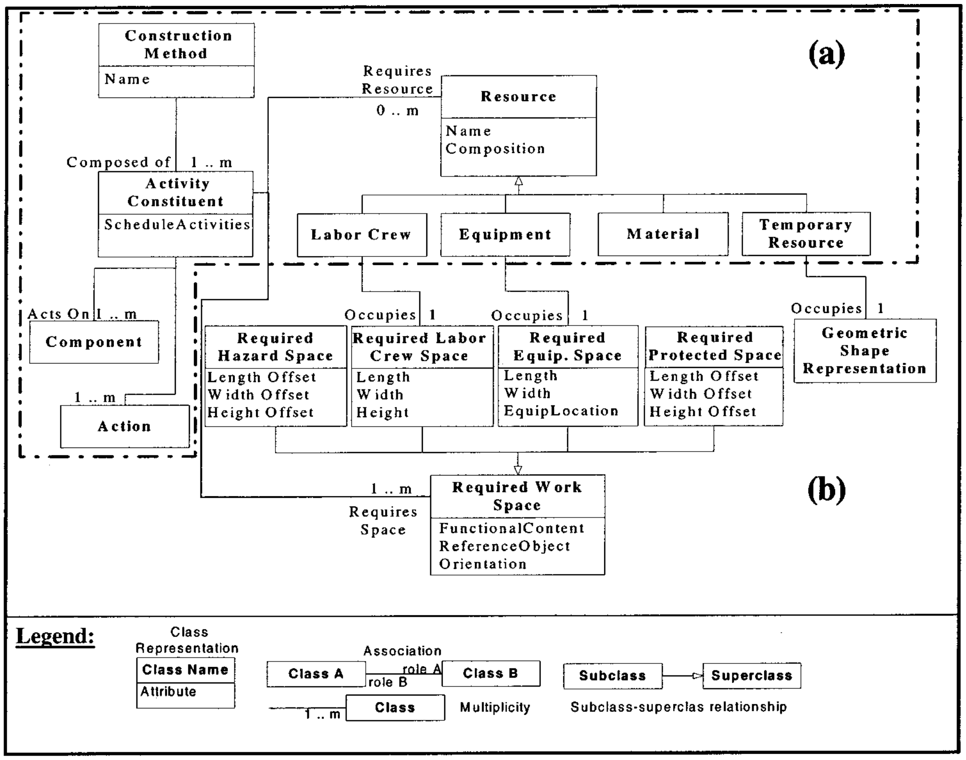


Fig. 4. Modified construction method models with generic work space representations using UML (Fowler and Scott 1999): (a) original CAR representation; (b) addition of spaces to CAR

tional content attribute to differentiate the spaces' distinct uses. For example, during the installation of windows from the outside using a swing stage, a hazard space is generated due to the risk of falling objects. In another case, for example, during the welding of steel members, a hazard space is generated due to the danger caused by fire sparks. It is important to note the reasons for these two hazard spaces. For example, if the hazard space in the first case conflicts with a protected space, such as the one required during the curing of concrete, it can damage the component. If the hazard space in the second case conflicts with the same protected space, it will not create any problem. The functional content attribute captures these types of reasons for the required spaces. Hence, when a user defines the functional content of a space with this attribute, a system can easily detect and categorize time-space conflicts existing in a schedule (Akinci 2000).

Fig. 4(b) shows the extensions to the initial construction method models to include the microlevel space requirement knowledge. The functional content, the reference object, and the orientation attributes apply to all subclasses of microlevel spaces. The parameters describing the size of the spaces change for each space type, since some spaces have fixed sizes and others have varying sizes. The next section further elaborates on this issue.

Two of the four space types modeled represent the spaces occupied by resources required by a construction method—the labor crew space and the equipment space. Therefore, we added a relationship called "occupies" to the labor crew and the equipment resources to represent the relationship between the labor crew resource and the labor crew space, and between the equipment resource and the equipment space.

The other two spaces modeled, the hazard space and the protected space, do not functionally relate to a space required by a resource. Therefore, there is no direct relationship between these two spaces and the resource requirements of construction methods.

Two other resources, material and temporary resources, also occupy space at construction sites. Materials occupy three different types of spaces at various times at construction sites—material storage spaces, material staging spaces, and material handling paths. Modeling of these spaces was outside the scope of the work presented in this paper.

Temporary resources are another category of resources that occupy space at construction sites. Examples of temporary resources are scaffolding and shoring. Temporary resources generally have separate activities for setup and dismantling. Once temporary resources are set up, they occupy a fixed space until they are dismantled. Generally, major temporary resources, such as scaffolding, have their own drawings associated with them. Hence, we assumed that the space requirements of such resources will be derived from those drawings and will be represented as any other building element in three dimensions during the time that they will be used at the site. This assumption and the corresponding space requirement representation match with the representation of the space requirements of temporary resources specified by IFC 2.0 (Industry 1998).

Values for Representing Microlevel Spaces

The previous section provided a schema including a set of common attributes of representing different work space types. This schema is empty unless we define the different values necessary for representing each type of space according to the three common attributes identified.

This section elaborates on the construction work space ontology developed by defining the different values necessary to describe the four types of spaces, modeled according to the attributes defined in the ontology. Table 1 shows the values identified to represent each space type according to the three com-

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mon attributes—reference object, orientation, and volumetric parameters. The next three sections describe how we derived the values to represent each space type, and discuss the similarities and the differences between the values used in describing the four types of work spaces modeled.

Reference Object Values

The function of the space determines the values to describe reference objects. For example, given that the function of the labor crew space is to provide space for the labor crew to install the components, the labor crew space is described with respect to the component. Similarly, in determining the reference object for the equipment space, we also investigated the function of the equipment. In this research, we modeled only staging equipment (such as rolling scaffolding, scissor lifts, swing stages, etc.), which supports labor crews and the components during installation. The spaces required by other types of equipment are not represented in the described model. Given that the function of the equipment space is to provide space for the staging equipment supporting either the building component or the labor crew, the equipment space is described with respect to the building component or the labor crew. Hence, the superintendent who defines the construction method that will be used in executing a certain group of activities will determine the type and the function of the equipment that will be used, and as a result will define the reference object for the space that a piece of equipment will occupy. As Table 1 shows, the reference object values differ from one type of space to another, since the function of each space type is different.

Orientation Values

The orientation values can be defined with two approaches.

1. *Define all possible combinations of orientations of a space with respect to its reference object in three-dimensional space*. This approach results in a set of orientation values that is general and comprehensive, since it covers all possible orientation scenarios. The literature on the qualitative representation of positional information in computer science contains examples of this approach (Allen 1983; Egenhofer and Franzosa 1991; Mukerjee 1998). These authors identified and represented all possible orientations between two objects along one dimension or two dimensions, with the goal of creating a general reference model for orientation representation without focusing on any particular problem or domain. They demonstrated the complexity of identifying all possible orientations even within the two-dimensional space, and concluded that this complexity would increase with the addition of the third dimension. Therefore, instead of defining all possible combinations of orientations for representing work spaces, we implemented the second approach for representing orientations.
2. *Identify the relevant orientation descriptions by performing case studies*. Due to the complexity of the first approach, some researchers suggested identifying only the orientation descriptions relevant for a specific problem space (Hernandez 1994; Clementini et al. 1997; Mukerjee 1998). This approach works for representing work spaces, since most installation activities access the building components predominantly using a limited set of directions. Table 1 shows the orientation descriptions identified in this research through interviews and case studies.

Table 1. Set of Values for Representing Four Different Types of Work Spaces

Parameter	Labor crew space	Equipment space	Hazard space	Protected space
Reference object	Building component	Building component labor crew space	Labor crew space	Building component
Orientation	Above, below, outside, inside, around the connected side, around	Above, below	Above, below, around	Around
Length (volumetric parameter)	User defined fixed number or length of the reference object as default	User defined fixed number or length of the reference object as default	User defined offsets from the reference object	User defined fixed offsets from the reference object
Width (volumetric parameter)	User defined fixed number or width of the reference object as default	User defined fixed number or width of the reference object as default	User defined fixed number offsets from the reference object	User defined fixed offsets from the reference object
Height (volumetric parameter)	User defined fixed number or height of the reference object as default	Variable according to the location of the equipment	User defined fixed number or variable according to the location of the reference object	User defined fixed number offsets from the reference object

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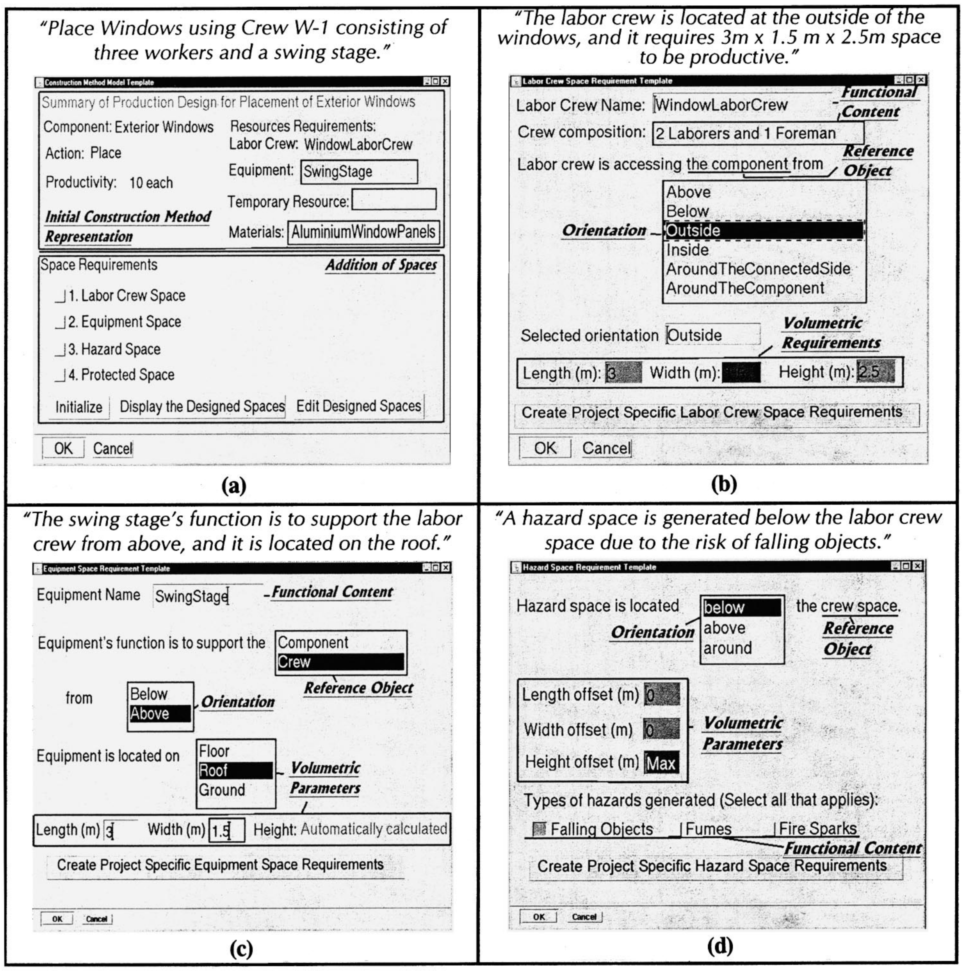

Fig. 5. Space templates implemented in 4D WorkPlanner Space Generator: (a) construction method template; (b) labor crew space template; (c) equipment space template; (d) hazard space template

Values for Describing Size Requirements

In representing the size requirements, we approximate the geometric representation of the work spaces as a rectangular prism. For the four types of spaces modeled, we found the rectangular prism to be an acceptable approximation.

Each of the four microlevel spaces has a different type of volumetric behavior. Project-specific instances of some space types, such as the labor crew space, occupy a fixed volume. The volumes of spaces occupied by other work space types, e.g., equipment space and hazard space, vary from one instance to another.

The attributes and the corresponding values used to describe the size of the volume required by spaces change according to their varying volumetric behaviors (Table 1). Spaces that have a fixed size relative to a reference object, such as the labor crew space, can be described using fixed length, width, and height attributes. However, for spaces whose sizes vary for each different project-specific instance (e.g., the equipment space and the hazard space), other attributes, such as the location of the equipment, must be used to derive their sizes.

Space Templates for Capturing Spatial Knowledge Related to Construction Methods

We developed a prototype system, 4D SpaceGen, to automate the generation of project-specific activity space requirements (Akinci 2000). For this system, we created space templates linked to construction method templates to capture the spatial requirements of construction methods. We implemented these space templates based on the generic space representations described in the previous sections. This section describes the space templates implemented in 4D SpaceGen by using an example construction method—placing windows using a swing stage [Fig. 2(b)]. In addition to this construction method, we were able to model and capture the space requirements of 20 different construction methods used for exterior (skin) work on commercial building structures. Examples of the construction methods include installation of windows from the outside using a scissor lift, installation of windows from the outside using scaffolding, installation of windows from the outside using a swing stage, installation of windows from the inside, installation of the roof membrane, installation of roof tiles, installation of wall panels from the outside using rolling scaffolding, and so forth.

To capture the space requirements related to construction methods, 4D SpaceGen starts by asking the user to fill out a construction method template [Fig. 5(a)] for a particular method. The construction method template consists of two sections. The first section contains component, action, and resource slots to capture the construction method attributes defined in previous research (Darwiche et al. 1988; Jägbeck 1994; Stumpf et al. 1996; Aalami 1998; Froese and Rankin 1998). The second section of the construction method template has options to describe the labor

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crew, equipment, hazard, and protected spaces associated with the construction method. The description of these spaces is optional, since not all construction methods require all four types of spaces. For example, the construction method of placing windows using a swing stage requires a labor crew space, an equipment space, and a hazard space [Fig. 2(b)]. However, the construction method of placing windows from the inside using three laborers requires only a labor crew space [Fig. 2(d)]. Therefore, after users decide on which construction method they are going to use, they need to determine the different types of spaces needed for that construction method. Hence, depending on the types of spaces that they need, they will push the appropriate buttons on the construction method template [Fig. 5(a)] to invoke the related space template to be filled out.

In the case of placing windows using a swing stage, the user needs to define a labor crew space, an equipment space, and a hazard space, since this operation involves labor crew and equipment and there is a hazard space generated during this operation underneath the swing stage because of the possibility of falling objects. Figs. 5(b–d) show the labor crew space template, the equipment space template, and the hazard space template generated when the user chooses the corresponding options.

All of the space templates created have four sections [as highlighted in Figs. 5(b–d)]—(1) a functional content section, where the user describes why a particular space is needed; (2) a reference object section; (3) a set of orientation descriptions; and (4) a set of parameters describing the volumetric requirements of the space. These parts correspond to the attributes defined in the ontology. The available values for each section match the values identified for the generic space representation (Table 1).

By filling out the space templates, users define the spaces they need for the construction methods they plan to use. 4D SpaceGen interprets these user-defined computer-interpretable generic space descriptions and generates the project-specific activity space requirements automatically. Akinci (2000) describes the system architecture and the mechanisms implemented in 4D SpaceGen.

Validation of Ontology Developed

We validated the ontology developed through three retrospective cases observed at three different jobsites—(1) Haas School of Business (O'Brien 1998); (2) Portside Housing (Akinci and Fischer 1998); and (3) San Francisco International Airport Boarding Area A (Akinci and Fischer 2000b). In addition, a graduate student and a visiting fellow from the Center for Integrated Facility Engineering used the ontology to perform a prospective test case in an office-building project. We were able to model all of the required spaces by the activities studied in these four cases using the ontology presented in this paper.

All of our test cases have focused on activities associated with exterior enclosure work. In total, we modeled the spaces required by 20 construction methods for installing 12 different components associated with exterior enclosure work. These include the representation of the spaces required by different methods of installing the same component; e.g., four different construction methods used for installing windows, and four different construction methods for placing wall panels.

We validated the ontology developed only with respect to the installation of a certain group of components, such as exterior enclosure components. The number of components and methods modeled and the 100% success rate in the retrospective and prospective tests of industrial construction cases have made us believe in the power of our ontology with respect to exterior enclosure work. Further, modeling of different construction methods for installing different types of components shows the generality of the ontology. There might be unique cases for which the values identified in our ontology do not cover the specific position of a space. We believe that the specifications for those cases can be approximated to one of the values shown in Table 1. Additional case studies focusing on representing spaces associated with other types of work will further validate the power and generality of the 4D SpaceGen orientation vocabulary developed.

Conclusions

The types of microlevel spaces required by construction activities, their locations with respect to the components being installed, and their sizes change with the construction methods used. This research formalized an ontology for representing activity space requirements generically within construction method models. Within this formalism, each space type is represented generically as having a certain orientation with respect to its reference object, and as having a fixed or variable size. The reference objects, the orientation descriptions, and the parameters describing the size of the space change for each type of space modeled. Therefore, we identified different values for representing these common attributes of labor crew spaces, equipment spaces, hazard spaces, and protected spaces.

This research has shown that construction method modeling provides a good basis for the generic representation of activity space requirements. This approach takes advantage of the reusability of the same construction method for all related instances of construction activities. The generic representation of work spaces has representational validity; it has been shown to be similar to the way users describe their space requirements. Finally, the ontology is general and comprehensive enough to model the four types of microlevel work spaces.

The ontology provides a computer-interpretable way of capturing and representing generic activity space requirements. It constitutes an essential step toward achieving the explicit and proactive management of activity space requirements prior to construction. Other steps are to use these generic representations of spaces to automate the generation of activity space requirements and to analyze a proposed construction schedule for time-space conflicts. Akinci (2000) describes these other steps.

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