Automated Generation of Work Spaces Required by Construction Activities

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Abstract: To provide a safe and productive environment, project managers need to plan for the work spaces required by construction activities. Work space planning involves representing various types of spaces required by construction activities in three dimensions and across time. Since a construction schedule consists of hundreds of activities requiring multiple types of spaces, it is practically impossible to expect project managers to specify manually the spatiotemporal data necessary to represent work spaces in four dimensions. This paper presents mechanisms that automatically generate project-specific work spaces from a generic work space ontology and a project-specific IFC (industry foundation class) based 4D production model. The generation of these work spaces leads to a space-loaded production model. Within this model, work spaces are represented as being related to the relevant construction activities and methods and as having attributes that describe when, where, and how long they exist, and how much volume they occupy. These space-loaded production models enable richer 4D CAD simulations, time-space conflict analysis, and proactive work space planning prior to construction.

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Introduction

Space is one of the key resources at construction sites. Many construction process models, such as Sanvido's model (Sanvido 1984), Howell's model (Oglesby et al. 1989), the work process model (Hetrick and Khayyal 1987), and the factor model (Thomas and Sakarcan 1994), list work spaces as key resources required by construction activities. These models suggest that activity space requirements, like any other resource requirement of activities, be managed during planning and scheduling.

The lack of management of activity space requirements during planning and scheduling results in time-space conflicts in which an activity's space requirements interfere with another activity's space requirements or work-in-place. Currently, time-space conflicts occur frequently at construction sites (Riley and Sanvido 1997) and significantly hinder the performance of interfering activities [e.g., Rad (1980), Oglesby et al. (1989), Sanders et al. (1989), Howell and Ballard (1997), Akinci (2000)].

Compared to other resource requirements, management of work spaces of construction activities poses unique challenges. The requirements for most resources, such as laborers, equipment, and material, change only through time. However, the spaces required by activities change in all three dimensions and over time. In addition, there are multiple types of spaces required by activities, which all have different positional requirements (Riley 1994; Akinci 2000).

Finally, construction superintendents, when asked, describe the spaces that they need generically using qualitative positional descriptions (e.g., "outside the component," "below the labor crew space," and so on). These generic space descriptions need to be interpreted according to project-specific data to represent the project-specific work spaces in the *x*, *y*, *z*, and time dimensions. As a result, it is too tedious for project engineers to manually represent the project-specific activity space requirements represented in 4D models. There is a need for automated mechanisms to generate project-specific spaces required by activities and to represent those spaces in four dimensions.

This paper focuses on this need and describes methods to automate the generation of work space requirements of construction activities. It specifically describes methods to generate micro-level activity space requirements (for example, labor crew space, equipment space, hazard space), which represent the core spaces enabling the execution of the related construction activities. In the rest of the paper, the terms "micro-level spaces" and "work spaces" will be used interchangeably.

During the research discussed in this paper, we developed a prototype system, 4D WorkPlanner Space Generator (4D SpaceGen), which automates the generation of work space requirements of activities based on user-defined generic space requirement knowledge and project-specific production model (integrated product and process model) information. This paper describes the system architecture of 4D SpaceGen and the mechanisms implemented for automated generation of work spaces.

Motivating Case

This section uses a case that occurred during the construction of the Haas School of Business in Berkeley to demonstrate the use-

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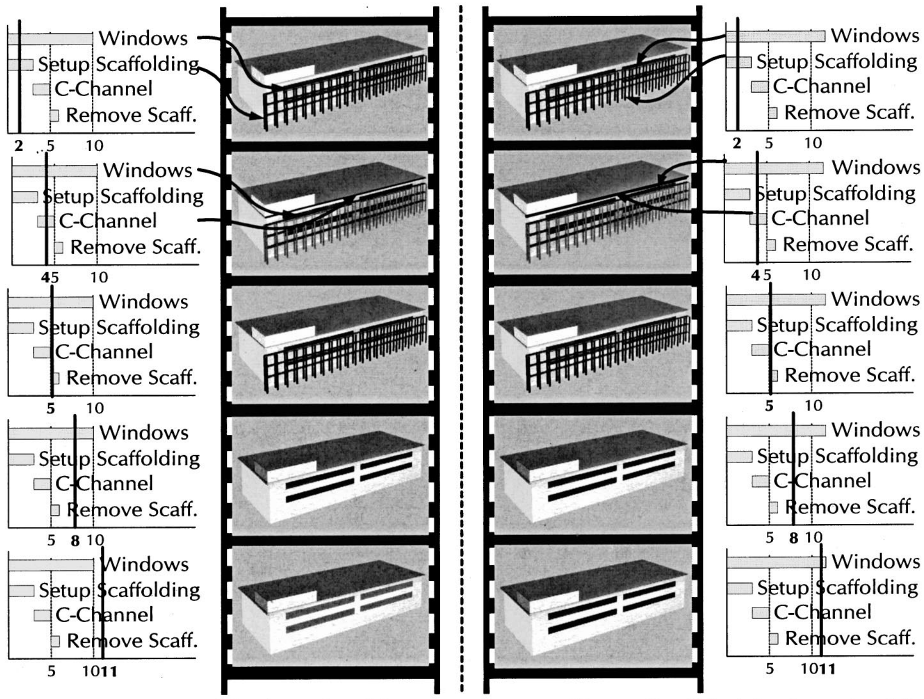

Figure 1a. Schedule alternative # 1 **Figure 1b**. Schedule alternative # 2

Legend: Ongoing Activity

Fig. 1. Gantt charts and 4D CAD simulations of two different schedules

fulness of generating and representing different types of micro-level spaces required by construction activities and to show the limitations of current project management tools in enabling the management of work spaces. Figs. 1(a and b) show snapshots from 4D CAD simulations of two different schedules consisting of four activities on one side of a building: scaffolding setup and removal, window installation, and c-channel installation.

The Gantt charts and the 4D CAD simulations of these two schedules look essentially the same. Therefore, by looking at the Gantt charts and the 4D CAD simulations, one might assume that both schedules would be executed in a similar manner on site. However, there is a difference between the two schedules: different construction methods are used for installing the windows. The construction method for installing the windows used in Fig. 1(a) requires the labor crew to place the windows from the outside of the building using a scissor lift. In contrast, the construction method for installing the windows used in Fig. 1(b) requires the labor crew to place the windows from the inside. Fig. 2 shows the space requirements of these two window installation methods.

The visual comparisons of the two Gantt chart schedules and the corresponding 4D CAD simulations do not enable the identification of this difference in space utilization between the two construction methods. However, identification of this difference is crucial, since there is a spatial conflict in the schedule shown in

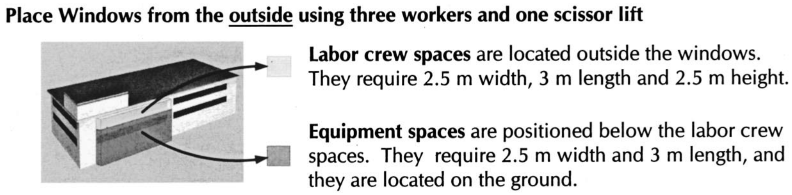

Figure 2a. Work space requirements for placement of windows from the outside using three workers and one scissor lift.

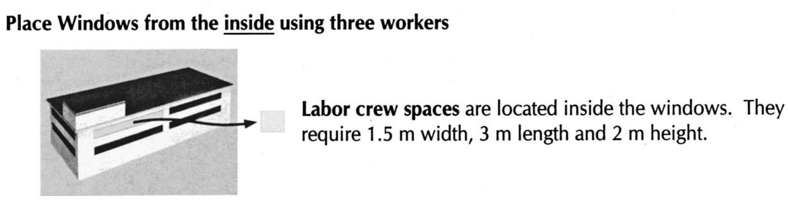

Figure 2b. Work space requirements for placement of windows from the inside using three workers.

Fig. 2. Generic spatial descriptions of two construction methods of placing windows

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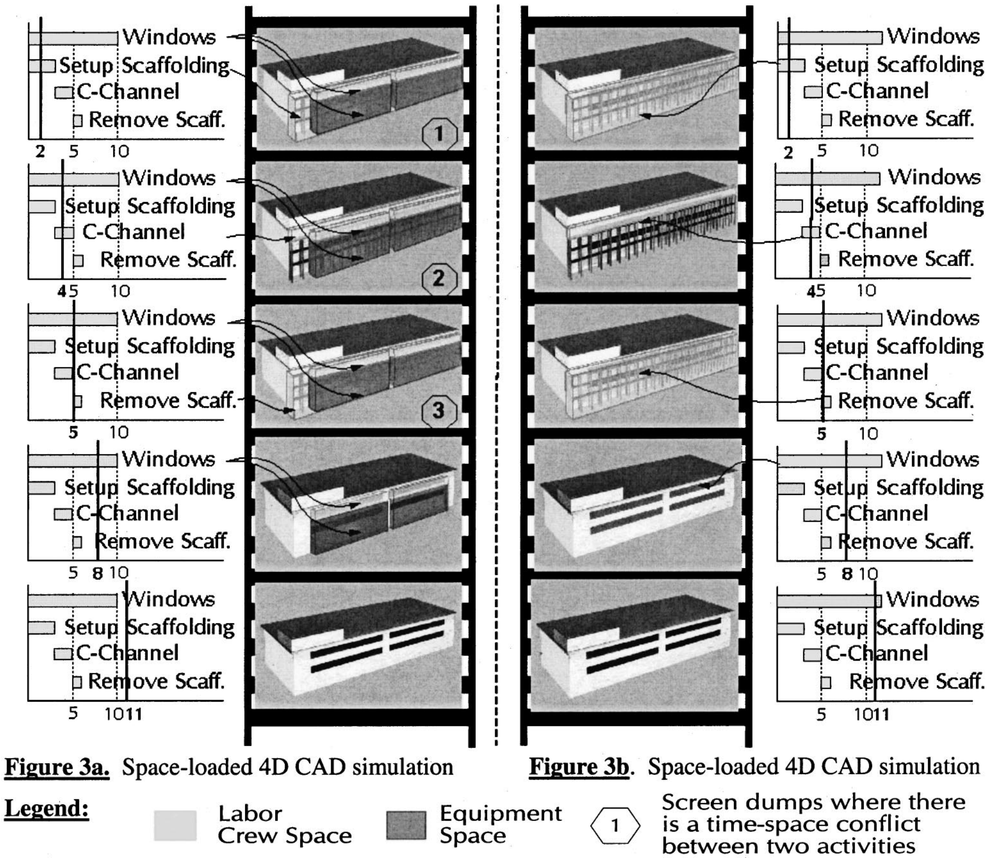

Fig. 3. Space-loaded 4D CAD simulations highlight differences between two schedules

Fig. 1(a) between the scaffolding required by the c-channel installation and the labor crew and equipment spaces required by the window installation. In contrast, there is no such conflict in the schedule shown in Fig. 1(b). As a result, the schedule in Fig. 1(a) cannot be implemented as planned, but the schedule in Fig. 1(b) can be implemented without any spatial conflicts between activities.

4D CAD simulations can be made more informative by adding the spaces required by construction activities. Figs. 3(a and b) show the space-loaded 4D CAD simulations of the two schedules given in Figs. 1(a and b) correspondingly. Space-loaded 4D CAD simulations show the spaces required by activities in addition to the building components being installed. The difference between the two schedules and their corresponding spatial conflict problems becomes more apparent in space-loaded 4D CAD simulations (Fig. 3) than in basic 4D CAD simulations (Fig. 1). Through visual analysis of space-loaded 4D CAD simulations, the user can identify the three conflicts existing in the first schedule.

One of the goals of the research project described in this paper was to automate the generation of work spaces being represented in four dimensions and hence to automate the creation of space-loaded 4D models.

Related Research

Researchers have tried many different approaches to automate the consideration of activity space requirements during planning and scheduling. Our research builds on and extends mainly the static and dynamic layout planning and space-scheduling approaches described herein.

1. Static or dynamic site layout planning (Eastman 1975; Tommelein et al. 1991, Tommelein and Zouein 1993; Choi and Flemming 1996; Alshawi 1997; Hegazy and Elbeltagi 1999): The site layout planning algorithms automate the allocation of macrolevel spaces, which are the coarse spaces located at the site, according to user-defined qualitative and quantitative adjacency constraints (for example, close, far, and so on) between spaces. Hence, mechanisms for site layout planning reason mainly about the adjacencies between spaces to generate project-specific instances of where the spaces should be located at the site.

   Our approach is similar to site layout planning since both generate project-specific spaces from generic user-defined constraints. However, the mechanisms that we implemented reason mainly about the orientation of the spaces and assume a specific adjacency condition. The main reason for this assumption is that microlevel spaces, by definition, are located within proximity of the component being installed. For example, in the case described above, the labor crew space is defined as being located outside of the windows with no explicit adjacency description (e.g., labor crew space is close to windows). This space requirement description when applied to the microlevel space representation context assumes that the labor crew space is connected to the outside of the windows [Fig. 2(a)].

   Hence, in generating microlevel spaces, the reasoning about orientations of spaces is more important than the reasoning about the adjacencies between spaces since in all of the cases it is implicitly assumed that all microlevel spaces are connected to the relevant sides of their reference objects.

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Since the mechanisms implemented in site layout planning reason mostly about adjacencies, they do not completely apply to the generation of microlevel spaces. Our approach complements the site layout planning approach by formalizing mechanisms to reason about the qualitative orientation descriptions of work spaces.

2. Space scheduling (Tommelein et al. 1992; Zouein and Tommelein 1993; Riley 1994; Thabet and Beliveau 1994; Choo et al. 1999). The space-scheduling approach focuses on modeling the different types of work spaces required by construction activities. Hence, the types of spaces modeled in space scheduling are similar to our work. However, space scheduling assumes that the user specifies the geometric attributes of the project-specific activity space requirements. The algorithms developed in space scheduling mainly focus on creating a schedule to eliminate spatial conflicts once the user defines all of the microlevel spaces.

   If this approach were applied to the case described in Fig. 1(a), the user would have to define an (x, y, z) insertion point and the corresponding dimensions on the x, y, z coordinates of a total of 11 different spaces required by the activities (Fig. 3). Given that hundreds of activities require multiple types of spaces in a given schedule, it would be practically prohibitive to expect the user to describe and enter each of these activity space requirements manually (Akinci 2000). Even though a decentralized approach to construction management can decrease the number of data to be entered by the user, the data requirements from the users are still large enough to make it prohibitively time-consuming for them to enter the spatial information manually. For example, a window subcontractor who is going to install the windows using a swing stage has to model three types of spaces (labor crew space, equipment space, hazard space) in x, y, z, and time (t) dimensions for each window in the design model. Typically, midsize building has hundreds of windows. This suggests that for a midsize building project a window subcontractor would need to enter in the order of 300 space instances and similarly specify around 2,400 data points to represent each space in x, y, z, and t. Consequently, even in decentralized systems it is prohibitively time-consuming to enter and update each of the points manually.

Our approach captures the spatial knowledge generically in relation to the construction methods being used and, based on product models of buildings, automates the generation of project-specific spaces with respect to the volume of the reference objects that are represented in the CAD model. Consequently, it relieves the user of entering enormous amounts of data to represent project-specific activity space requirements. In addition, users can alter the construction methods and activity sequences quickly and still consider the work space needs for each activity explicitly in the model.

In short, the construction space management literature describes useful background but does not describe detailed methods to automate the generation of microlevel activity space requirements. Our research complements the research done within this area by formalizing the mechanisms necessary to generate project-specific microlevel construction spaces from generic qualitative descriptions of space needs and a project-specific production model.

4D WorkPlanner Space Generator—System Architecture

4D WorkPlanner Space Generator (4D SpaceGen) automates the generation and visual display of project-specific activity space requirements. Fig. 4 shows the IDEF diagram (SoftTech 1981) of the system and highlights the specific inputs and outputs of the system using the "placement of windows from a scissor lift" construction method [Fig. 2(a)] as an example.

4D SpaceGen takes an IFC-based (IAI 1998) 4D production model—an integrated product and process model—as input (Fig. 4). This 4D production model is generated by another system, Construction Method Modeler (Aalami 1998), in which the user defines the construction methods that will be used in installing certain groups of components, and the system automatically generates the activities necessary to install the building components and links these activities to the building components. Hence, the 4D production model relates the construction activities to the building components, the required resources, and the selected construction methods. There are other commercially available methods of relating construction activities to building components. Off-the-shelf 4D CAD systems such as Bentley Schedule Simulator (Bentley 2001) provide an integration environment where the user manually links the construction activities to the relevant building components. Hence, the output of these 4D CAD systems can also provide an integrated product and process model to be used as input by the 4D WorkPlanner Space Generator.

4D SpaceGen assumes that the level of detail in the production model is at the level of a 3-week look-ahead schedule, in which the activities are decomposed according to their action types and are related to batches of components. Batches, in this context, represent the appropriate level of detail determined by the user according to the construction methods and installation patterns utilized at the site. We chose to represent this level of detail since the production model at this level starts to have meaningful representations about *how* the activities are going to be executed (Halpin and Riggs 1992; Ballard 1997). Moreover, the production model representation at this level is less detailed and hence more manageable than the one represented at the fundamental field action level (Halpin and Riggs 1992).

4D SpaceGen starts by asking the user to fill out the space templates related to each construction method that will be used. Superintendents or project engineers are the users of the system since they know the different types of construction methods used during the construction of a specific set of components. There are four space templates, associated with the labor crew space, equipment space, hazard space, and protected space requirements. Each space template asks the user to describe the orientation of a specific space type with respect to its reference object. The user also defines the size of the space required within each template. Akinci (2000) describes the space templates developed to capture the activity space requirement information generically in relation to the construction method being applied. The control box in Fig. 4 shows the information that the user defines in space templates.

4D SpaceGen interprets the user-defined generic space descriptions using project-specific 4D production model information and generates project-specific activity space requirements represented in four dimensions. The output box in Fig. 4 shows the project-specific representation of the activity space requirements. 4D SpaceGen outputs a space-loaded production model in which project-specific activity space requirement information is integrated with the initial 4D production model representation, similar to any other resource requirement of activities (Fig. 4).

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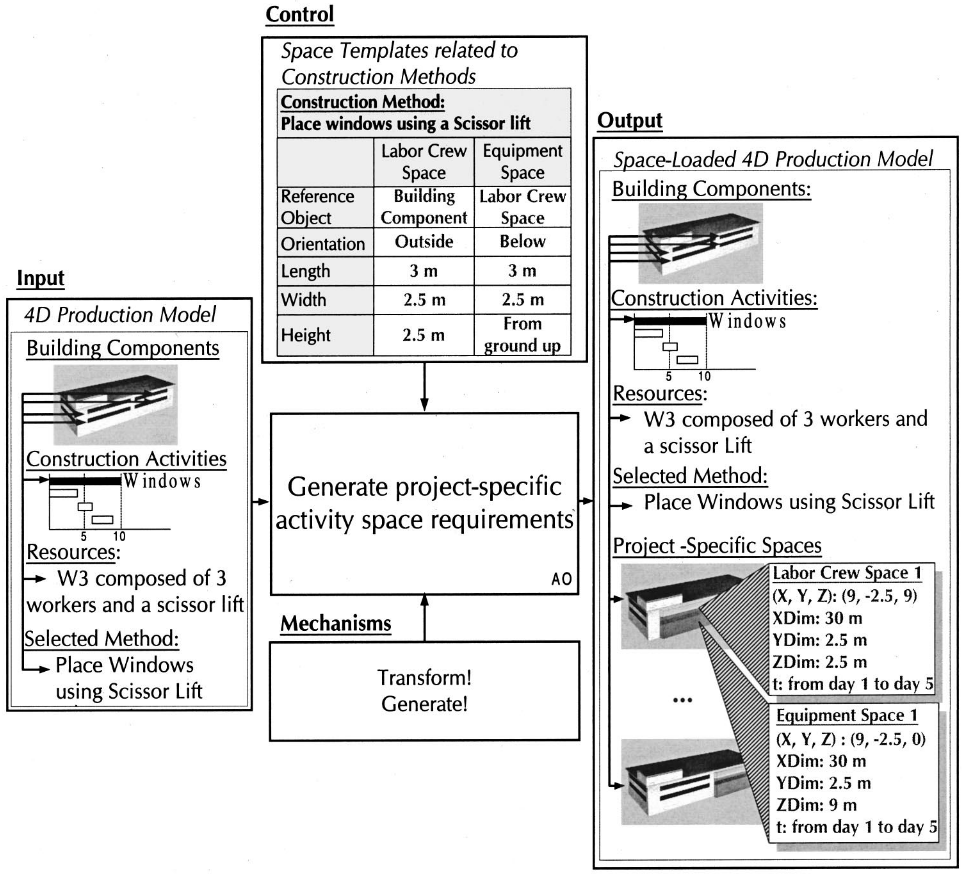

Fig. 4. IDEF of 4D WorkPlanner Space Generator

Mechanisms for Automated Generation of Project-Specific Space Requirements

The generic space representation includes a qualitative description of the position of a space and a quantitative description of the size of a space (as shown in the control box of Fig. 4). On the other hand, the project-specific space representation includes quantitative descriptions of the length in the x, y, and z dimensions and the times that each space will be required (as shown in the output box of Fig. 4). The automated generation of the activity space requirements involves interpretation of the generic space descriptions and generation of the corresponding project-specific spaces represented in four dimensions.

Transformation Matrix

The core concept in the mechanisms formalized and implemented for automated generation of activity space requirements is the transformation matrix. The transformation matrix provides a way to represent the positional relationship between two graphical objects quantitatively. Research presented in the Computer Science literature uses the transformation matrix to generate the specific locations of objects from qualitative positional descriptions (Claus et al. 1998). Our use of the transformation matrix is similar. We use the transformation matrix to represent the qualitative orientation descriptions used by superintendents to describe the positional relationships between work spaces and their reference objects quantitatively.

Fig. 5 gives an example of the two ways of representing the positional relationship between the window labor crew space and

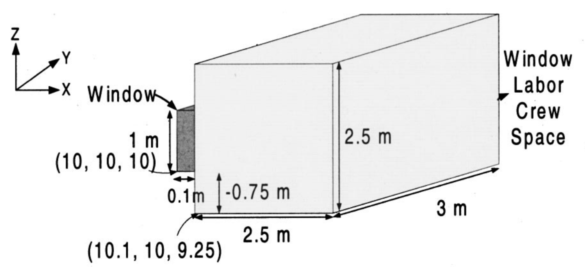

Figure 5a. The graphical representation of the positional relationship

Labor crew spaces for placing windows are located outside of the window components, and they require 3 m length, 2.5 m width, and 2.5 m height

Figure 5b. The qualitative representation of the positional relationship

$$T = \begin{bmatrix} 1 & 0 & 0 & 0.1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -0.75 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 5c. The quantitative representation of the positional relationship

Fig. 5. Qualitative and quantitative representation of positional relationship between window and window labor crew space

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the window component, shown graphically in Fig. 5(a). Fig. 5(b) describes the generic qualitative space representation, and Fig. 5(c) shows the project-specific representation of the position of the labor crew space with respect to the window component using the transformation matrix.

Representation of the positional relationship between a space and its reference object using the transformation matrix enables the generation of the space represented in three dimensions by using the (X, Y, Z) coordinates of the reference object. Eq. (1) (Claus et al. 1998) shows that the coordinates of a space can be calculated by multiplying the transformation matrix with a vector of coordinates of its reference object.

Within this equation the rotation matrix (R) is represented as an identity matrix since, in this research, all of the construction spaces are modeled in parallel to the components being installed.

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \\ 1 \end{bmatrix} = \begin{bmatrix} & & & \Delta_x^{(O,S)} \\ & R & & \Delta_y^{(O,S)} \\ & & & \Delta_z^{(O,S)} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_O \\ Y_O \\ Z_O \\ 1 \end{bmatrix}; \quad R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where (X_S, Y_S, Z_S) = insertion point of construction space to be generated; (X_O, Y_O, Z_O) = insertion point of reference object; $\Delta_x^{(O,S)}$ = distance between insertion point of reference object and insertion point of construction space along X dimension; $\Delta_y^{(O,S)}$ = distance between insertion point of reference object and insertion point of construction space along Y dimension; $\Delta_z^{(O,S)}$ = distance between insertion point of reference object and insertion point of construction space along the Z dimension; and R = rotation matrix representing rotation of space with respect to the reference object.

By using Eq. (1), the system determines the absolute locations of the spaces required. For example, the system automatically determines the location of the labor crew space shown in Fig. 5(a) using Eq. (1), the transformation matrix shown in Fig. 5(c), and the location of the window component shown in Fig. 5(a).

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0.1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -0.75 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 10 \\ 10 \\ 10 \\ 1 \end{bmatrix} = \begin{bmatrix} 10.1 \\ 10 \\ 9.25 \\ 1 \end{bmatrix} \tag{2}$$

The next section describes the steps involved in interpreting the generic work space descriptions to generate the transformation matrices and to generate project-specific work spaces. It also describes how the temporal and functional contents are added to the project-specific representation of activity space requirement by using the relationships explicitly represented in 4D production models.

Steps for Generating Project-Specific Spaces

When the user defines a type of space required by a construction method generically, including its orientation with respect to a reference object and its size requirements, 4D SpaceGen first automatically identifies the set of activities to which the construction method applies. Once the related activities are identified, the transformation mechanisms start generating project-specific spaces required for each of the related construction activities by following four steps:

Table 1. Relationship between Qualitative Orientation Descriptions and Features of Reference Objects

Qualitative orientation description	Corresponding product feature
Above	Top side
Below	Bottom side
Outside	Exterior space boundary
Inside	Interior space boundary
Around connected side	Connection surface

Step 1: Determine Number of Instances of Project-Specific Construction Spaces

In determining the number of project-specific spaces needed, 4D SpaceGen uses the 4D production model entered into the system (Fig. 4) and first identifies the number of instances of the project-specific reference objects to which a construction activity relates. It then creates a project-specific space for each reference object.

For example, in the case described above, the labor crew space for window installation is located at the outside of the windows. Hence, the reference objects for the window labor crew spaces are the window components on Side A of the building. Therefore, in this case, in determining the number of project-specific window labor crew spaces needed, 4D SpaceGen identifies the number of project-specific instances of windows that the window installation activity processes. Since the window installation activity acts on four windows on Side A of the building, 4D SpaceGen makes four instances of the project-specific labor crew spaces required to install the four corresponding window components on Side A.

Step 2: Identify Relevant Features of Reference Object According to Orientation Description

Once the project-specific instances of the reference object are identified, the next step is to interpret the qualitative orientation descriptions of the spaces, such as "above" and "outside." In this research, we identified and modeled six orientation descriptions for micro-level spaces: outside, inside, above, below, around, and around the connected side (Akinci 2000).

Interpreting these qualitative orientation descriptions involves identifying the relevant face or feature of the reference object to which the space generated will be connected. We have developed an orientation-feature match table (Table 1) so that the space generation mechanisms can identify the relevant faces of the reference objects.

IFCs (IAI 1998) explicitly represent the last three features shown in Table 1. For example, the `IfcRelSeparatesSpaces` relationship models the relationship between components and their exterior and interior space boundaries. Similarly, the `IfcRelConnectsElements` relationship models the connection relationship between two building components, and it stores the geometric information about the connection sides of both components. IFCs do not have an explicit representation of the top or the bottom sides of a component. We implemented a simple reasoning algorithm along the z-dimension to extract these two features automatically from the 3D CAD building model.

Step 3: Generate Transformation Matrices and Corresponding 3D Project-Specific Activity Space Requirements

Once the relevant features of the reference objects are identified, the next steps are to generate the transformation matrices and the corresponding project-specific spaces using the transformation

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matrices. In generating the transformation matrix, the mechanisms implemented consider the size requirements of the space as defined by the user.

Some spaces, such as labor crew spaces, have fixed sizes, and others, such as equipment spaces, have variable sizes. For example, in Figs. 2(a and b), the labor crew spaces are defined as having a fixed length, width, and height versus the equipment space in Fig. 2(a), which is defined as having a fixed length and width but a variable height. Akinci (2000) describes the different size requirements of spaces modeled. We implemented two separate mechanisms in 4D SpaceGen to be able to automate the generation of spaces with fixed requirements and spaces with variable size requirements.

The size requirements of spaces are represented as rectangular prisms. Therefore, the mechanisms implemented for the generation of spaces reason only about rectangular prism shapes. Our test cases have shown that this shape condition is not a limiting factor for the types of spaces that we modeled.

The mechanisms implemented are

1. Mechanisms for generating spaces with fixed size requirements: These mechanisms compare the size requirement of the space to the size of the reference object. If any dimension of the space the user requires defined is greater than the corresponding dimension of the reference object, the mechanisms create offsets from the two sides of the reference object along that dimension by dividing the excess length into two equal parts. If any dimension of the space is less than the corresponding dimension of the reference object, the dimension of the reference object governs.
2. Mechanisms for generating spaces with variable size requirements: These spaces vary in size because their height changes depending on the location of the space. For example, the height of the scissor lift supporting the window labor crew [Fig. 2(a)] and consequently the space it occupies change with the location of the windows and the labor crew. In these cases, 4D SpaceGen checks the elevation of the location of the space (for example, ground, roof, floor) as described by the user and the elevation of the location of the corresponding project-specific instance of its reference object. The difference in these two elevations determines the height of the space.

Once the transformation matrices for all the spaces are created, the project-specific spaces are automatically generated and represented in three dimensions using Eq. (1) described earlier.

Step 4: Add Temporal and Functional Content Information to Spaces Generated

The first three steps generate the project-specific spaces occupied by an activity represented in three dimensions. The project-specific spaces, however, also need to be represented in time. Therefore, this final step adds the temporal information to the 3D representation. 4D SpaceGen uses the relationships between activities and the occupied project-specific spaces to extract the scheduled times of the activities and to add that temporal information to the project-specific activity space representation.

In addition to adding temporal information, 4D SpaceGen also adds the functional information for the spaces generated. Since the functions of the labor crew space and the equipment space are to provide spaces for the labor crew and the equipment to be productive, the functional contents of these two spaces are the labor crew and the equipment required by the related activity. In adding the functional content to the space representations, 4D SpaceGen creates relationships between the project-specific labor crew space and the labor crew and between the equipment space and the equipment.

As a result of these four steps, the project-specific activity space requirements are generated and represented in four dimensions, and a space-loaded production model is created.

Definition and Representation of Space-Loaded Production Models

The output of 4D SpaceGen is a space-loaded production model where work space requirements of activities are explicitly represented in an integrated model. Within this integrated model, construction activities are related to the *types* of spaces, and by tracing that relationship we can access *where* the spaces are located and *how large* these spaces are. Similarly, work spaces are linked to the *related construction activities* and by following that link, we can determine the times and the durations for which each space will be required. Fig. 6 shows the main classes of the space-loaded production model representation.

There are two space representations within space-loaded production models: (1) a generic space representation related to construction method models, and (2) a project-specific space representation related to construction activities. Since 3D CAD models are increasingly available in IFC-format, we explored IFC space representations to determine whether they can represent work spaces.

IFCs (IAI 1998) define two classes for the representation of spaces within the architectural/engineering/construction and facility management industries:

1. `IfcSpace` is defined as "areas or volumes that provide certain functions within a building" (IAI 1998). IFCs represent `IfcSpace` as a volume enclosed by certain building components. This is an architectural view of spaces that is similar to space representations implemented in other building models (Ekholm and Fridqvist 1997). We cannot use this space formalism for representing project-specific work spaces since work spaces are not bounded simply by physical building components. Moreover, construction spaces change over time, and `IfcSpace` lacks temporal content.
2. `IfcConstructionZoneAggregationProduct` is defined as an area on a product (that is, `IfcProduct`) (IAI 1998). Thus, it represents a part of the product on which a work task or group of work tasks takes place or a cost estimate is calculated. We cannot use `IfcConstructionZoneAggregationProduct` for representing micro-level activity space requirements because of the semantic differences. `IfcConstructionZoneAggregationProduct` is defined either as part of a product or as the aggregation of a set of products, whereas the micro-level activity space requirements are not part of a product.

Since neither of the space representations within an IFC appropriately represents micro-level activity space requirements, we created two new classes of space objects and corresponding relationships to represent the generic and project-specific space requirements. Fig. 6 shows these two new classes, *Required Space* and *Occupied Space*. Their attributes have been described previously.

Possible Uses of Space-Loaded 4D Production Models

A consistent formalism, such as the one shown in Fig. 6, allows the sharing of the project-specific space representation generated

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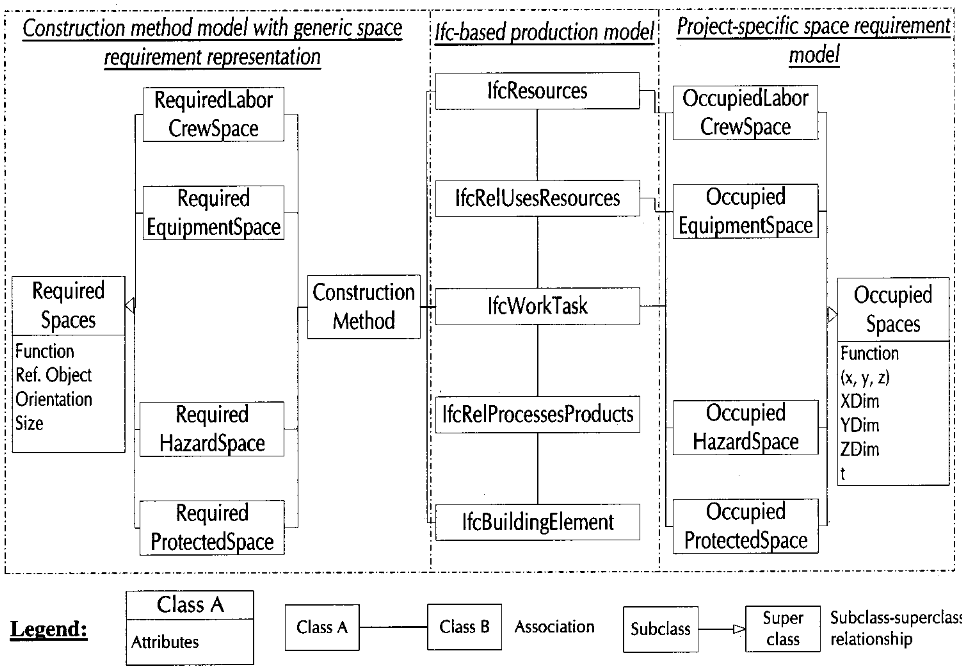

Fig. 6. Space-loaded production model representation

by 4D SpaceGen with other programs, for example, a time-space conflict analysis program that detects and analyzes conflicts, or a 4D CAD simulation program that displays the conflicts detected, or a scheduling program that modifies the schedule generated by considering the spatial requirements of activities. Hence, the space-loaded 4D production models can be used to:

Make 4D Simulations More Realistic

Currently, 4D models visually simulate the construction of a building over time by highlighting building components according to their scheduled installation time (Fig. 1). 4D simulation by itself has proven to be a much better environment for construction planning than Gantt charts or CPM schedules (Collier and Fischer 1995; Songer et al. 1998; Staub et al. 1999; Koo and Fischer 2000). However, 4D models based on 3D models from designers do not represent activity space requirements (Fig. 6). Space-loaded production models augment basic 4D models by representing 4D activity space requirements. As a result, the simulations display not only the building components but also the spaces required for the installation of those components (Fig. 3). We implemented a space-loaded 4D CAD simulation in VRML. Fig. 3 shows snapshots of an example of this visual simulation of work spaces required by construction activities.

Automate Spatial Conflict Analysis

Space-loaded production models contain the information necessary to automate spatial conflict detection and analysis. We implemented another prototype system linked to 4D SpaceGen to detect spatial conflicts between activities and classify the spatial conflicts. Akinci (2000) discusses how space-loaded production models are used to automate time-space conflict analysis.

Automate Modification of Schedules to Minimize Spatial Conflicts

Space-loaded production models can also be used for automated modification of a schedule to minimize the spatial conflicts between activities. Research efforts in the space-scheduling area have developed and implemented some scheduling strategies for this purpose. Examples of such space scheduling systems developed are MoveSchedule (Zouein and Tommelein 1993) and SCaRC (Thabet and Beliveau 1994). Space-loaded production models created by 4D SpaceGen could be used as input by these systems.

Validation

The transformation mechanisms formalized and implemented in this research are general enough to interpret different orientation descriptions and to generate spaces with different volumetric behaviors (described above). We have validated the mechanisms implemented retrospectively at three job sites and prospectively at one job site. 4D WorkPlanner Space Generator was able to generate the project-specific spaces of a total of 20 construction methods applied to 12 different types of building components. Most of the construction methods and the building components modeled were related to the exterior (skin) work associated with commercial building structures. Examples of the construction methods include installation of windows from outside using scissor lift, installation of windows from outside using scaffolding, installation of windows from outside using swing stage, installation of windows from inside, installation of roof membrane, installation of roof tiles, installation of wall panels from outside using rolling scaffolding, and so on. Similarly, examples of the building components modeled include windows, wall panels, roof membrane, roof tile, c-channel, HVAC ductwork, and so on.

The retrospective cases demonstrated the generality of the implemented mechanisms since those cases involved the generation of spaces for different types of construction methods applied to installing the same types components. For example, for retrospective cases, we modeled four different construction methods of installing windows and two different construction methods of installing wall panels. These cases showed that the mechanisms implemented are general enough to interpret the predefined set of

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orientation descriptions for the generation of four types of work spaces. Akinci (2000) provides screen dumps of the outputs obtained through the 4D SpaceGen system for these different construction methods applying to the same components.

In addition, a graduate student and a visiting fellow at the Center for Integrated Facility Engineering at Stanford University conducted a prospective case study within which they interviewed a group of superintendents working at a construction site about the different types of spaces their crews needed. According to these descriptions, they modeled the space requirements of 10 different construction activities acting on two components. They compared the output of the system with the actual observations they made on site and found that the spaces generated by the system were equivalent to the spaces occupied by the corresponding activities at the site. Akinci (2000) shows comparisons of the output of the system with a picture from the site showing the actual space usage for a specific activity. This result demonstrated the power of the mechanisms implemented in this research.

Conclusions

Project-specific activity space requirements can be generated automatically by interpreting generic space descriptions and by using 4D production model information. Construction superintendents describe the spaces required generically in relation to the construction methods they plan to use. The generic space descriptions represent the position of each space qualitatively as being oriented with respect to a reference object and represent the size of each space quantitatively. The goal of the space generation mechanisms presented in this paper is to interpret these generic space descriptions and to generate the project-specific spaces represented in four dimensions. The transformation matrix together with the project-specific 4D production model enables the interpretation of the generic space descriptions and allows the generation of project-specific spaces.

4D production models provide a simple yet powerful way of representing design and construction information. The computer-interpretable and explicit representation of construction information within these models allows the development of necessary reasoning mechanisms to automate a certain task, such as the generation and maintenance of project-specific work spaces, which would otherwise be too tedious to perform.

The space generation mechanisms implemented are general enough to interpret the predefined set of orientation and size requirements for the generation of four types of work spaces. The spaces generated through these mechanisms realistically represent the spaces occupied by the corresponding activities on construction sites.

The automated generation of activity space requirements significantly reduces the amount of data entered by the user and enables the user to visualize the space usage on site and to detect spatial conflicts between activities prior to construction. Consequently, it enables proactive space management at construction sites.

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