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AUTOMATED GENERATION OF WORK SPACES REQUIRED BY CONSTRUCTION ACTIVITIES

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

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 spatio-temporal data necessary to represent work spaces in four dimension. This paper presents mechanisms that automatically generate project-specific work spaces from a generic work space ontology and a project-specific IFC (Industry Foundation Classes) based 4D production model. The generation of these work spaces leads to a space-loaded production model. Work spaces know to which activities and construction methods they belong, when, where and for how long they exist and how much volume they occupy. A space-loaded production model enables richer 4D CAD simulations, time-space conflict analysis and proactive work space planning prior to construction.

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1. 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. Consequently, 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 requirement or work-in-place. Currently, time-space conflicts occur frequently at construction sites (Riley and Sanvido 1997), and they significantly hinder the performance of interfering activities (e.g., Rad 1980; Oglesby et al. 1989; Sanders et al. 1989; Howell and Ballard 1995; Akinci et al. 2000b).

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 along 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, and all of them have different positional requirements (Riley 1994; Akinci et al. 2000a). 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", etc.). 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 impossible for project engineers to manually represent the project-specific activity space requirements. There is a need for automated mechanisms to generate project-specific spaces required by activities and 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. Micro-level activity space requirements (e.g., labor crew space, equipment space, hazard space) represent the core spaces required by activities. These work spaces are located within the proximity of the components being installed, and they are associated with the direct installation activities. In the rest of the paper, the terms "micro-level spaces" and "work spaces" will be used interchangeably.

The prototype system developed, 4D WorkPlanner Space Generator (4D SpaceGen), takes a project-specific IFC (Industry Foundation Classes) based 4D production model, which is an integrated product and process model (Aalami et al. 1998), as input. It first asks the users to describe generically the different types of micro-level spaces they require for the construction methods they plan to use. Akinci et al. (2000a) describe a computer-interpretable way of representing work spaces generically within construction method models. This generic space representation models each type of space qualitatively as being oriented with respect to a reference object (such as a building component), and as requiring a size defined as a set of volumetric parameters (such as length, width and height).

4D SpaceGen uses this information together with the project-specific production model information to automatically generate the project-specific activity space requirements represented in four dimensions. The challenge in automating the generation of activity space requirements is to develop transformation mechanisms that are general enough (1) to interpret the different qualitative positional descriptions used in generic space representations (e.g., above, below, outside, etc.), and (2) to generate several types of spaces with varying volumetric requirements.

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 model, work spaces know *to which* activities they belong, *when* and *where* they exist and *how much* volume they occupy. This information is necessary to detect spatial conflicts between activities prior to construction and to manage spaces during planning. Based on this space-loaded production model, another system we developed automatically detects and analyzes spatial conflicts between activities in a given schedule (Akinci et al. 2000b).

This paper describes the system architecture of 4D SpaceGen, the mechanisms implemented in 4D SpaceGen to automate the generation of space-loaded production models, and the representation and possible uses of these models.

2. A MOTIVATING CASE

This section uses a case that occurred during the construction of the Haas School of Business in Berkeley to demonstrate the usefulness 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. Figures 1a and 1b 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 core difference between the two schedules: different construction methods are used for installing the windows. The construction method for installing the windows used in Figure 1a 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 Figure 1b requires the labor crew to place the windows from the inside. Figure 2 shows the different space requirements of these two window installation methods.

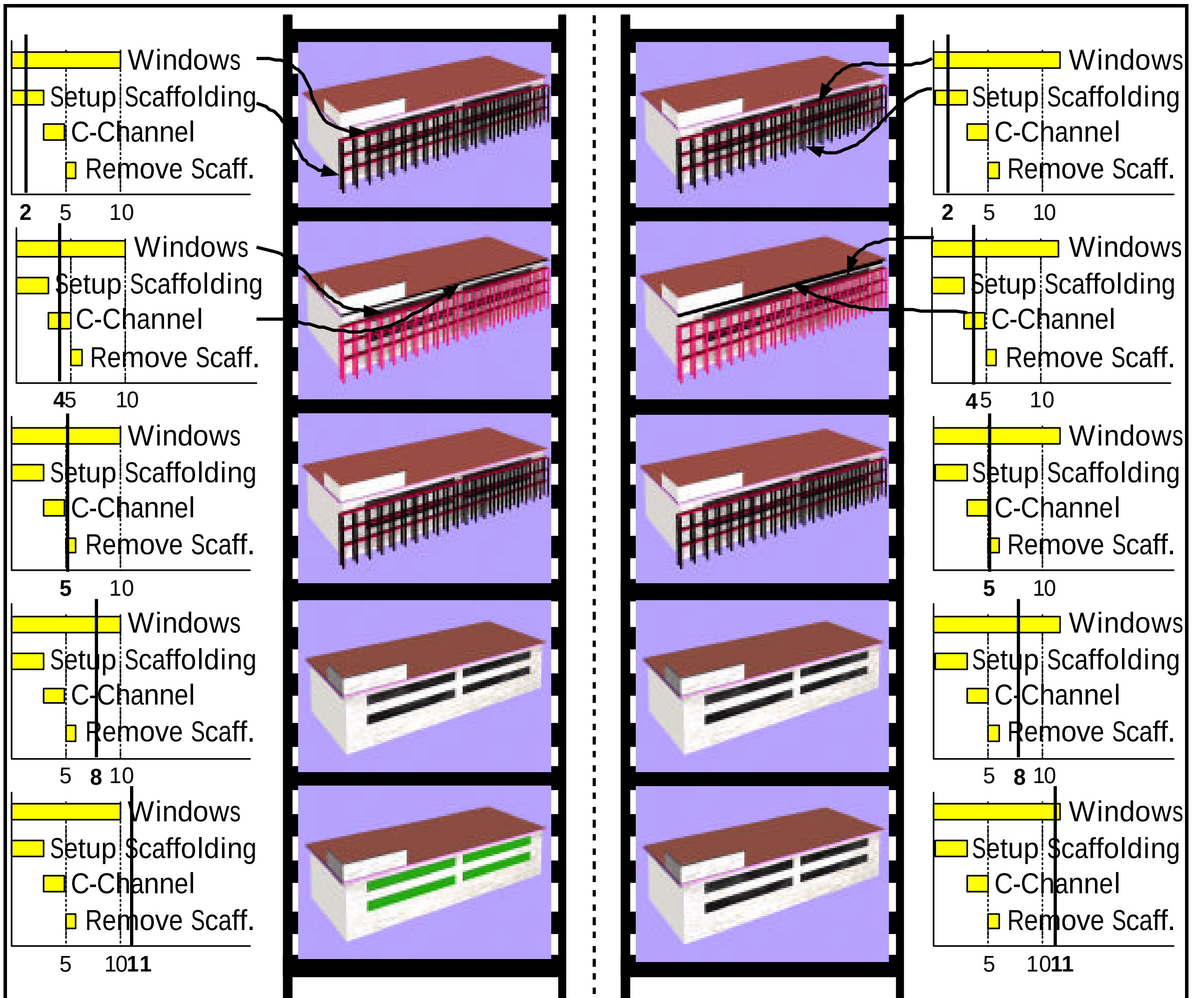
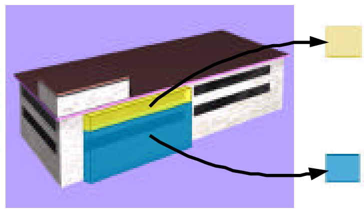


Figure 1a. Gantt chart and 4D CAD simulation of schedule alternative # 1	**Figure 1b**. Gantt chart and 4D CAD simulation of schedule alternative # 2

Legend: ■ Ongoing Activity

Figure 1. Gantt charts and 4D CAD simulations of two different schedules. This figure shows that current 4D visualization tools do not enable the identification of differences between schedules resulting from differences in construction methods.

Place Windows from the outside using three workers and one scissor lift

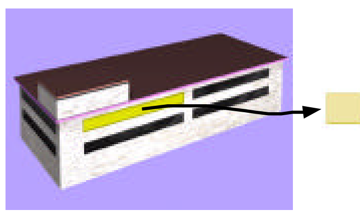


Labor crew spaces are located outside the windows. They require 2.5 m width, 3 m length and 2.5 m height.

Equipment spaces are positioned below the labor cew spaces. They require 2.5 m width and 3 m length, and they are located on the ground.

Figure 2a. The work (labor and equipment) space requirements for the placement of windows from the outside using three workers and one scissor lift.

Place Windows from the inside using three workers



Labor crew spaces are located inside the windows. They require 1.5 m width, 3 m length and 2 m height.

Figure 2b. The work (labor) space requirements for the placement of windows from the inside using three workers.

Figure 2. The generic spatial descriptions of the two construction methods of placing windows

The visual comparisons of the two Gantt chart schedules and the corresponding 4D CAD simulations do not enable the identification of this core difference in space utilization between the two construction methods. However, identification of this core difference is crucial, since there is a spatial conflict in the schedule shown in Figure 1a between the scaffolding required by the c-channel installation and the labor crew and the equipment spaces required by the window installation. In contrast, there is no such conflict in the schedule shown in Figure 1b.

Since it is difficult for contractors to relate the construction methods and their corresponding spatial requirements in actual practice, time-space conflicts often go undetected until construction starts (Rad 1980; Sanders et al. 1989; Riley 1994; Riley and Sanvido 1997; Akinci et al. 1998). In the Haas School of Business case (O'Brien 1998), the general contractor scheduled the activities as in Figure 1a. Since the time-space conflict went undetected until the start of construction, the contractor had to react to the time-space conflicts between the window installation and the scaffolding used for c-channel installation by delaying the window installation activity until the c-channel was installed and the scaffolding was removed.

Figures 3a and 3b show the space-loaded 4D CAD simulations of the two schedules given in Figures 1a and 1b 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 than in basic 4D CAD simulations

Through visual analysis of space-loaded 4D CAD simulations, the user can identify the three conflicts existing in the first schedule. These conflicts are: (1) the conflict between the labor crew space required for the scaffolding setup and the equipment and the labor crew spaces required for the window installation, (2) the conflict between the scaffolding space required for the c-channel installation and the labor and the equipment spaces required for the window installation, and (3) the conflict between the labor crew space required for the removal of the scaffolding and the equipment and the labor crew spaces required for the window installation.

The prototype system we developed, 4D SpaceGen, automatically generates and displays the spaces required by construction activities (Figure 3). The challenge in automating the generation of project-specific activity space requirements is to formalize mechanisms that relate the different orientation and volumetric requirement descriptions used in generic space representation to project-specific building design and schedule information. For example, in Figure 2, the labor crew space is described as located <u>outside the windows</u> requiring a <u>fixed volume</u>. On the other hand, the equipment space is described as located <u>below the labor crew space</u> and as having a <u>variable volume</u>. The reasoning mechanisms should be general enough to interpret both of these descriptions and generate project-specific spaces represented in four dimensions for different types of spaces.

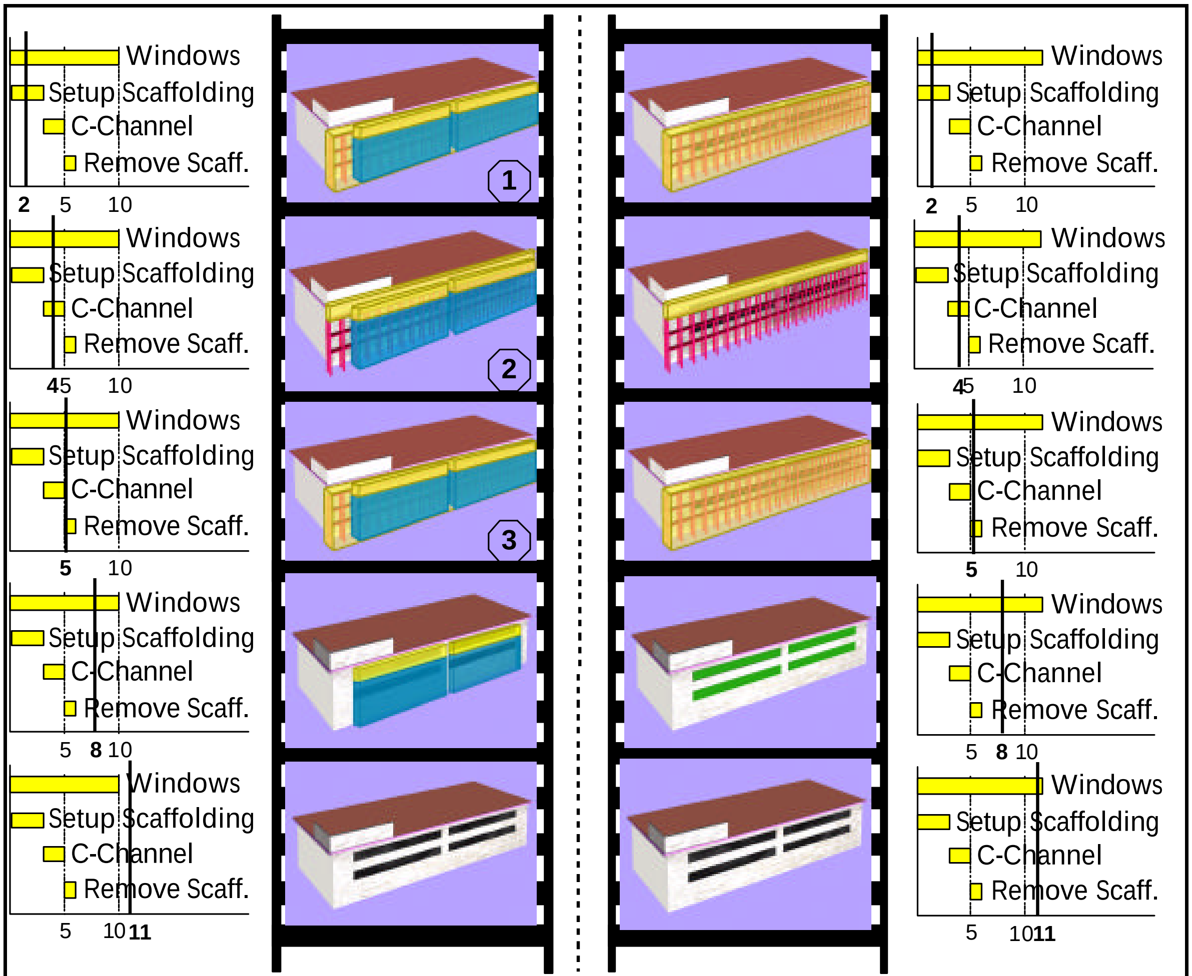


Figure 3a. Space-loaded 4D CAD simulation of schedule alternative # 1

Figure 3b. Space-loaded 4D CAD simulation of schedule alternative # 2

Legend: Labor Crew Space; Equipment Space; (1) Screen dumps where there is a time-space conflict between two activities

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

3. RELATED RESEARCH

Researchers have tried many different approaches to automate the consideration of activity space requirements during planning and scheduling. We grouped these approaches into four categories: (1) Static or dynamic layout planning, (2) Line of balance, (3) Path-planning, and (4) Space-scheduling. Akinci and Fischer (1998) describe each of these four approaches in detail. Figure 4 shows the inputs and outputs of these approaches.

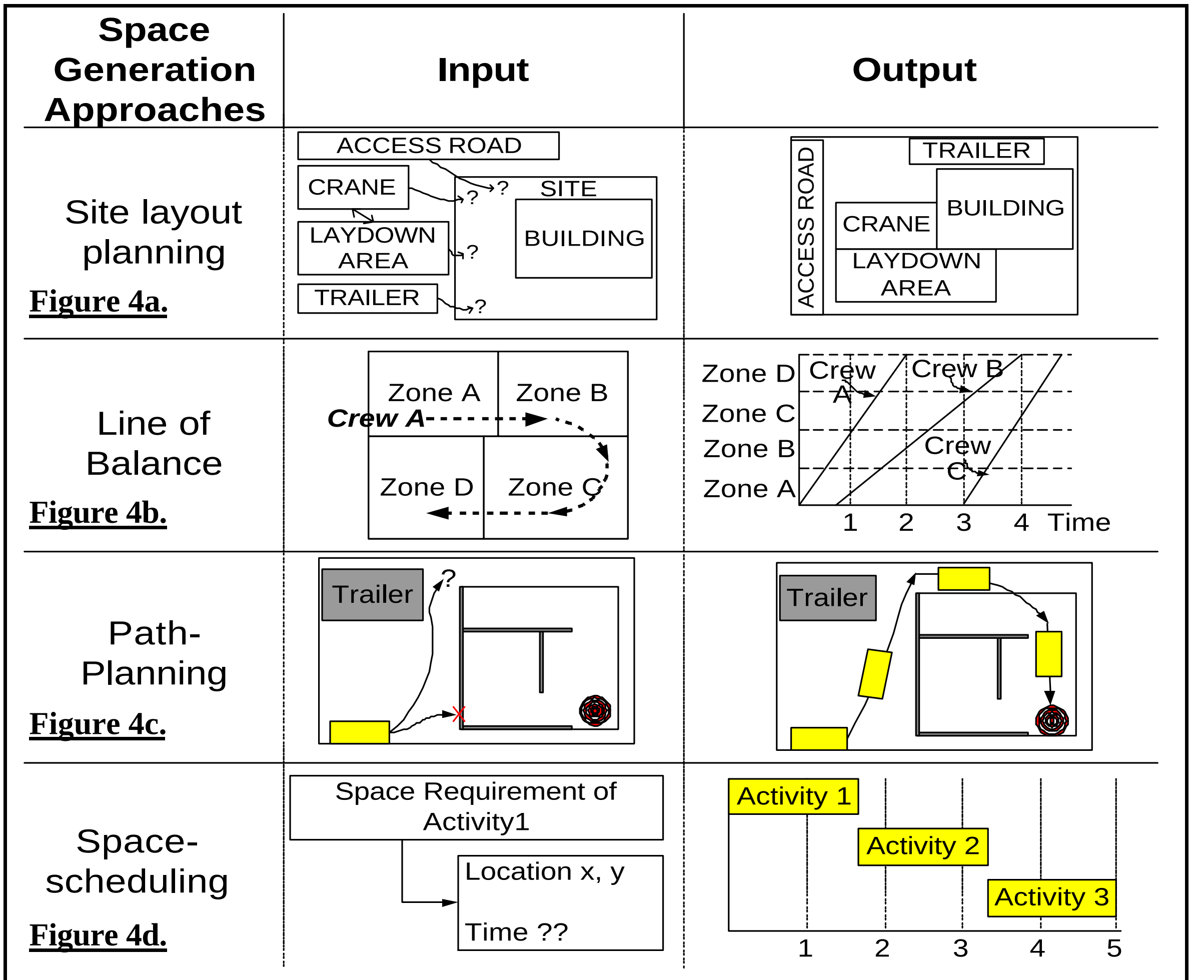


Figure 4. Four different approaches for generation of activity space requirements defined in the construction space management literature.

(1) <u>Static or dynamic site layout planning</u> (Eastman 1975; Levitt et al. 1989, Tommelein and Zouein 1993; Choi and Flemming 1996; Alshawi 1997; Choo and Tommelein 1999; Hegazy and Elbeltagi 1999) (Figure 4a): The site layout planning algorithms automate the allocation of macro-level spaces, which are the coarse spaces located at the site, according to user-defined qualitative adjacency constraints (e.g., close, far, etc.) 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 implemented in site layout planning cannot be used for generating micro-level work spaces. As the case demonstrated, the work spaces are described as being oriented with respect to their reference objects, and no adjacency descriptions are used explicitly to define the relationship between a work space and its reference object. For example, in the motivating test case, the window labor crew space is described as being located at the outside of the windows, which is a more precise description than being close to the windows (Figure 2a). Therefore, to generate micro-level spaces, the reasoning about orientations of spaces is more important than the reasoning about the adjacencies between spaces. Since the mechanisms implemented in site layout planning reason about adjacencies, they do not apply to the generation of micro-level spaces. Our approach complements the site layout planning approach by formalizing mechanisms to reason about the qualitative orientation descriptions of work spaces.

(2) Line of balance (O'Brien 1975; Birell 1981; Stradal and Cacha 1982; Halpin and Riggs 1992; Howell et al. 1993; Yamamoto and Wada 1993) (Figure 4b): The line of balance approach divides the building into zones such that each trade can move from one zone to another without disruption. The line of balance approach assigns only one crew to each zone at a time.

The application of this approach to the case described in Section 2 would prohibit the placing of windows and the hanging of the c-channel at the same time, on the same side of the building. However, as shown in Figure 1b, in some cases, it is possible to execute both of the activities at the same time on the same side without creating a conflict. Our work extends the line of balance approach by generating a more detailed representation of the different types of spaces required by construction activities.

(3) Path-planning (Latombe 1988; Zhu and Latombe 1989; Morad et al. 1992) (Figure 4c): The path-planning approach generates a collision-free path for a given object and its manipulation mechanisms. This approach contains a more detailed representation of construction spaces than our approach. For example, path planning will generate the specific material transportation paths required to install each of the windows and c-channel components.

Path planning is viable when modeling one material path around fixed obstacles. Hence, in most cases, the path planning approach assumes that the state of a facility under construction is fixed. When the state of the facility changes continuously over time, and when multiple paths and mobile objects need to be considered for each state, the path planning approach becomes very complex. Because of its complexity, the path-planning approach has been used most frequently to model the paths required by critical operations.

(4) Space-scheduling (Tommelein et al. 1992; Zouein and Tommelein 1993; Riley 1994; Thabet and Beliveau 1994; Thabet and Beliveau 1997; Choo and Tommelein 1999) (Figure 4d): 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 micro-level spaces. If this approach were applied to the case described in Figure 1a, the user would have to define a (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 (Figure 3). Given that there are hundreds of activities requiring 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 et al. 2000a). Our approach captures the spatial knowledge generically in relation to the construction methods being used and 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 from entering enormous amounts of data to represent project-specific activity space requirements.

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

4. 4D WORKPLANNER SPACE GENERATOR – SYSTEM ARCHITECTURE

4D WorkPlanner Space Generator (4D SpaceGen) automates the generation and the visual display of project-specific activity space requirements. Figure 5 shows the IDEF diagram (IDEF0 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 (Figure 2a) as an example.

4D SpaceGen takes an IFC based (IAI 1998) 4D production model – an integrated product and process model – as input (Figure 5). This 4D production model is generated by another system, Construction Method Modeler (Aalami 1998). The 4D production model relates the construction activities to the building components, the required resources and the selected construction methods. The next section describes the 4D production models in more detail.

4D SpaceGen assumes that the level of detail in the production model is at the level of a three-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 according to the subcontractors' construction methods and installation patterns. 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 by representing each of the activities involved in a technological sequence discretely (Halpin and Riggs 1992; Ballard 1997). For example, at this level there are separate activities representing forming, placing, and curing of a concrete installation operation. 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. There are four space templates, associated with the labor crew space, the equipment space, the hazard space, and the 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 et al. (2000a) describe the space templates developed to capture the activity space requirement information generically in relation to the construction method being applied. The control box in Figure 5 shows the information that the user defines in space templates.

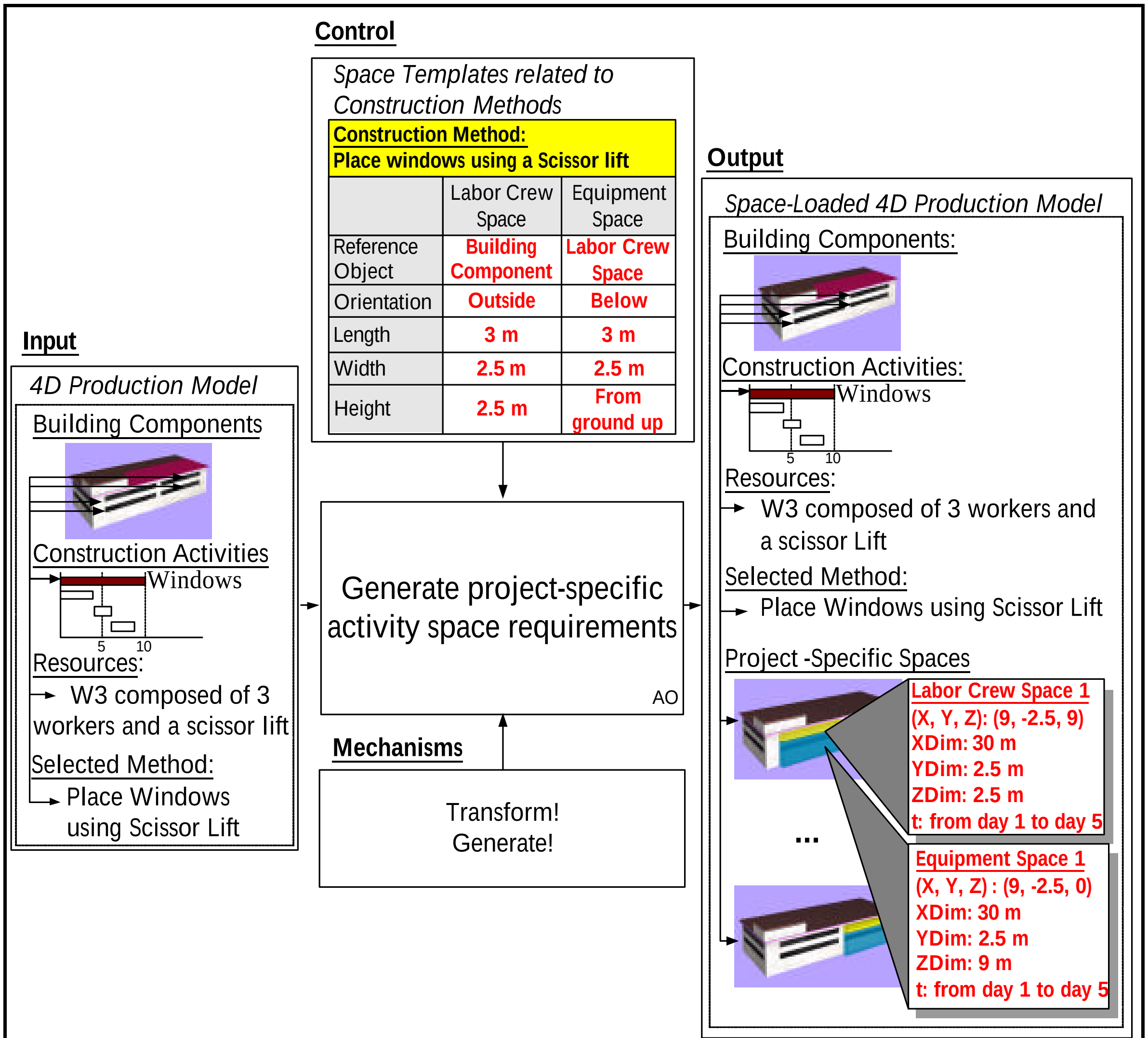


Figure 5. IDEF0 diagram (IDEF0 1981) of 4D WorkPlanner Space Generator (4D SpaceGen) and details of the window installation test case shown for one example case.

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 Figure 5 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 to the initial 4D production model representation, similar to any other resource requirement of activities (Figure 5).

5. USE OF IFC-BASED 4D PRODUCTION MODELS IN GENERATING PROJECT-SPECIFIC ACTIVITY SPACE REQUIREMENTS

Representation and generation of project-specific activity space requirements in four dimensions need geometric, temporal, and resource information. A construction *product model* provides geometric and topological information, and a construction *process model* provides temporal and resource information. Research on product and process models, especially on integration of these two models, has been growing rapidly over the last decade (Bjork 1991; Froese 1992; Gielingh and Suhm 1993; Luiten et al. 1993; Luiten 1994; Aouad et al. 1994; Luiten and Fischer 1995; Aouad et al. 1997; Aalami 1998).

Currently, two major efforts, Building Core Model (ISO 1994) and Industry Foundation Classes (IFC) (IAI 1998), are developing standard project model representations for the Architecture, Engineering, and Construction (A/E/C) and the Facility Management industries to enable the interoperability between separate stand-alone systems. Recently, some research projects have demonstrated the use of IFC to support construction scheduling and cost estimating (Froese et al. 1999; Staub-French and Fischer 2000), and facility management tasks (CIFE 1999; Yu et al. 1999). These efforts have concluded that the production model representation within IFC Release 2.0 (Beta 4 revision) (IAI 1998) generally supports current scheduling and estimating practices. Consequently, we formalized project-specific spaces as extensions of the standard production model as represented in IFC Release 2.0 Beta 4 (IAI 1998). Figure 6 shows the initial 4D production model representation with formalized relationships between product, process, and resource models based on IFC Release 2 Beta 4. The figure uses the Unified Modeling Language (UML) (Fowler and Scott 1999) notation in showing the relationships between different classes.

The generation of activity space requirements from a generic space description depends heavily on an explicit computer-interpretable construction method representation. IFC Release 2.0 represents construction methods as a string within the

WorkMethod attribute of the IfcWorkTask class. Hence, the IFC currently lack a computer-interpretable representation of construction method knowledge, on which our work can build. Therefore, for this work, we built on the construction method model representation formalized by Aalami (1998). We extended that construction method representation to include generic space requirement knowledge (Akinci et al. 2000a). Figure 6 shows the addition of a computer-interpretable construction method representation to the 4D production model defined in IFC.

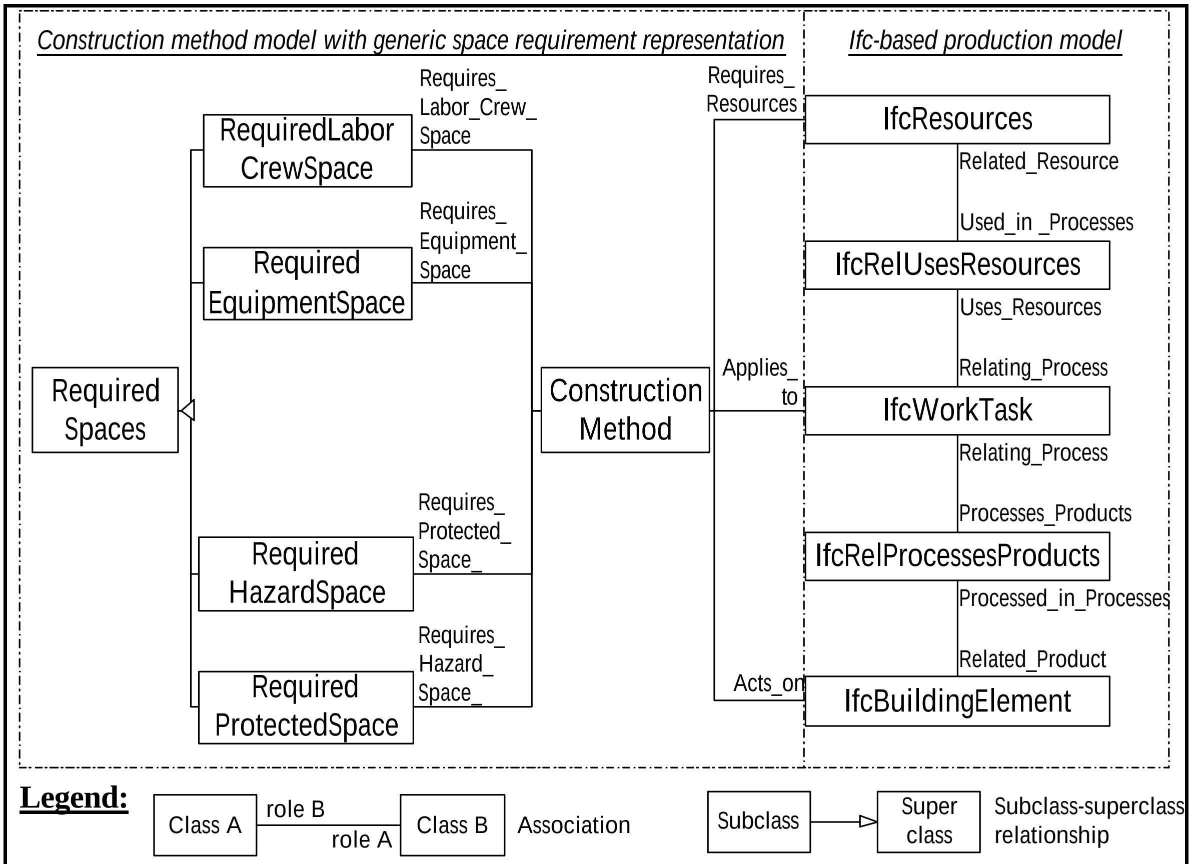


Figure 6. The extensions that we made to the IFC model to incorporate an explicit computer-interpretable construction method model and related work space representation.

The IFC-based production model section of Figure 6 includes the project-specific representation of construction activities (IfcWorkTask), components (IfcBuildingElement), resources (IfcResources), and the relationships between the activities and resources (IfcRelUsesResources), and between activities and building components (IfcRelProcessesProducts). The construction method model section of Figure 6 shows the generic representation of construction methods and the corresponding space requirements. Each construction method applies to a set of project-specific construction activities, shown as `Applies_to` relationship in Figure 6.

4D SpaceGen mainly uses this relationship in generating the project-specific work spaces required by construction activities. Through this relationship, 4D SpaceGen knows to which construction activities the generic spaces described by the user apply. Once that relationship is established, the next step is to interpret the generic space descriptions within construction method models and to interpret those descriptions to generate project-specific spaces represented in x, y, z, and time dimensions. The next section describes the mechanisms implemented to automate the generation of project-specific spaces.

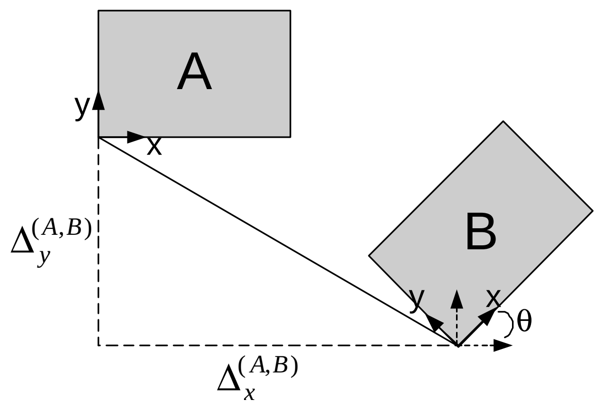
6. MECHANISMS FOR AUTOMATED GENERATION OF PROJECT-SPECIFIC SPACE REQUIREMENTS

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 Figure 5). 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 Figure 5). The challenge in the automated generation of the activity space requirements is to interpret the generic space descriptions and to generate the corresponding project-specific spaces represented in four dimensions.

Computer Science literature uses a transformation matrix to represent the relationship between two graphical objects quantitatively. Hence, the transformation matrix representation can translate the qualitative positional descriptions within the generic space representations to quantitative representations needed for generation of project-specific spaces. The next section elaborates on the transformation matrix concept and describes how we used it to generate project-specific spaces. The following section describes the mechanisms implemented to generate project-specific spaces represented in four dimensions.

6.1. Transformation Matrix

The transformation matrix is a formalism developed to represent the positional relationship between two graphical objects quantitatively. The transformation matrix (*T*) specifies the translation and the rotation operations that map the coordinates of one object to another (Figure 7) (Claus et al. 1998). The transformation matrix consists of two sections: (1) a rotation matrix (*R*) representing the rotation of object B with respect to object A, and (2) a translation vector *(D)* representing the distance in the x, y, z coordinates between the insertion points of object A and object B.



$$T = \begin{bmatrix} & R & & \begin{matrix} \Delta_x^{(A,B)} \\ \Delta_y^{(A,B)} \\ \Delta_z^{(A,B)} \end{matrix} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad R = \begin{bmatrix} \cos q & -\sin q & 0 \\ \sin q & \cos q & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Figure 7. The positional relationship of Object B with respect to Object A using a transformation matrix.

Some of the 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 <u>qualitative</u> orientation descriptions used by superintendents to describe the positional relationships between work spaces and their reference objects <u>quantitatively</u>. Figure 8 gives an example of the two ways of representing the positional relationship between the window labor crew space required and the window component. Figure 8b describes the generic qualitative space representation, and Figure 8c shows the project-specific representation of the position of the labor crew space with respect to the window component using the transformation matrix. Both of these representations model the positional relationship between the window labor crew space and the window shown in Figure 8a

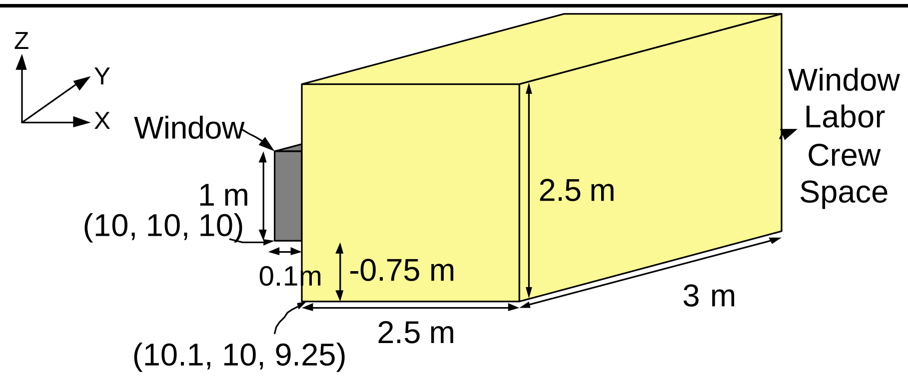


Figure 8a. The graphical representation of the positional relationship between the window labor crew space and the window

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

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

Figure 8b. The qualitative representation of the positional relationship

Figure 8c. The quantitative representation of the positional relationship

Figure 8. The qualitative and quantitative representation of positional relationship between the window and the labor crew space.

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. Equation 1 describes how the coordinates of the spaces can be generated by multiplying the transformation matrix with a vector of coordinates of the reference object.

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

$$\begin{Bmatrix} X_S \\ Y_S \\ Z_S \\ 1 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \Delta_x^{(O,S)} \\ 0 & 1 & 0 & \Delta_y^{(O,S)} \\ 0 & 0 & 1 & \Delta_z^{(O,S)} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} X_O \\ Y_O \\ Z_O \\ 1 \end{Bmatrix} \qquad \text{Eqn. (1)}$$

Where;

(X_S, Y_S, Z_S): the insertion point of the construction space to be generated

(X_O, Y_O, Z_O): the insertion point of the reference object

$\Delta_x^{(O,S)}$: the distance between the insertion point of the reference object and the insertion point of the construction space along the X dimension

$\Delta_y^{(O,S)}$: the distance between the insertion point of the reference object and the insertion point of the construction space along the Y dimension

$\Delta_z^{(O,S)}$: the distance between the insertion points of the reference object and the insertion point of the construction space along the Z dimension

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 the functional contents are added to the project-specific representation of activity space requirement by using the relationships explicitly represented in 4D production models.

6.2. 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 as requiring a certain size, 4D SpaceGen first automatically identifies the set of activities to which the construction method applies. It uses the `Applies_to` relationship between the `ConstructionMethod` and `IfcWorkTask` objects shown in Figure 6.

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:

1. Determine the number of instances of project-specific construction spaces needed.
2. Identify the relevant feature of the reference object according to the orientation description.
3. Generate the transformation matrices and the three-dimensional representation of project-specific spaces.
4. Add the temporal and functional content to the spaces generated.

6.2.1. Determining the number of instances of project-specific construction spaces

The first step in generating project-specific activity space requirements is the identification of the number of project-specific instances of spaces required to perform an activity. In determining the number of project-specific spaces needed, 4D SpaceGen first identifies the number of instances of the project-specific reference objects to which a construction activity relates, and it makes an instance of a project-specific space for each instance of a 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 by following the `IfcRelProcessesProducts` relationship between construction activities and building elements (Figure 6). In the case described above, the window installation activity acts on four windows on Side A of the component. Consequently, 4D SpaceGen makes four instances of the project-specific labor crew spaces required to install the four corresponding window components on Side A. For the c-channel installation case, only one labor crew space instance is needed since the c-channel installation activity processes only one c-channel component.

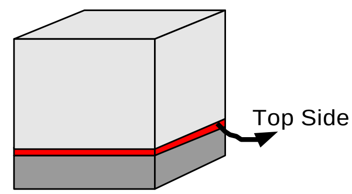
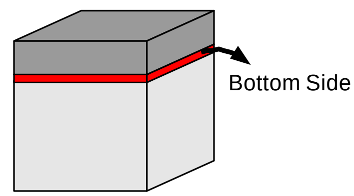
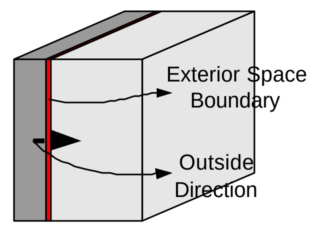
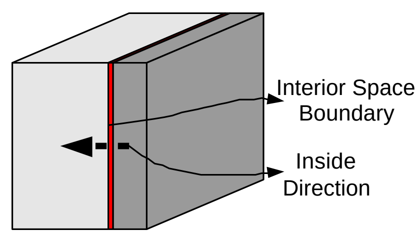
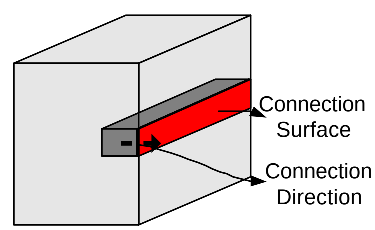
In summary, the different types of relationships between construction activities and the project-specific instances of the reference object determine the number of project-specific space instances needed. The 4D SpaceGen mechanisms generate project-specific spaces for both “one-to-one” and “one-to-many” relationships between construction activities and corresponding reference objects.

6.2.2. Identifying the relevant feature of the reference object according to the orientation description

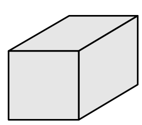
Once the project-specific instances of the reference object are identified, the next step is to interpret the qualitative orientation descriptions of the spaces, such as “above” and “outside.” Akinci et al. (2000a) describe the different orientation values identified for generic work space representation in 4D SpaceGen.

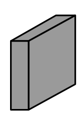
Interpreting the qualitative orientation descriptions involves identifying the relevant face of the reference object to which the space generated will be connected. We have developed an orientation-feature match table (Figure 9). The space generation mechanisms use this orientation-feature match table to identify the relevant faces of the reference objects, to which the space to be generated will be connected.

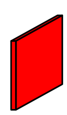
IFC (IAI 1998) explicitly represent the last three features shown in Figure 9. For example, the reified `IfcRelSeparatesSpaces` relationship models the relationship between components and their exterior and interior space boundaries. Similarly, the reified `IfcRelConnectsElements` relationship models the connection relationship between two building components, and it stores the geometric information about the connection sides of both components. IFC do not have an explicit representation of the top side or the bottom side of a component. We implemented a simple reasoning along the z-dimension to extract these two features automatically from the CAD building model.

Qualitative orientation description	Corresponding product feature and example
Above e.g., the labor crew space is <u>above</u> the roof	Top Side 
Below e.g., the scissor lift space is <u>below</u> the labor crew placing windows	Bottom Side 
Outside e.g., the window labor crew space is <u>outside</u> the windows	Exterior Space Boundary 
Inside e.g., the window labor crew space is <u>inside</u> the windows	Interior Space Boundary 
Around the Connected Side e.g. the c-channel labor crew is located <u>around the connected side</u> of the c-channel	Connection Surface 

<u>Legend:</u>

 Space defined

 Reference Object

 Corresponding feature of the reference object

<u>Figure 9.</u> The relationship between qualitative orientation descriptions and the features of the reference objects used to generate project-specific spaces.

6.2.3. Generating the transformation matrices and the corresponding 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 to generate the corresponding project-specific spaces using the transformation matrices. In generating the transformation matrix, the mechanisms implemented consider the size requirements of the space as defined by the user.

As shown in Figure 2, some spaces, such as labor crew spaces, have fixed sizes, and others, such as equipment spaces, have variable sizes. Akinci et al. (2000a) describe the different size requirements of different types of spaces. 4D SpaceGen has two separate mechanisms associated with the generation of spaces with fixed and variable size requirements. Since the size requirements of spaces are represented as rectangular prisms, the mechanisms implemented for generation of spaces only reason about rectangular prism shapes. These mechanisms are:

(1) Mechanisms for generating spaces with fixed size requirements

The mechanisms for generating spaces with fixed size requirements compare the size requirement of the space to the size of the reference object. If any of the dimensions of the space required defined by the user 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 of the dimensions of the space is less than the corresponding dimension of the reference object, the dimension of the reference object governs. Figure 10 shows an example of two window installations in which the size of the project-specific labor crew space generated is different even though the labor crew space requirement description is the same. The differences in sizes result from the different sizes of the components.

Labor crew space requires 2.5 m width, 3 m length and 2.5 m height at the outside of the components.

Figure 10a. Generic description of the labor crew space requirement.

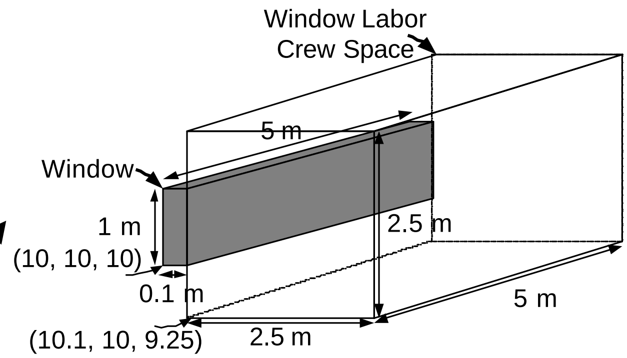


Figure 10b. The size of the component overrides the length, width and height requirements of the spaces when the component is bigger than the requirements.

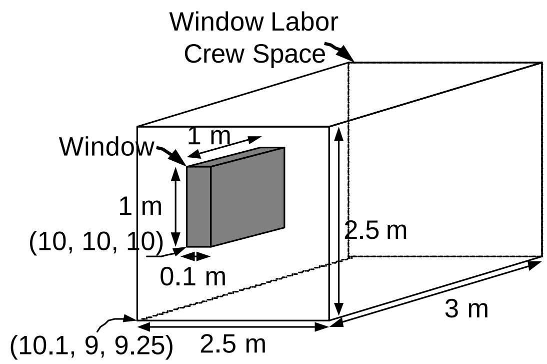


Figure 10c. The geometric representations of the project-specific spaces have offsets from the component representation when the length, width, or height requirements of the space are bigger than the size of the component.

Legend:

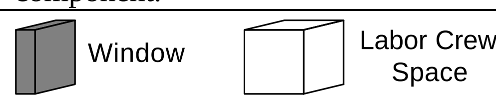


Figure 10. The transformation mechanisms in 4D WorkPlanner Space Generator generate different sizes of project-specific spaces for the same space requirement description by considering the size of the component relative to the size of the space required.

(2) Mechanisms for generating spaces with variable size requirements

For these spaces, the changes in the sizes result from the changes in the heights of the spaces. For example, the height of the scissor lift supporting the window labor crew (Figure 2a) changes with the location of the labor crew.

In generating the transformation matrices and the corresponding project-specific representations of spaces with variable size requirements, 4D SpaceGen checks the elevation of the location of the space (e.g., 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.

For example, the scissor lift used in the placing of windows (Figure 2a) is defined as located on the ground and as supporting the labor crew. 4D SpaceGen assumes the ground level having a zero elevation relative to the building, and therefore, it assigns the elevation of the related labor crew space instance as the height of the project-specific equipment space.

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

6.2.4. Adding the temporal and functional content information to the 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 across time. Therefore, this final step adds the temporal information to the 3D representation. To add the temporal information to the project-specific spaces, 4D SpaceGen follows the relationships between activities and the occupied project-specific spaces. Using that relationship, it extracts the scheduled times of the activities and adds 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, 4D SpaceGen creates relationships between the project-specific labor crew space and the labor crew and between the equipment space and the equipment (shown in Figure 11).

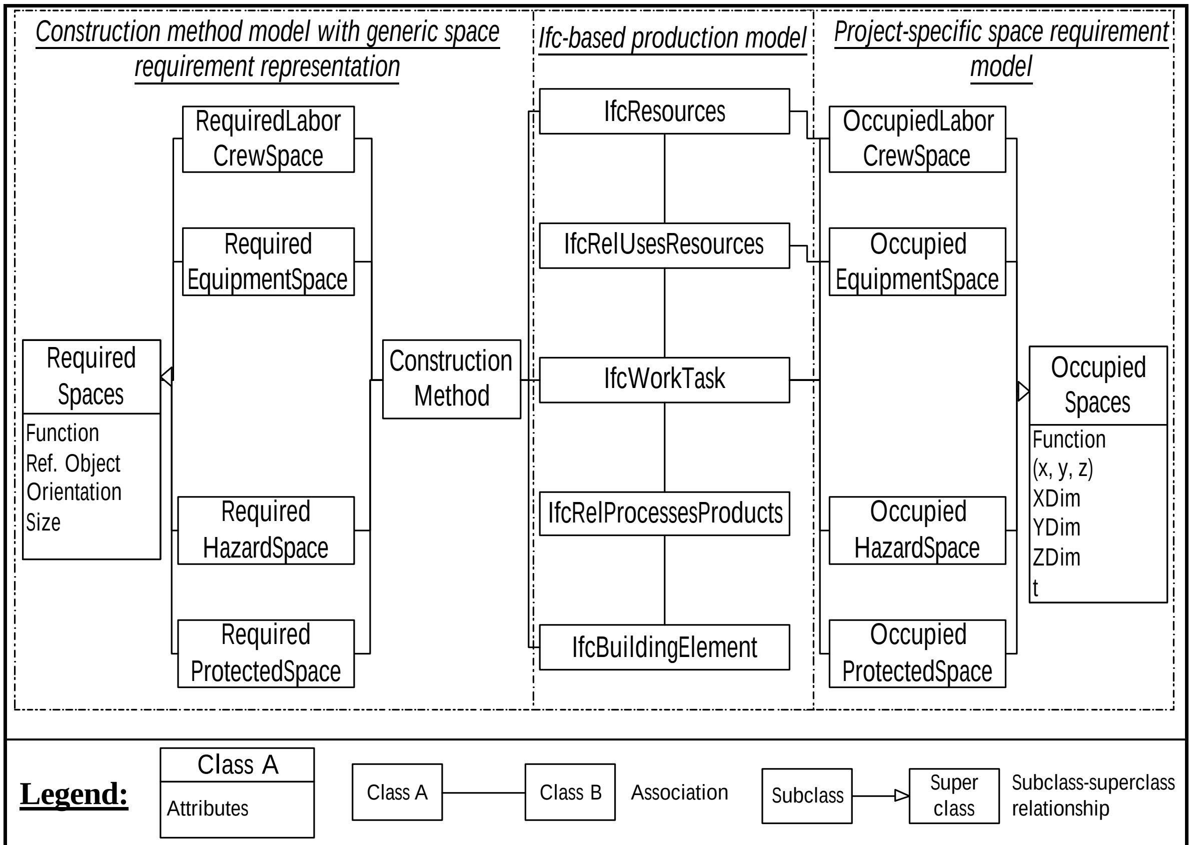


Figure 11. Space-loaded 4D production model representation includes generic and project-specific space representation.

As a result of the four steps described above, the project-specific activity space requirements are generated and represented in four dimensions. Figure 11 shows the main classes of the space-loaded production model.

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. We have created two new classes for representing spaces since the space representations in IFC cannot be used for representing work space requirements of activities.

IFC defines 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). IFC represents `IfcSpace` as a volume enclosed by certain building components. This is an architectural view of spaces, which 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 (i.e., `IfcProduct`) (IAI 1998). Thus, it represents a part of the product on which a work task or a 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 may or may not have a relationship with a product.

Since neither of the space representations within IFC can be used appropriately for representing micro-level activity space requirements, we created a new class of space objects and corresponding relationships. Within this integrated representation, construction activities know *what types* of spaces they require, *where* the spaces are located, and *how large* these spaces are. Similarly, work spaces know *to which activities* they belong, *when* and *where* they exist, and *how large* they are. The next section describes possible uses of these space-loaded 4D production models.

7. POSSIBLE USES OF SPACE-LOADED 4D PRODUCTION MODELS

A consistent formalism, such as the one shown in Figure 11, allows the sharing of the project-specific space representation generated by 4D SpaceGen with other programs (e.g., 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 CAD simulations more realistic, enable the automation of the identification and analysis of time-space conflicts and allow modification of a schedule according to spatial conflicts.

(1) Making 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 (Figure 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; Koo and Fischer 1998; Songer 1998; Staub et al. 1999). However, 4D models based on 3D models from designers do not represent activity space requirements (Figure 11). Space-loaded production models augment basic 4D models by representing 4D activity space requirements. They can be linked to a 4D CAD simulation system to make the simulations more realistic. Now, the simulations do not only display the building components but also the spaces required for the installation of those components (Figure 3). We implemented a space-loaded 4D CAD simulation in VRML (Hartman and Wernecke 1996). This simulation uses the space-loaded 4D production model, to simulate the construction process and display the spaces used by construction activities.

(2) Automating time-space 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 et al. (2000b) discuss how space-loaded production models are used to automate time-space conflict analysis.

(3) Automating the modification of schedules to minimize spatial conflicts between activities

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.

8. 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. 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.

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 orientation descriptions for the generation of four types of work spaces.

In addition, a graduate student and a visiting fellow at the Center for Integrated Facility Engineering at Stanford University conducted a prospective case study in which they went to a job site and interviewed the superintendents about the different types of spaces their crews needed. According to these descriptions, they modeled the space requirements of ten 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 similar to the spaces occupied by the corresponding activities at the site. This result shows the power of the mechanisms implemented in this research.

9. 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, which are integrated product and process 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 of project-specific work spaces, which would otherwise be impossible to perform.

The space generation mechanisms implemented in this research 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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11. REFERENCES

Aalami, Florian. (1998). “Using Method Models to Generate 4D Production Models,” *Ph.D. thesis*, Department of Civil Engineering; Stanford University, Stanford.

Aalami, F., Fischer, M. and Kunz, J. (1998). “AEC 4D Production Model: Definition and Automated Generation.” *Working Paper # 52*, CIFE, Stanford.

Akinci, B. and Fischer, M. (1998). “Time-Space Conflict Analysis Based on 4D Production Models.” *Congress on Computing in Civil Engineering*, ASCE, 342-353.

Akinci, B., Fischer, M., Kunz, J. and Levitt, R. (2000a). “Representing Work Spaces Generically Within Construction Method Models.” *Working Paper # 57,* CIFE, Stanford.

Akinci, B., Fischer, M, Levitt, R. and Carlson, B. (2000b). “Automated Detection and Analysis of Time-Space Conflicts.” *Working Paper # 59*, CIFE, Stanford.

Akinci, B., Fischer, M. and Zabelle, T. (1998). “A Proactive Approach for Reducing Non Value Adding Activities due to Time-Space Conflicts.” *Sixth Annual Conference of the International Group for Lean Construction (IGLC-6),* Guarujá, São Paulo, Brazil, 1-18.

Alshawi, Mustafa. (1997). “SPACE: An Integrated Environment for the Construction Environment.” Time Research Institute, Salford University, Salford.

Aouad, G., Betts, M., Brandon, P., Brown, F., Child, T., Cooper, G., Ford, S., Kirkham, J., Oxma, R., Sarshar, M. and Young, B. (1994). “ICON: Integration of Construction Information.” Department of Surveying and Information Technology Institute, University of Salford, Salford, UK.

Aouad, Ghassan, Child, Terry, Marir, Fahri and Brandon, Peter. (1997). “Open Systems for Construction (OSCON), draft industry report.” Department of Surveying, University of Salford, Salford, UK.

Ballard, G. (1997). “The Last Planner.” http://www.ce.berkeley.edu/~tommelein/LastPlanner.html.

Birell, G. (1981). “Construction Planning - Beyond the Critical Path.” *Journal of the Construction Division,* ASCE, 106(CO3), 389-407.

Bjork, B. C. (1991). “A Unified Approach for Modeling Construction Information.” *Building and Environment*, 27(2), 173-194.

Choi, B. and Flemming, U. (1996). “Adaptation of a Layout Design System to a New Domain: Construction Site Layouts.” *Computing in Civil Engineering*, New York, 711-717.

Choo, H. Y. and Tommelein, I. (1999). “Space Scheduling Using Flow Analysis.” *IGLC-7,* Berkeley, CA, 299-311.

CIFE. (1999). “Facilities Management: Move Management Charette.” *online document; http://www.stanford.edu/group/CIFE/IFC/CIFE-CharretteWhitePaper.html*, Stanford.

Claus, B., Eyferth, K., Gips, C., Hornig, R., Schmid, U., Wiebrock, S. and Wysotzki, F. (1998). “Reference Space for Spatial Inference in Text Understanding.” *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, C. Freksa, C. Habel, and K. Wender, eds., Springer, Berlin, 241-266.

Eastman, C. (1975). *Spatial Synthesis in Computer-Aided Building Design*, John Wiley and Sons, New York.

Ekholm, A. and Fridqvist, S. (1997). “Concepts of Space in Computer Based Product Modeling and Design.” *15th ECAADE Conference,* Vienna, http://info.tuwien.ac.at/ecaade/proc/ekholm/ekholm.html.

Fowler, M. and Scott, K. (1999). *UML Distilled*, Addison Wesley Longman, USA.

Froese, T., Fischer, M., Grobler, F., Ritzenthaler, J., Yu, K., Sutherland, S., Staub, S., Akinci, B., Akbas, R., Koo, B., Barron, A. and Kunz, J. (1999). “Industry Foundation Classes for Project Management - A Trial Implementation.” *ITCON (Electronic Journal of Information Technology in Construction),* Vol. 4, 17-36, http://www.itcon.org/1999/2/.

Froese, T. M. (1992). “Integrated Computer-Aided Project Management Through Standard Object-Oriented Models,” *Ph.D. Thesis*, Department of Civil Engineering; Stanford University, Stanford.

Gielingh, W. F. and Suhm, A. K. (1993). “IMPPACT Reference Model: An Approach for Integrated Product and Process Modeling of Discrete Parts Manufacturing.” *Research Report # 2165,* ESPRIT, Darmstadt, Germany.

Halpin, D. and Riggs, L. (1992). *Planning and Analysis of Construction Operations*, John Wiley and Sons, Inc., New York.

Hartman, J. and Wernecke, J. (1996). *The VRML 2.0 handbook: Building Moving Worlds on the Web*, Addison-Wesley, Reading, MA.

Hegazy, T. and Elbeltagi, E. (1999). “EvoSite: Evolution-Based Model for Site Layout Planning.” *Journal of Computing in Civil Engineering*, 13(3), 198-206.

Hetrick, M. and Khayyal, S. A. (1987). "An Integrated Facility Construction Process Model." *Technical Report # 5*, CIC Research Program, Department of Architectural Engineering, University Park, PA.

Howell, G., Laufer, A. and Ballard, G. (1993). "Interaction Between Subcycles: One Key to Improved Methods." *Journal of Construction Engineering and Management*, 119(4), 714-728.

IAI. (1998). "Industry Foundation Classes 2.0." *Specifications Volumes 1-4*, Industry Alliance for Interoperability, Washington, D. C.

IDEF0. (1981). "Integrated Computer-Aided Manufacturing (ICAM), Architecture Part II, vol. IV - Function Modeling (IDEF-0)." SoftTech, Inc, Waltham, MA.

ISO. (1994). "Building Construction Core Model, Project Proposal." *Document # N341*, ISO TC184/SC4/WG3.

Latombe, J. (1988). "Global Path Planning Approaches for Material Movements in a Worksite." *Technical Report # 3*, Center for Integrated Facility Engineering, Stanford University, Stanford.

Levitt, R., Tommelein, I., Hayes-Roth, B. and Confrey, T. (1989). "SightPlan: A Blackboard Expert System for Constraint Based Spatial Reasoning about Construction Site Layout." *Technical Report # 20*, Center for Integrated Facility Engineering, Stanford.

Luiten, B. (1994). "Computer Aided Design for Construction in the Building Industry," *Ph.D. Thesis*, Department of Civil Engineering; Delft University.

Luiten, B. and Fischer, M. (1995). "SPACE CAKE: System for Project Management in Civil Engineering using Computer-Aided Knowledge Engineering." *Working Paper # 40*, CIFE, Stanford University, Stanford.

Luiten, G. T., Froese, T. M., Bjork, B., Cooper, G., Junge, R., Karstila, K. and Oxman, R. (1993). "An Information Reference Model for Architecture, Engineering and Construction." *First International Conference on the Management of Information Technology for Construction*, Singapore, 391-406.

Morad, A., Cleveland, A., Beliveau, Y., Francisco, V. and Dixit, S. (1992). "Path-Finder: AI-based Path Planning System." *Journal of Computing in Civil Engineering*, 6(2), 114-128.

O'Brien, J. J. (1975). “VPM Scheduling for High-Rise Buildings.” *Journal of the Construction Division, ASCE*, 101(CO4), 895-905.

O'Brien, W. (1998). “Capacity Costing Approaches for Construction Supply-Chain Management,” *Ph.D. Thesis*, Department of Civil and Environmental Engineering; Stanford University, Stanford.

Oglesby, C. H., Parker, H. W. and Howell, G.A. (1989). *Productivity Improvement in Construction*, McGraw-Hill Inc., New York, N. Y.

Rad, P. (1980). “Analysis of Working Space Congestion from Scheduling Data.” *American Association of Cost Engineers Transactions*, F4.1-F4.5.

Riley, D. (1994). “Modeling the Space Behavior of Construction Activities,” *Ph.D. Thesis,* Department of Architectural Engineering; Pennsylvania State University, University Park.

Riley, D. and Sanvido, V. (1997). “Space Planning for Mechanical, Electrical, Plumbing and Fire Protection Trades in Multi-Story Building Construction.” *5th ASCE Construction Congress,* Minneapolis, MN, 102-109.

Sanders, S. R., Thomas, H. R. and Smith, G. R. (1989). “An Analysis of Factors Affecting Labor Productivity in Masonry Construction.” *PTI # 9003,* Pennsylvania State University, University Park, PA.

Sanvido, Victor. (1984). “Designing Productivity Management and Control Systems for Construction Projects,” *Ph.D. Thesis,* Department of Civil Engineering; Stanford University, Stanford.

Songer, A., Diekmann, J. and Al-Rasheed, K. (1998). “Impact of 3D Visualization on Construction Planning.” *Proceedings of the 1998 International Computing Congress on Computing in Civil Engineering*, Boston, ASCE, 321-329.

Staub-French, S. and Fischer, M. (2000). “Practical and Research Issues in Using Industry Foundation Classes for Construction Cost Estimating.” *Working Paper # 56*, CIFE, Stanford.

Stradal, O. and Cacha, J. (1982). “Time Space Scheduling Method.” *Journal of the Construction Division*, 108(CO3), 445-457.

Thabet, W. and Beliveau, Y. (1994). "Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings." *Journal of Construction Engineering and Management*, 120(1), 96-116.

Thomas, R. and Sakarcan, A. (1994). "Forecasting Labor Productivity Using Factor Model." *Journal of Construction Engineering and Management*, 120(1), 228-239.

Tommelein, I. and Zouein, P. (1993). "Interactive Dynamic Layout Planning." *Journal of Construction Engineering and Management*, 119(2), 266-287.

Yamamoto, K. and Wada, K. (1993). "Resource Constrained Time-Space Scheduling Model." *Proceedings of the 5th International Conference Computing in Civil Engineering*, Anaheim, California, 1794-1801.

Yu, K., Froese, T. and Grobler, F. (1999). "A Development Framework for Data Models for Computer-Integrated Facilities Management." *Automation in Construction*, (accepted for publication).

Zhu, D. and Latombe, J. (1989). "New Heuristic Algorithms for Efficient Hierarchical Path Planning." *Technical Report # 18,* Center for Integrated Facility Engineering, Stanford University, Stanford.

Zouein, P. and Tommelein, I. (1993). "Space Schedule Construction." *Proceedings of the 5th International Conference on Computing in Civil Engineering*, ASCE, 1770-1777.