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CIFE Working Paper #57
June, 2000

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REPRESENTING WORK SPACES GENERICALLY IN CONSTRUCTION METHOD MODELS

Burcu Akinci[1], Martin Fischer[2], John Kunz[3], Ray Levitt[4]

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. It enables a prototype system that captures the spatial requirements associated with construction methods and automates the generation of project-specific spaces represented in three dimensions and across time.

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1. INTRODUCTION

Construction activities need a set of work spaces to be executed in a safe and 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. We classify these 12 spaces into three categories:

(1) *Macro-level spaces*: the large-scale spaces located across sites, e.g., storage, staging, layout, unloading and prefabrication areas.

(2) *Micro-level 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.

During construction, all of these spaces change in three dimensions (x, y, z) and across time. Project managers need to represent and manage all of the various 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 2000b).

In our research, we focus on representing micro-level spaces to enable project managers to plan for these spaces during planning and scheduling. Micro-level spaces, such as labor crew space, equipment space, hazard space, and protected space, constitute the core activity space requirements associated with the direct installation work. Therefore, any problem resulting from time-space conflicts between the micro-level 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 2000a; Akinci et al. 2000b). In the rest of the paper, the terms “micro-level spaces” and “work spaces” will be used interchangeably.

Current project management tools do not enable project managers to manage micro-level activity space requirements during planning. Figure 1 shows three common views of the window installation activities on a construction project: (1) a 3D graphical view of the building obtained through a graphics program (e.g., AutoDesk 1998; Bentley 1998), (2) a Gantt Chart schedule created using scheduling software (e.g., Microsoft 1997; Primavera 1998), and (3) a 4D CAD simulation created by a 4D CAD tool (e.g, Intergraph 1999; Jacobus 1997; Parametric 1997).

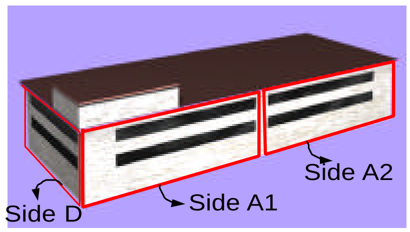


Figure 1a. 3D CAD

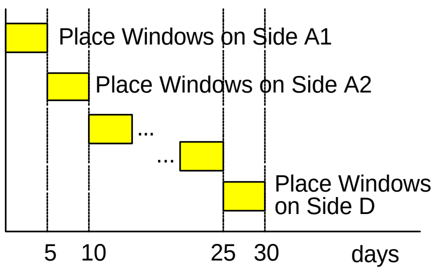


Figure 1b. Gantt chart schedule

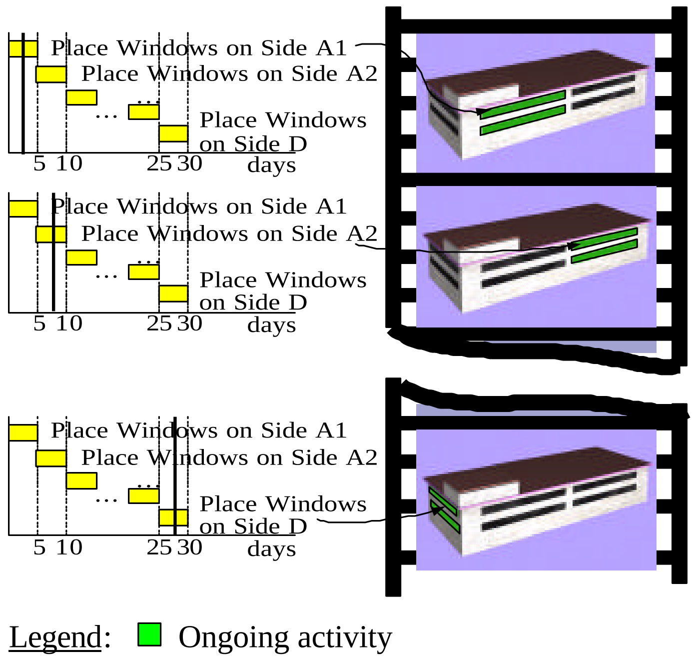


Figure 1c. 4D CAD simulation

Figure 1. Three commonly used views of a project do not show the work spaces required to execute installation activities at the site.

None of these three commonly used views of a construction project explicitly represents the work spaces required by the activities. The 3D graphical view lacks the temporal information to represent the work spaces. The Gantt Chart view lacks the 3D geometric information to represent the spaces. 4D CAD simulations include both the temporal and 3D geometric information to display when and where the activities are going to occur. However, they typically incorporate the spaces occupied by building components of the permanent facility. Hence, they lack information about the types, locations and sizes of work spaces that activities require.

Planning for micro-level construction spaces requires the spaces to be represented in four dimensions. In the simple case described above, 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. Figure 2a shows the project-specific instances of the equipment space and the labor crew space required during the placement of each window.

Figure 2b 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. These are the (x, y, z) insertion points, the dimensions on the x, y, z axes, and the start and end times for the use of the space.

Explicitly or intuitively, a project manager needs to define these eight spatio-temporal data items manually for all of the project-specific work space instances. The small case shown in Figure 2 has four instances of spaces occupied by six window installation activities requiring 196 spatio-temporal data items. This example suggests that it is practically prohibitive to expect project managers to specify manually all of the spatio-temporal information to represent project-specific activity space requirements and to update manually this information as the design or the schedule changes.

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.

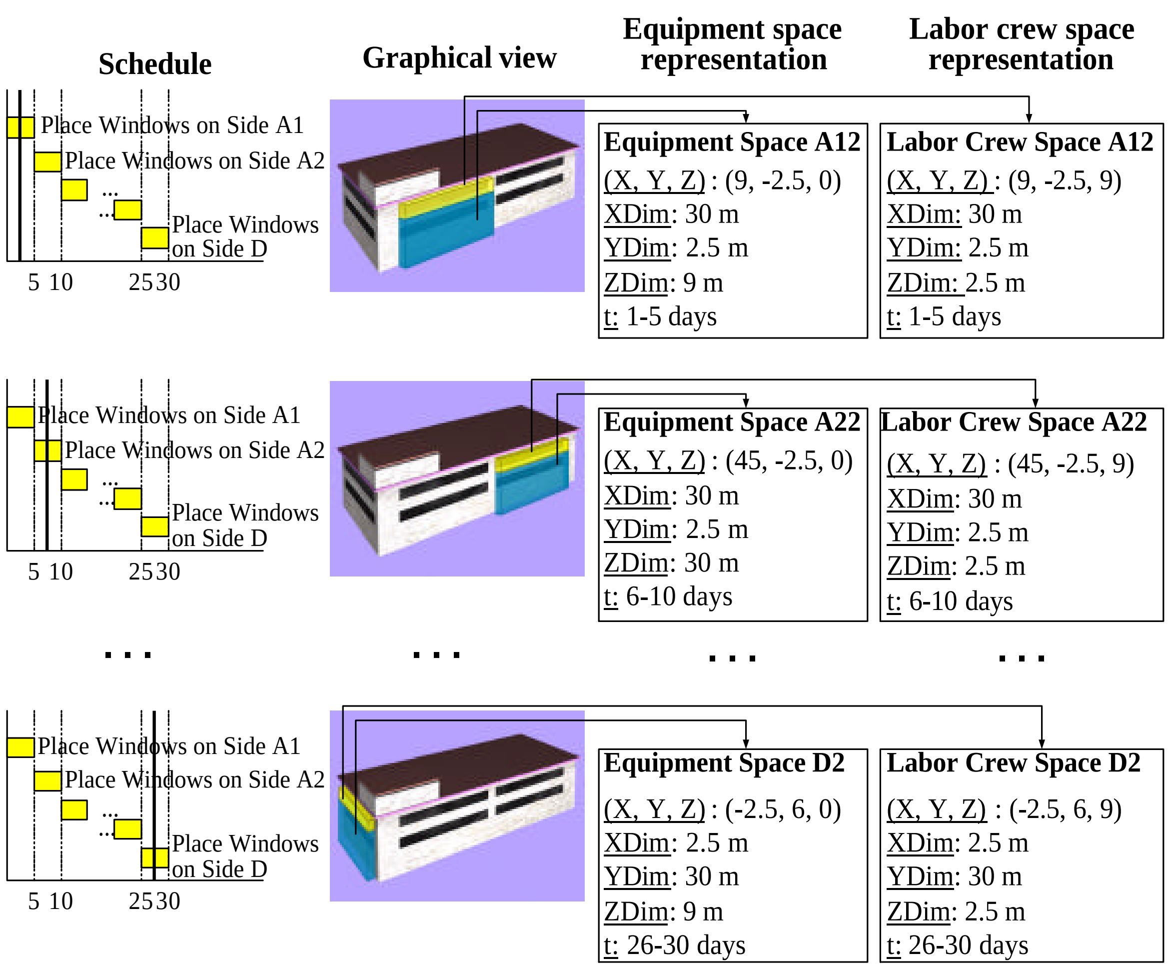


Figure 2a. Graphical representation of the project-specific space instances

Figure 2b. Symbolic representation of the project-specific space instances

Legend: Labor crew space Equipment space

Figure 2. The project-specific space representation requires the specification of eight spatio-temporal data items for each project-specific space instance.

Subcontractors, when asked, can often describe the micro-level spaces required by their activities using generic terms in relation to the construction methods that they are going to use. For example, the window subcontractor described the spaces required in the case above generically 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 Figure 2. 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 to enable subcontractors to describe the spaces they need generically, and have the computer automatically interpret that knowledge according to project-specific design and schedule information to generate project-specific spaces represented in x, y, z and time.

There are three desirable characteristics of a generic space representation:

(1) *Generality*. A generic space representation should be able to model the different work space requirements of various construction methods used by subcontractors. Hence, the first step in representing the different types of spaces required by construction methods is the formalization of the relationships between construction methods and work spaces. In addition, a general space representation should also include all of the attributes necessary to represent different types of spaces required by activities. In developing an ontology of spaces, we abstracted the common attributes of representing four different types of work spaces. These spaces are labor crew space, equipment space, hazard space, and protected space.

(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. This research extends the current construction method model representations to include the space descriptions. 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 four sides of the building. In developing the generic space ontology, we explored different qualitative positional representation frameworks to identify a set of positional descriptions that meet the reusability criteria.

(3) C*omprehensiveness.* A generic space representation should include all of the 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 a labor crew space. On the other hand, the size of the equipment space changes according to the elevation of the labor crew space. Therefore, in that case, 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. We formalized the different vocabularies used by subcontractors in describing the different spaces they need. Consequently, we developed a set of values to describe the position and the volumetric requirements of different types of micro-level spaces.

It was not the goal of this research to meet the comprehensiveness criteria by developing a library of construction methods and their space requirements. Therefore, in this research, instead of developing a library of all construction methods, we developed space templates linked to construction method templates to enable users to define the space requirements of different construction methods. These space templates are based on our generic space ontology.

We developed a prototype system, 4D WorkPlanner Space Generator (4D SpaceGen), that uses the spatial requirement knowledge captured generically in the space templates to generate the project-specific instances of spaces automatically and to represent them quantitatively in x, y, z and time dimensions. Akinci et al. (2000a) describe the mechanisms implemented in this system to transform the generic space representations to project-specific space instances.

2. RELATIONSHIP BETWEEN CONSTRUCTION METHODS AND THEIR SPATIAL REQUIREMENTS

As discussed above, subcontractors define the micro-level spatial requirements of activities generically according to the construction methods they plan to use. This section explores the relationship between construction methods and micro-level space requirements by describing the various spatial requirements of four different methods of placing windows.

Four alternative construction methods for placing windows are:

(1) *Place windows using Crew W-1 consisting of three workers and a scissor lift*: The workers place the windows from the outside, and they use a scissor lift located on the ground to reach them. Figure 3a describes the necessary equipment space and the labor crew space.

(2) *Place windows using Crew W-2 consisting of three workers and a swing stage*: The workers place the windows from the outside, and they use a swing stage located on the roof to reach them. This method creates a hazard space below the workers due to the risk of falling objects. Figure 3b describes the labor crew space, the equipment space, and the hazard space required by this method.

(3) *Place exterior windows using Crew W-3 consisting of three workers and a scaffolding*: In this method the workers place the windows from the outside, and they use a scaffolding already built at the site to reach the exterior windows. Figure 3c describes the necessary labor crew space and the temporary resource space.

4) *Place exterior windows using Crew W-4 consisting of three workers*: The workers place the windows from the inside. Figure 3d describes the necessary labor crew space.

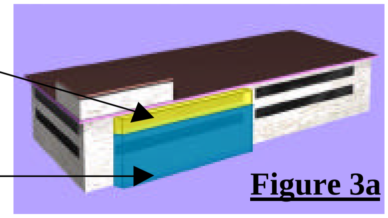
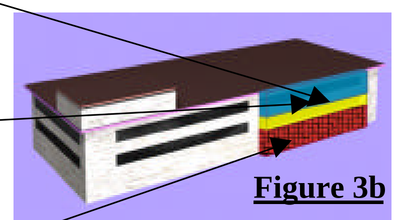
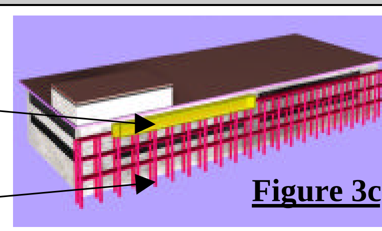
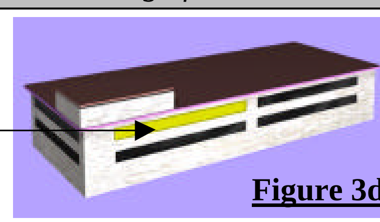
Spatial Requirements	Description	Graphical Representation
Method 1: *Place windows from the outside using Crew W-1 consisting of three workers and one scissor lift*		
Labor Crew Space	Located at the outside of the windows requiring 2.5 m width, 3 m length and 2.5 m height.	 **Figure 3a**
Equipment Space	Supports the labor crew from below requiring 2.5 m width and 3 m length, and it is located on the ground.	
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 3b**
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, requiring 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.	
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 3c**
Temporary Resource	Fixed space determined by the scaffolding around the building.	
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 3d**

Figure 3. The different types of work spaces required by four construction methods for placing windows.

Figure 3 shows that for the same "window installation" activity, the types of micro-level spaces required, their orientations with respect to the components being installed, and their size change with the construction method being used. Hence, an ontology for generic space representation needs to model the relationship between construction methods and spaces explicitly.

3. 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.

3.1 Background Research on Construction Space Management

Many previous research studies focused on representing macro-level spaces required by construction activities (Levitt et al. 1989; 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 micro-level spaces (Rad 1980; Riley 1994; Thabet and Beliveau 1994; Riley 1998).

All of the researchers, who modeled micro-level 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; Tommelein and Zouein 1993; Riley 1994; Thabet and Beliveau 1994; Zouein and Tommelein 1994; Riley 1998). The spatio-temporal attributes identified in previous research are similar to those shown in Figure 2b. Most of these 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 feasible for users to define the geometric and temporal information for all of the project-specific instances of spaces required by construction activities. Moreover, since users (e.g., subcontractors) describe their spatial requirements generically using qualitative positional descriptions, it would be an additional mental burden to the users to convert these generic descriptions to the project-specific representations.

In summary, previous research does not 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. Hence, there is a need for a computer-interpretable representation of work spaces.

3.2 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 (e.g., Aalami 1998). The main components of construction method models are **C**omponents, **A**ctions and **R**esources [**CAR**] (Darwiche et al. 1988; Jagbeck 1994; Stumpf et al. 1996; Froese and Rankin 1998; Aalami 1998). Figure 4a shows the **CAR** representation of two of the four window placement methods. As shown by previous research efforts this representation enables the automated generation of project-specific construction plans and schedules.

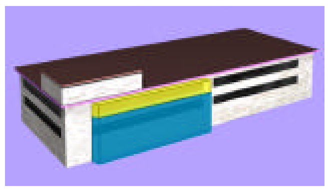
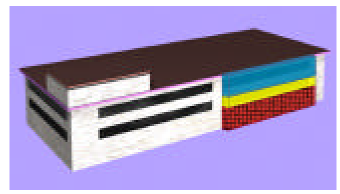
For automated planning, construction method knowledge explains *why* certain groups of construction activities and sequences exist. However, it does not explain *how* activities are going to be executed, i.e., where the crew will be located with respect to the component, for what purpose the equipment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

The **CAR** representation defines Resources as *who* does the work including manpower 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 extended the **CAR** construction method model representation to include activity space requirements. As Figure 4b shows, the representation of four types of the four types of work spaces enhances the representation of the knowledge of *how* construction activities are executed.

	Method 1 Place Windows using Crew W-1	**Method 2 Place Windows using Crew W-2**
Components	Exterior Windows	Exterior Windows
Actions	Place	Place
Resources	Crew W-1	Crew W-4
Labor Crew	3 window laborers	3 window laborers
Equipment	Scissor lift	Swing stage
Material	Window panels	Window panels

Figure 4a. **CAR** representation of the two construction methods of placing windows.

Spaces		
Labor Crew Space	Outside the windows requiring 2.5 m width, 3 m length and 2.5 m height	Outside the windows requiring 1.5 m width, 3 m length and 2.5 m height
Equipment Space	From ground to the labor crew space	From roof top to the labor crew space
Hazard Space	---	From the labor crew space to the ground
Protected Space	---	---

Legend: Labor Crew Space Equipment Space Hazard Space

Figure 4b. Work space requirements of the two construction methods of placing windows.

Figure 4. Representation of spatial knowledge within construction method models extends the construction method representation.

4. AN ONTOLOGY FOR GENERIC WORK SPACE REPRESENTATION

So far the paper has demonstrated the need for a generic representation of micro-level work space knowledge to enable professionals to include work spaces in schedules and 4D models. As our test have shown (Akinci 2000) the explicit representation of work spaces brings out time-space conflicts between activities much more clearly than current schedule and 4D representations. The basis for such an explicit representation is an ontology for the generic space representation for generic space representation.

This construction work space ontology abstracts the common attributes of the generic space descriptions (such as those given in Figure 3) to represent 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). We also interviewed seven superintendents from four different trades to see how they describe the spaces they require for their activities generically.

The next section describes these common attributes of representing different types of spaces. Identification of these common attributes suggests that it is possible to represent activity space requirements generically and in a computer-interpretable way. The following section describes the extensions we made to previously defined construction method model representations to include the micro-level spaces.

4.1 Common Attributes of Generic Space Representations

From our interviews and observations, we identified the following three common attributes of a generic representation of different types of work spaces:

(1) <u>Reference object</u>, in relation to which the space is located.

(2) <u>Orientation,</u> describing the orientation of the space with respect to its reference object.

(3) <u>Volumetric parameters</u>, representing the size of the space (e.g., length, width, height).

Figure 5 shows the formalized representation of the space descriptions shown in Figure 3 using these three common attributes. We do not represent genetic temporal attributes since we assume that micro-level spaces modeled will be required throughout the duration of each construction activity.

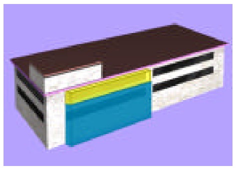
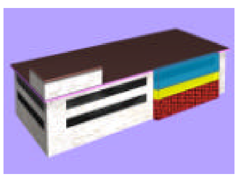
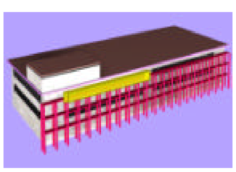
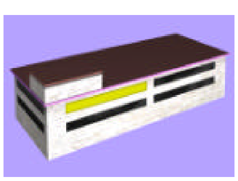
Graphical Representation	Labor Crew Space Representation	Equipment Space Representation	Hazard Space Representation
1. Place windows using Crew W-1 consisting of three workers and a scissor lift			
	Ref. Object: Window Orientation: Outside Parameters: Length: 3 m Width: 2.5 m Height: 2.5 m	Ref. Object: 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 Crew W-2, consisting of 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 Crew W-3, consisting of three workers and a scaffolding			
	Ref. Object: Window Orientation: Outside Parameters: Length: 3 m Width: 3 m Height: 2.5 m		
4. Place windows using Crew W-4, consisting of three workers			
	Ref. Object: Window Orientation: Outside Parameters: Length: 3 m Width: 2.5 m Height: 2.5 m		

Figure 5. Formal representation of the spaces required by the four construction methods of installing windows (Figure 3).

These three sets of attributes identified for generic representations of micro-level spaces are similar to the attributes used for qualitative representation of positional information in computer science (Clementini et al. 1997; Freksa et al. 1998; Hernandez 1994; 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*. The following sections discuss these common attributes in more detail and explain why the ontology we developed is general, reusable and comprehensive.

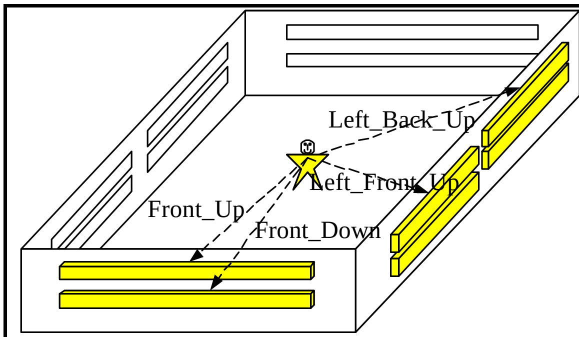
Previous research on qualitative representation of positional information identified three different ways of representing the reference frame (Clementini et al. 1997; Claus et al. 1998):

(1) *Egocentric*, in which an observer is assumed to be 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.

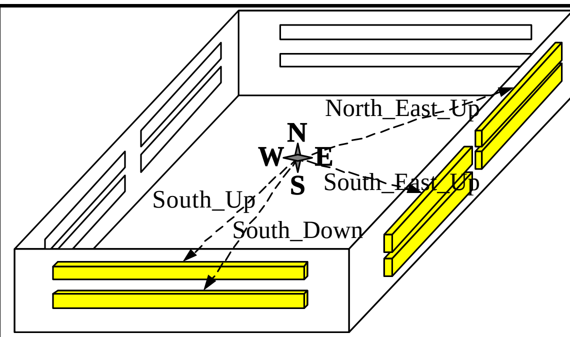
The egocentric representation of work spaces would require allocating a fixed location for the observer and stating the orientation of each space with respect to that location (Figure 6a). The description of the position of each space would be different for each project-specific space instance. Consequently, this representation does not meet the reusability criteria and cannot be used for 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, etc. The geocentric representation of work spaces (Figure 6b) 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 generic representation of spaces.

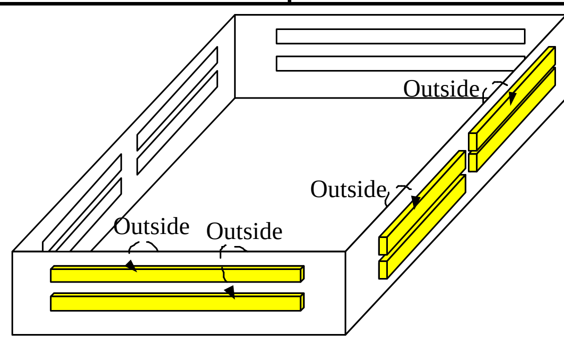
(3) *Allocentric*, in which the primary objects are described relative to a distinguished reference structure. In allocentric representations, the relative position of the primary object does not change with respect to its related reference object, even though the location of the reference object might 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 (Figure 6c). Consequently, we modeled the positional information of spaces using an allocentric representation.



<u>Figure 6a.</u> *Egocentric* representation



<u>Figure 6b.</u> *Geocentric* representation



<u>Figure 6c.</u> *Allocentric* representation

<u>Figure 6</u>. *Egocentric*, *geocentric* and *allocentric* representation of the labor crew spaces required during placing of windows.

The next sections describe how we added these common attributes to construction method representation.

4.2 Representing Space Requirements in Construction Method Models

We extended the representation of construction activities (Figure 7a) by including the four types of micro-level spaces required by installation activities. These are:

(1) <u>labor crew space</u>: the space required by the labor crew to be productive

(2) equipment space: the space required by the equipment supporting the labor crew or the component during installation

(3) hazard space: the space generated due to the hazardous nature of an activity

(4) protected space: the space required to protect the component for a certain period of time.

As described in the previous section, all of these spaces have three common attributes (reference object, orientation and a set of parameters describing the size). In addition, each space also has a functional 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. 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 et al 2000b)

Figure 7b shows the extensions to the initial construction method models to include the micro-level space requirement knowledge. The functional content, the reference object and the orientation attributes apply to all subclasses of micro-level 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 directly 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. These are material storage spaces, material staging spaces, and material handling paths. The first two of these spaces are macro-level construction spaces, and the third is an example of a path at construction sites. Modeling of macro-level construction spaces and paths are outside of the scope of this work.

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 set up and dismantling. Once temporary resources are set up, they occupy a fixed space until they are dismantled. Therefore, we modeled the spaces occupied by the temporary resources in a similar fashion to the space required by building components, using project-specific geometric shape representations. Consequently, the generic conceptual space model does not include a separate representation schema for the spaces occupied by temporary resources.

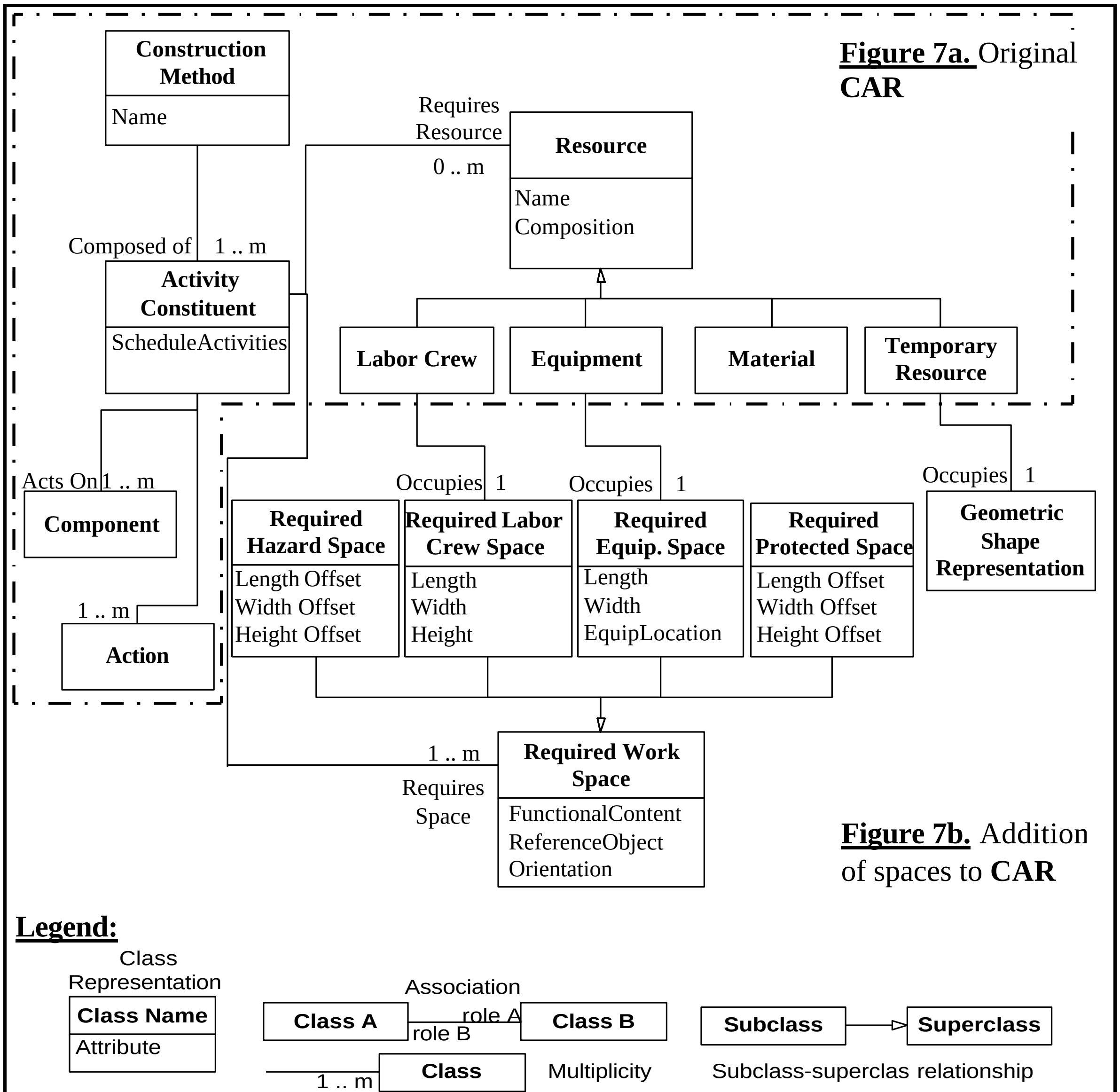


Figure 7. Modified construction method models with generic micro-level space representation using UML (Fowler and Scott 1999).

So far, we discussed the classes and attributes defined in the ontology developed to represent work spaces generically within construction method models. Hence, we provided a general schema including the common attributes of different work space types. This general schema is empty unless we define the different values necessary for representing each of the space types modeled according to the three common attributes. The next section describes the different values we identified to represent the four types of micro-level spaces. These values capture the generic activity space requirement knowledge. The following section then describes the space templates developed based on the values identified to enable users to capture the specific micro-level space requirements of activities.

5. VALUES IDENTIFIED FOR REPRESENTING MICRO-LEVEL SPACES

This section elaborates the construction work space ontology by defining the different values necessary to describe the four types of spaces, modeled according to the attributes defined in the ontology. Table 1 overviews the values identified to represent each space type according to the three common attributes: reference object, orientation, and volumetric parameters. As Table 1 shows there are similarities and differences in the vocabulary used to describe each space type. The next three sections describe how we identified the values of the reference object, orientation and volumetric parameters for each space, and why there are similarities and differences between the values describing the four types of micro-level spaces.

	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
Volumetric Parameters: *Length*	Fixed or length of the reference object as default	Fixed or length of the reference object as default	Offsets from the reference object	Offsets from the reference object
Width	Fixed or width of the reference object as default	Fixed or width of the reference object as default	Offsets from the reference object	Offsets from the reference object
Height	Fixed or height of the reference object as default	Variable according to the location of the equipment	Fixed or variable according to the location of the reference object	Offsets from the reference object

Table 1. A set of values for representing four different types of work spaces.

5.1 Reference Object Values

The function of the space determines the values to describe reference objects. Since the function of each type of space is different, the reference object values differ from one type of space to another. Table 2 shows the functions of the micro-level spaces and the corresponding reference object values.

Space Type	Function	Reference Object Values
Labor Crew Space	Represents the space required by the labor crew installing the building component.	Building Component
Equipment Space	Represents the space required by the equipment supporting either the building component or the labor crew.	Building Component Labor Crew Space
Hazard Space	Represents the hazard space generated by the labor crew during installation.	Labor Crew Space
Protected Space	Represents the space required to protect the building component for a certain period of time.	Building Component

Table 2. Functions of the spaces and the corresponding reference objects.

5.2 Orientation Values

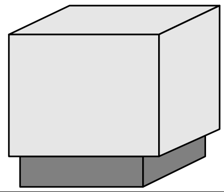
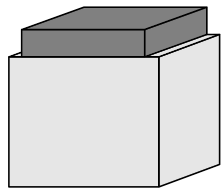
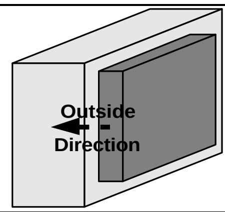
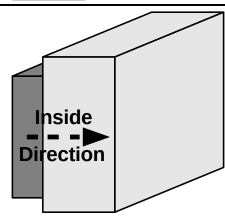
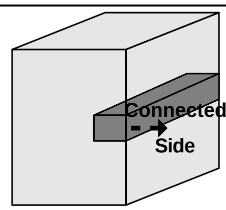
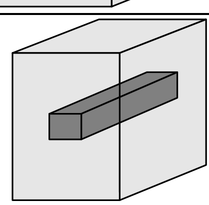
The orientation values can be defined with two approaches:

(1) *Define all possible combinations of orientations of a space with respect to its reference object in the 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 qualitative representation about positional information in computer science contains the examples of this approach (Allen 1983; Egenhofer and Franzosa 1991; Mukerjee 1998). These authors identified and represented all possible orientations or topological relationships between two objects along one dimension or two dimensions, with the goal of creating a general reference model for orientation or topology 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 certain set of directions.

We identified a set of orientation descriptions for the four micro-level work spaces according to our observations at three job sites and interviews with seven superintendents. These orientation descriptions represent orientation and topological relationships between the work spaces and their reference objects. Table 1 shows the orientation values identified as a result of those observations and interviews and Figure 8 describes them in more detail.

Orientation description	Graphical representation	Explanation	Examples from the case
Above		The space is located above the reference object, and the bottom side of the space touches the top side of the reference object.	The space for the swing stage is located above the labor crew space placing the windows (Figure 4b).
Below		The space is located below the reference object, and the top side of the space touches the bottom side of the reference object.	The space for the scissor lift is located below the labor crew space placing the windows (Figure 4a). The hazard space is located below the labor crew space placing the windows (Figure 4b).
Outside		The space is located at the outside of the reference object, and the inner side of the space touches the exterior space boundary of the reference object.	The window labor crew is located at the outside of the windows (Figures 4a, 4b, 4c).
Inside		The space is located at the inside of the reference object, and the inner side of the space touches the interior space boundary of the reference object.	The window labor crew is located at the inside of the windows (Figures 4d).
Around the connected side		The space is located around the connected side of the reference object, and the space partially encloses the reference object.	No example in the case discussed in Figure 4
Around		The space is located around the reference object, and the space fully encloses the reference object.	No example in the case discussed in Figure 4

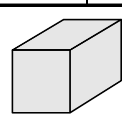
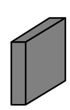
Legend:  Space to be defined  Reference Object

Figure 8. Orientation descriptions and the corresponding explanations regarding topological and orientation relationships between work spaces and their reference objects.

5.3 Values for Describing 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 micro-level 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. Figure 9 exemplifies the different volumetric behaviors of different types of spaces.

The attributes and the corresponding values used to describe the size of the space required by work spaces change according to their varying volumetric behaviors. 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.

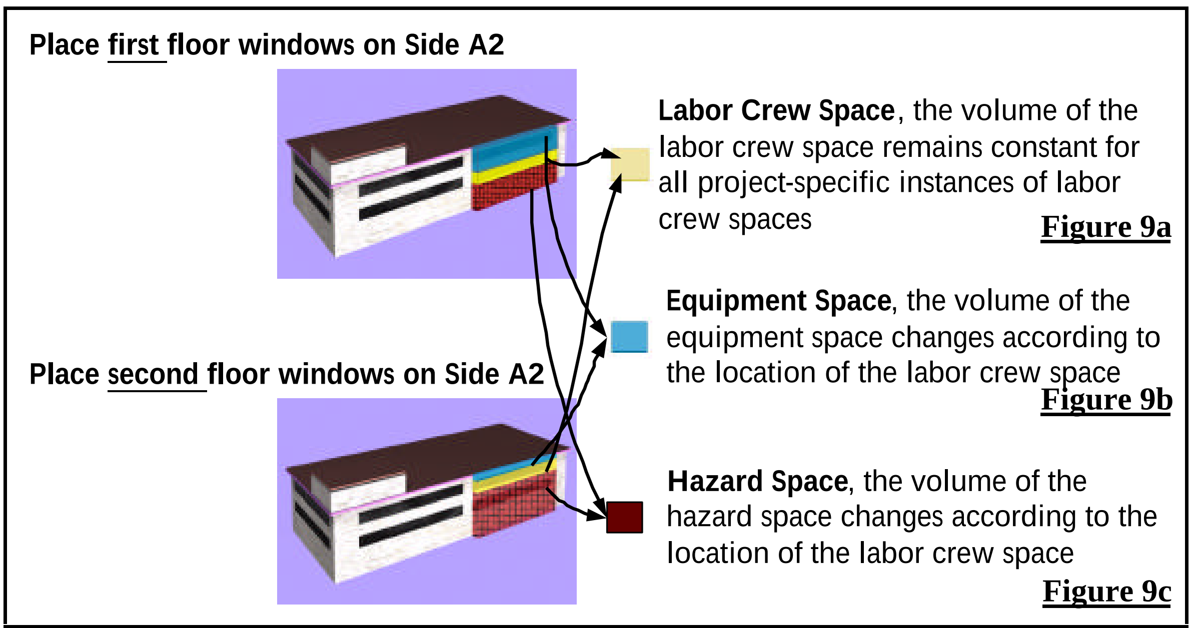


Figure 9. Different volumetric behaviors of different types of spaces for using the placement of windows using a swing stage.

Below is a description of different size requirements of each space type including the corresponding volumetric parameters and values used to represent them:

(1) Volumetric parameters to represent labor crew spaces. Labor crews generally require a fixed volume to be productive. This volume remains constant for all of the project-specific labor crew spaces (Figure 9a). Therefore, we represent the volumetric requirements of labor crew spaces with fixed numbers for length, width, and height.

(2) Volumetric parameters to represent equipment spaces. We model the space required by staging equipment, which supports the labor crew or the component during installation. Examples of material staging equipment are scissor lift, rolling scaffolding, swing stage, etc. In most cases, the length and the width of the staging equipment are constant, but the height changes according to the difference between the location of the equipment (e.g., ground, floor, roof) and the location of the project-specific instance of the reference object (building component or labor crew). Figure 9b illustrates how the height of a swing stage changes according to the location of the labor crew.

We represent the length and the width requirements of equipment spaces using constant numbers, similar to the labor crew space representation. Since the height of the equipment space changes, instead of explicitly representing the height of the space, we represent the location of the equipment as on the ground, on each building story or on the roof. We implemented transformation mechanisms (Akinci et al. 2000a) that use this information about the location of the equipment together with the information from project-specific 4D production model to derive the heights of the project-specific spaces.

(3) Volumetric parameters to represent hazard spaces. Hazard spaces are generally defined as offsets from the labor crew space. Therefore, the length and the width of hazard spaces are represented using fixed numbers as length offset and width offset from the labor crew space. The heights of hazard spaces can be fixed or variable. For example, the height of the hazard space due to the risk of falling objects varies according to the elevation of the labor crew space from the ground level (Figure 9c). In other cases, the height does not change and is represented as a fixed number, e.g., the hazard space generated due to fire sparks during a welding process. Therefore, we keep the height representation of hazard spaces flexible. Users can choose to

define them as a fixed number or keep them variable by stating that the height is from the labor crew space all the way to the ground.

(4) Volumetric parameters to represent protected spaces. Protected spaces are generally defined as an envelope around the related building component to protect the component for a certain period of time. Therefore, we represent the volumetric requirements of protected spaces with fixed numbers as length offset, width offset, and height offset from the component.

So far, we have described the ontology developed and the corresponding values identified to represent labor crew spaces, equipment spaces, hazard spaces and protected spaces generically within construction method models. The next section describes how this ontology enables users to capture the spatial requirements associated with construction methods.

6. SPACE TEMPLATES FOR CAPTURING OF SPATIAL KNOWLEDGE RELATED TO CONSTRUCTION METHODS

We developed a prototype system, 4D WorkPlanner Space Generator (4D SpaceGen), to automate the generation of project-specific activity space requirements (Akinci et al. 2000a). For this system, we created space templates linked to construction method templates to capture the spatial requirements of different construction methods. We implemented these space templates based on the generic space representations described in the previous sections.

We decided to link space templates to construction method templates instead of developing a library of construction methods with space descriptions since it is impossible to have a comprehensive list of construction methods. The space templates related to construction methods provide flexibility for the user to describe different construction methods instead of choosing from a predefined list of methods. This section describes the space templates implemented in 4D SpaceGen by using an example construction method: placing windows using swing stage (Figure 3b).

To capture the space requirements related to construction methods, 4D SpaceGen starts by asking the user to fill out a construction method template (Figure 10a) 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; Jagbeck 1994; Stumpf et al. 1996; Froese and Rankin 1998; Aalami 1998). The second section of the construction method template has options to describe the labor 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 (Figure 3b). However, the construction method of placing windows from inside using three laborers requires only a labor crew space (Figure 3d). Therefore, users choose which spaces are needed.

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. Figures 10b, 10c, and 10d 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 Figures 10b, 10c, 10d): (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 (Figure 5). The available values for each section match the values identified for generic space representation (Table 1).

"Place Windows using Crew W-1 consisting of three workers and a swing stage."

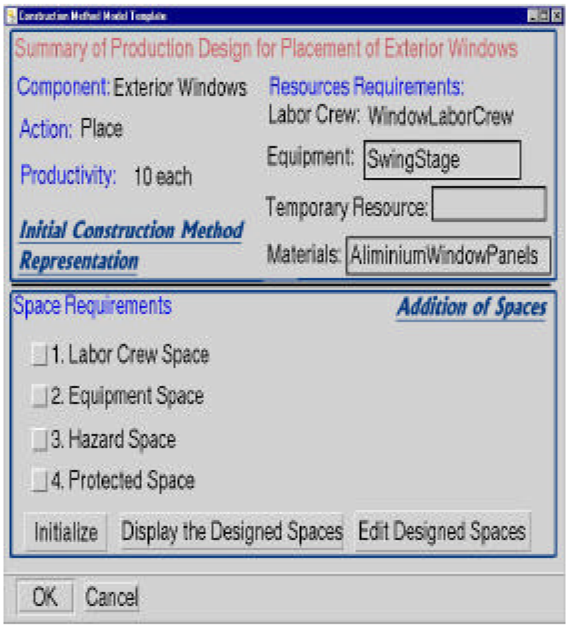


Figure 10a.Construction Method Template

"The labor crew is located at the outside of the windows, and it requires 3m x 1.5 m x 2.5m space to be productive."

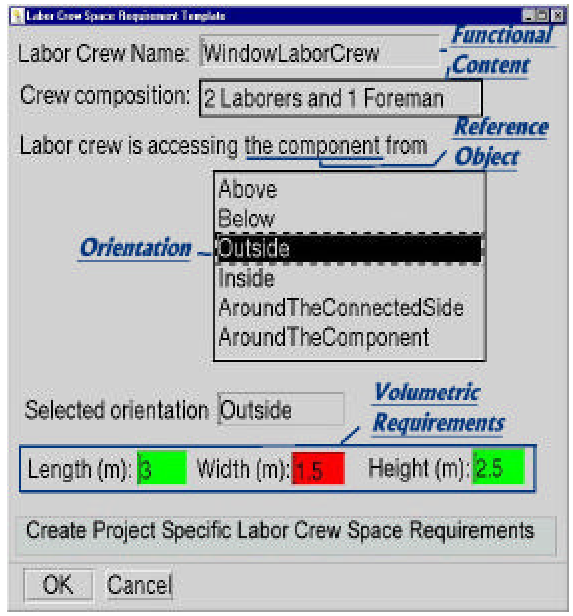


Figure 10b. Labor Crew Space Template

"The swing stage's function is to support the labor crew from above, and it is located on the roof."

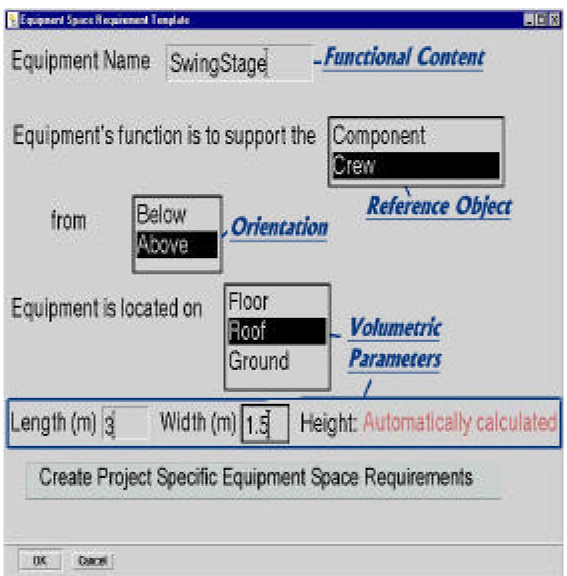


Figure 10c. Equipment Space Template

"A hazard space is generated below the labor crew space all the way to the ground due to the risk of falling objects."

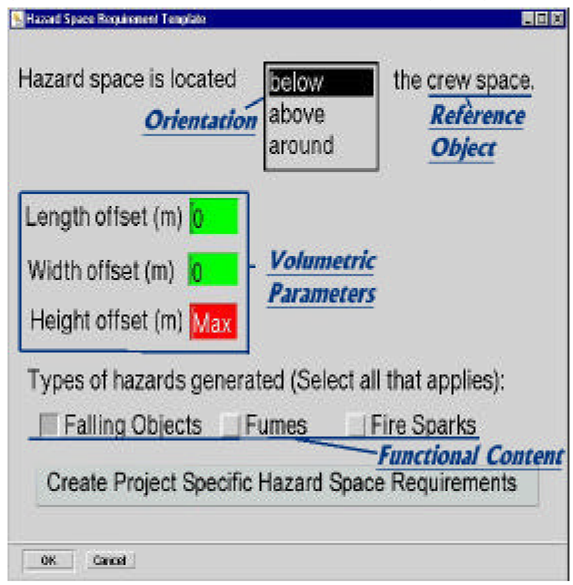


Figure 10d. Hazard Space Template

Figure 10. The space templates implemented in 4D SpaceGen match subcontractors' generic space descriptions and are based on the attributes and ontology developed.

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

7. VALIDATION OF THE ONTOLOGY DEVELOPED

We validated the ontology developed through three retrospective cases observed at three different job sites: (1) Haas School of Business (O'Brien 1998), (2) Portside Housing (Akinci and Fischer 1998), and (3) SFO (San Francisco International Airport) Boarding Area A (Akinci and Fischer 2000a). 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. In the retrospective cases, we modeled the spaces used by the activities we observed at the site in the computer by filling out the space templates, and we compared the corresponding project-specific spaces generated by 4D SpaceGen with the spaces occupied at the site. We were able to model all the required spaces using the ontology presented in this paper.

For the prospective test case, the graduate student and visiting fellow interviewed the superintendents in charge of a group of activities (installation of wall panels and window glazing) prior to construction. They modeled the spaces in the computer by filling out the space templates according to the information provided by the superintendents. They were able to represent all the spaces required by the installation of wall panels and window glazing activities with the ontology.

All of our test cases have focused on activities associated with exterior enclosure work. In total, we modeled the spaces required by twenty construction methods for installing twelve 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 of wall panels.

We validated the ontology developed only with respect to the installation of a certain group of components, such as exterior enclosure components. Because of the number of components and methods modeled and the 100% success rate in our retrospective and prospective tests of industrial construction cases, we argue for the power of our ontology and the space generation methods with respect to exterior enclosure work. Further, we claim that we demonstrated the generality of the ontology by being able to model different construction methods for installing different types of components. The retrospective and prospective cases provide evidence for this claim. 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 position specifications for those cases can be approximated to one of the orientation descriptions given in Figure 6. Additional case studies focusing on representing spaces associated with other types of works will further validate the power and generality of the 4D SpaceGen orientation vocabulary developed.

8. CONCLUSIONS

The types of micro-level spaces required by construction activities, their locations with respect to the components being installed, and their sizes change with the construction methods being used. This research formalized an ontology for representing activity space requirements generically within construction method models. Hence, it has integrated and extended previous research on construction space management and construction method modeling by developing a generic space representation formalism 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 space type are modeled. 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 micro-level work spaces.

The ontology provides a computer-interpretable way of capturing and representing generic activity space requirements. It constitutes an essential step towards 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 et al. (2000a) and Akinci et al. (2000b) describe these other steps.

9. ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the Center for Integrated Facility Engineering at Stanford University and of the National Science Foundation for this work. We also thank Pacific Contracting in San Francisco for providing access to their job sites, and Seungkoon Lyu and Masaaki Date for performing the prospective case study.

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