Enabling Construction 4D Topological Analysis for Effective Construction Planning

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Abstract: Construction four-dimensional (4D) models have emerged to become a powerful tool for effective construction planning and control. However, the emphasis has been visualization and 4D topological analysis capabilities are not well-incorporated in the existing practice. Some 4D models enabled space-time conflict detection or site layout analysis, subtypes of 4D topological analysis; these functions are fragmented and constrained in particular construction scenarios. This paper presents a generic construction 4D topology framework that enables 4D topological analysis to support a wide range of construction planning tasks. The framework includes a 4D topological representation method that formalizes the spatial-temporal relationships between construction activities, a topology categorization method that formats the 4D topological representations into task templates, and a mathematical method to conduct the analysis. The framework is tested in a prototype through a case study, which proves that the framework is able to facilitate many construction planning works such as space-time conflict detection and test for crane's cover range. **DOI: 10.1061/(ASCE)CP.1943-5487.0000463.** *© 2014 American Society of Civil Engineers.*

Author keywords: Construction four-dimensional (4D) model; Four-dimensional (4D) topology; Topological analysis; Construction planning.

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Introduction

Construction is a dynamic and complex process that involves a large number of activities that in turn interact with each other. Construction planning aims at decomposing the construction process into activities and organizing/sequencing these activities, in both spatial and temporal aspects. Nowadays, with increasing pressure for shorter delivery schedules and an increasing number of construction projects residing in congested areas, demands arise for better coordinating construction activities and managing limited site spaces through effective construction planning.

Construction of four-dimensional (4D) models has emerged to assist in many construction planning tasks. The early 4D technique typically combined a three-dimensional (3D) computer-aided design (CAD) model and a one-dimensional (1D) project schedule to visualize project progress graphically over time (Collier and Fischer 1996; William 1996). Such a visual analysis process relies on personal experience and expertise to identify construction problems, which is inefficient and error prone. Realizing the limitation, researchers have attempted to incorporate spatial-temporal analytical capabilities into construction 4D models to enable automatic space-time conflict detection (Guo 2002; Akinci et al. 2002b; Mallasi 2006; Chua et al. 2010; Chavada et al. 2012), site safety analysis (Zhang et al. 2013), and site layout and equipment planning (Irizarry and Karan 2012; Su and Cai 2014a; Kim and Teizer 2014). These studies proved the importance of considering both space and time in construction planning to avoid workspace conflicts that not only are counter-productive, but also might pose an unsafe condition to field crew.

Although the previous studies improved the analytical capabilities of 4D models, they are constrained by particular construction scenarios (workspace conflict detection, workspace safety, or workspace management for equipment or facilities) without abstracting the nature of the workspace problem into a higher level framework, a 4D topological relationship. The word topology in this paper refers to the mechanism that describes integrated spatial-temporal relationships between objects. For two spatial objects, their spatial topological relationship indicates a comparative location between each other, such as inside, overlap, and disjoint.

A construction 4D topology framework can enhance the understanding of the workspace problems and further improve the analytical capabilities of construction 4D models. This paper presents a construction 4D topology framework for effective construction planning. The rationale for this paper is such that (1) a generic 4D topology that extends the spatial topology into a 3D space plus time environment, which enables the description of dynamic spatial-temporal relationships between two objects; (2) the generic 4D topology can be customized into construction 4D topology to describe spatial-temporal relationships between construction activities; and (3) viewing a construction site as a dynamic environment in which construction activities occupy varying spaces at different times, construction activities can be modeled as spatial-temporal objects and their interactions can be systematically formatted into 4D topological relationships. Consequently, analyzing or querying the 4D topological relationships among construction activities is enabled.

Related Studies

Three-dimensional/4D construction models have been widely used in many construction projects. Hartmann et al. (2008) summarized seven application areas of 3D/4D construction models based on

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case studies and found analyzing construction operations via 4D animations is the most popular one. This 4D visualization method is capable of displaying the construction progress at particular times, simulating the construction for certain time intervals, or virtually stepping through construction schedules (Song and Chua 2006; Hartmann and Fischer 2007). However, the 4D visual analysis process still relies on personal experience and expertise to identify construction problems. Besides, it has been pointed out that visualizing 3D object at discrete points throughout the duration of the associated task (i.e., displaying the entire product for the whole task duration) is not representative of the construction process (Winch and North 2006). Challenges of overcoming the limitations arise in workspace modeling, 4D model creation, and 4D analysis.

Workspace modeling is an essential step before enabling 4D analysis. For the 4D visualization method, users are mentally modeling workspaces during the examination of construction animation. However, to enable 4D analysis, the workspace must be explicitly modeled so that computers can conduct analysis upon them. Many researchers have recognized the problem and made significant achievement, including the Akinci et al. (2002a) space template in the space-loaded 4D product model (a user input-based approach), the Mallasi (2006) approximation envelope (a product model-based approach), and the Su and Cai (2014b) lifecycle workspace modeling (a hybrid approach).

Four-dimensional analysis needs to be conducted on 4D models. A variety of methods for 4D model creation exist in published literatures. Besides the widely implemented manual linking method that manually links a schedule with the corresponding 3D model, representative works include but not limited to the following: (1) the automatic approach (deVries and Harink 2007) that adopts a fully automated process to generate schedules and 4D models by analyzing the spatial topology among a 3D model's components; (2) the manual assembly approach (Waly and Thabet 2003) that semiautomates the scheduling process by reassembling a 3D model using drag and drop operations, and recording the operation sequence; and (3) the graphical planning method (Su and Cai 2014a) that integrates critical path method (CPM) scheduling, workspace modeling, and 4D modeling into a unified process.

With the support of workspace modeling and 4D model creation methods, researchers have attempted to incorporate 4D analytical capabilities into 4D models. The most significant contribution of these attempts exists in the area of space-time conflict detection. For example, Akinci et al. (2002b) employed discrete event-simulation mechanisms for space-time conflict detection, which first identifies concurrent activities and then checks possible geometric clashes for each pair of the concurrent activities. An important breakthrough is that multiple types of conflicts are allowed to possibly occur between the same pair of conflicting activities. Guo (2002) defined space conflict as more than one space demands claim on a specific available space during the same time period and presented a quantification methodology for space conflicts. Chavada et al. (2012) proposed a conflict detection process that examines both the temporal conflicts between schedule and the spatial conflict between workspaces. The temporal conflict is considered to be a preliminary condition that is required to be checked prior to the workspace conflict. A significant contribution is the formalization of temporal conflicts that enhances the 4D concept. Moon et al. (2014) presented a schedule-workspace interference management system to minimize workspace conflicts by constructing a genetic algorithm (GA) process to identify a better alternative schedule. A widely adopted method for conflict detection by the studies is the snapshot scanning method that detects 4D conflicts by examining 3D objects at each representative time point.

Another essential contribution is the development of space taxonomy. Different types of space interference have different consequences; therefore, an accurate and efficient evaluation of space criticality relies on the development of a proper space taxonomy. A number of representative works have been developed in previous studies. For example, Akinci (2002b) classified six types of spaces required by construction activities, as follows: (1) building component space, (2) labor crew space, (3) equipment space, (4) hazard space, (5) protected space, and (6) temporary structure space. The conflicts from interferences of different types of spaces are also classified into four types, as follows: (1) design conflict caused by building component space overlaps, (2) safety hazard due to hazard space involved interferences, (3) damage conflict caused by protected space involved interferences, and (4) congestion from interferences between labor crew spaces and equipment spaces. Similarly, Wu and Chiu (2010) defined six space types as (1) path workspace, (2) material workspace, (3) labor workspace, (4) equipment workspace, (5) site layout workspace, and (6) building component workspace. Chavada et al. (2012) employs classification inspired by the manufacturing sector that distinguishes between value added and no-value added activities. Workspaces are divided into four categories, as follows: (1) main workspaces, (2) support workspaces, (3) object workspaces, and (4) safety workspaces.

A limitation of the previous studies is that they all focused on a particular scenario, such as space time conflict detection, without offering the capability for customization. Construction planning sometimes has more complicated requirements than detecting space-time conflicts. For instance, a crane's working range must cover its target area; however, when the crane is working on upper floors, spaces that below the lift but covered by the crane's working range become a restricted zone. Activities in the target area and the restricted zone all have space-time overlaps with the crane's workspace, but lead to entirely different plan decisions.

There are also many commercially available construction planning software with capabilities of 3D visualization and reporting, 3D clash detection, 4D scheduling, and five-dimensional (5D) (4D+cost) estimating. These software packages mainly provides traditional construction analysis capabilities, such as clash detection, quantity takeoff, flowline scheduling, and resource leveling, to improve construction planning experience. However, they neither consider workspace related interactions between construction activities nor support 4D topological analysis.

Four-Dimensional Topology Framework

A well-defined construction 4D topology framework is able to describe and capture, through analyzing topological relationships, a broad variety of interactions between construction activities such as detecting space time conflict, testing whether a crane's working range covers its targets, identifying if there are any labor working in a dangerous zone, and planning the location and duration of temporary facilities.

Existing 3D Topology Frameworks

The development of the Nine-intersection model (9IM) in the geographical information science (GIS) area is a substantial progress towards the formalization of spatial topological relationships (Egenhofer and Franzosa 1991). The 9IM examines the intersections **I** of each of the interior, boundary, and exterior of an Object A, with each of the interior, boundary, and exterior of another Object B, resulting in the 3×3 matrix

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$$\mathbf{I} = \begin{bmatrix} A^{\circ} \cap B^{\circ} & A^{\circ} \cap \partial B & A^{\circ} \cap B^{-} \\ \partial A \cap B^{\circ} & \partial A \cap B^{\circ} & \partial A \cap B^{-} \\ A^{-} \cap B^{\circ} & A^{-} \cap B^{\circ} & A^{-} \cap B^{-} \end{bmatrix} \quad (1)$$

A° denotes the interior, ∂A denotes the boundary, A^{-} denotes the exterior of Object A, and $\cap$ represents the intersection operator. Each element is a binary value resulting from the intersecting operation. It yields a total of 512 possible configurations although many of them are not achievable in practice. This framework is extended into 3D to describe spatial relationships between 3D objects by Zlatanova (2000). Fig. 1 illustrates the eight basic possible configurations between 3D objects. This framework provides a systematic and easy-to-implement method of detecting spatial relationships and a number of studies adopted the 9IM matrix in various application areas (e.g., Papadias and Theodoridis 1997; Kurata 2008; Ellul and Haklay 2009).

Three-dimensional topological relationships have also been studied in some areas such as CAD, solid modeling, and building information modeling (BIM). A representative technique is constructive solid geometry (CSG) that is able to create a complex surface or object by using Boolean operators to combine objects (Bundy and Wallen 1984). The CSG has been widely used in the design of game engines, such as in the Quake engine and Unreal engine, where simple geometry is desired or mathematical accuracy is important. In construction, Borrmann and Rank (2009) highlighted the importance of topological analysis and spatial query in deriving partial building models for highly collaborative design and engineering. The 3D topological analysis method they presented, as part of the effort toward the development of a spatial query language for BIM models, enables 3D topological analysis in a fuzzy manner so that the tradeoff between computational effort and the required accuracy can be controlled.

Spatial-Temporal Integrated Representation

The 3D spatial topology frameworks build a solid foundation toward the development of a 4D topology framework. In order to describe a 4D topological relationship, the temporal configurations, besides the 3D spatial configurations, must be formalized. The temporal relationships are the base of conventional construction scheduling and have been implemented in popular software such as *MS Project* and *P3*. We summarized them into 13 configurations considering temporal directions, indicated by prefixes ahead and after (Fig. 2).

A construction 4D topological relationship is an aggregation of the spatial and temporal relationship between two activities. A spatial temporal integrated representation method is created in the research reported in this paper to describe the 4D topological relationship between construction activities by elaborating the

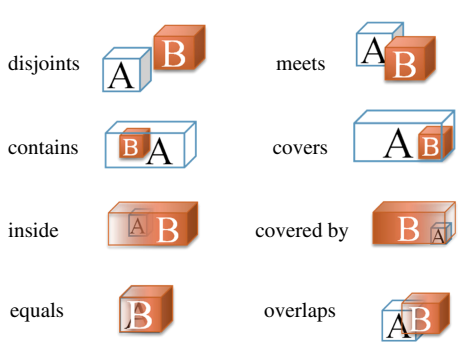

Fig. 1. Three-dimensional topological configurations in 9IM

Configuration	Illustration
A ahead-meets B	
A ahead-disjoint B	
A after-meet B	
A after-Disjoint B	
A ahead-overlaps B	
A ahead-covered by B	
A equals B	
A ahead-covers B	
A contains B	
A after-covers B	
A after-overlaps B	
A after-covered by B	
A inside B	

Fig. 2. Temporal configurations

spatial and temporal relationship between every pair of their space components. The representation method is illustrated using an example of two construction Activities A and B with their spatial and temporal layouts (Fig. 3). Considering Activities A and B are concreting activities, Activity A uses regular concrete so that a period of time for curing is required after concreting, while Activity *B* uses fast-setting concrete so that the required curing time can be ignored. Activity A is composed of three workspaces, as follows: (1) WS-A1 (for formwork installation and concreting), (2) WS-A2 (for curing), and (3) WS-A3 (for formwork stripping), and a product space PS-A (for the final product); and Activity B is composed of WS-B1 (for formwork installation concreting), WS-B2 (for formwork stripping), and PS-B (for the final product). All spaces are assumed to have the same height. Only labor workspace is considered in this illustrating example.

It is difficult to mentally identify workspace conflict even for the simplified example. Although Activity B is intentionally planned to start after Activity A's formwork installation and concreting, conflicts still exist. Table 1 describes Activity A and B's 4D topological relationship in details. The 12 cells cover every pair of space components between the two activities. Within each cell, a space component of an activity is examined with a space component of the

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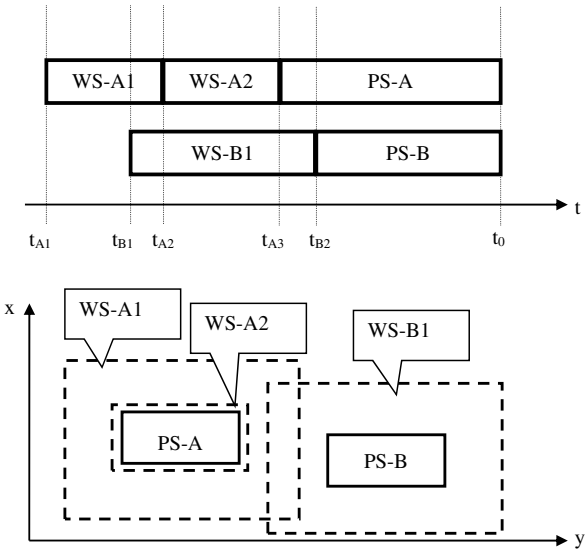

Fig. 3. Spatial temporal relationships between Activities A and B

other activity temporally and spatially. The result shows there are four cells with temporal and spatial overlaps.

The method is able to represent the dynamic interaction between activities; however, the output is difficult to read for human beings and to implement in practice without proper translation. For example, the case shown in Fig. 3 presents a situation of workspace congestion but it is inconvenient for a construction planner to identify the congestion by reading Table 1 due to the massive information amount. When there are more components within each activity, the situation becomes worse. The next section presents the topology categorization method to format the representation into simplified task templates.

Formalizing Task Templates by Topology Categorization

The topology categorization formats the 4D topological representation into different templates to solve space-time-related planning tasks such as space-time conflict detection, facility and equipment layout, and material transportation. Those tasks have different criteria or requirements of 4D topological analysis. For instance, space-time conflict detection compares two site activities to see if they have spatial and temporal intersects, while a crane's working range must cover the desired area and the crane's working duration must also cover the working period of the related activities. The principle of the topology categorization is to investigate the 4D topological criteria of a task and accordingly categorize the spatial (and temporal) configurations into groups. The result will form a template that serves as a designated tool for the task.

As introduced previously, there are eight spatial configurations and 13 temporal configurations. The spatial-temporal integrated representation utilizes them to comprehensively represent spatial and temporal relationships. The topology categorization method groups the configurations to make the representation more concise and efficient. For example, the main concern of space-time conflict detection is the keyword, intersect. As long as two geometries have spatial and time intersect, conflicts will occur. Among the eight spatial configurations, six can be considered as intersect, as follows: (1) cover, (2) covered by, (3) contains, (4) inside, (5) equals, and (6) overlaps (Fig. 4). The other two can be considered as no intersect, as follows: (1) meets, and (2) disjoints. The reason of considering meets as no intersect is that it indicates two-dimensional (2D) face intersection rather than 3D volume intersection and within a construction context such face intersects between spaces usually do not lead to fatal consequences.

The temporal topology configurations are similar as the spatial topology configurations. The only difference is that the temporal topology configurations have prefix ahead and after to indicate directions. This difference does not affect the categorization process in most cases. Therefore, a 4D topological relationship 4D intersect in a construction context can be defined as that two activities intersect spatially and temporally.

Another example is displayed in Fig. 5 to further illustrate the concept. When a planner examines whether a crane is positioned properly that the working range covers all desired areas and the working period covers all related activities' working periods, the keyword becomes cover. In this paper, general-cover is used to distinguish the keyword from the spatial topological configuration covers. There are three configurations qualified for general-cover, as follows: (1) covers, (2) contains, and (3) equals; three configurations considered as intersect but no cover, as follows: (1) covered by, (2) inside, and (3) overlaps; and two considered as no intersect, as follows: (1) meets, and (2) disjoints.

After categorization, each configuration can be represented by a value of weight according to its category to form a task template. Taking the space-time conflict detection task as an example, the six intersect configurations are assigned a value of 1 and the other two no-intersect configurations are assigned a value of 0, with the value 1 indicating conflict and the value 0 indicating no conflict. The crane's cover range test has three groups of configuration. A value of 2 is assigned to the no-intersect group, 1 to the intersect but no cover group, and 0 to the general-cover group, with the value of weight indicating the critical level of the problem.

Creating a 4D Topological Matrix

With a task template, a 4D topological matrix that represents a construction 4D topological relationship for the task can be created in three steps, as follows: (1) the first step forms a spatial matrix and a temporal matrix by examining the spatial and temporal relationship of each pair of space components (a spatial or temporal

Table 1. Four-Dimensional Topological Relationship of Activities A and B

Space	WS-A1	WS-A2	WS-A3	PS-A
WS-B1	*T*, after-disjoint *S*, overlaps	*T*, after-overlaps *S*, overlaps	*T*, ahead-overlaps *S*, overlaps	*T*, ahead-disjoint *S*, overlaps
WS-B2	*T*, after-disjoint *S*, overlaps	*T*, after-disjoint *S*, overlaps	*T*, after-overlaps *S*, overlaps	*T*, ahead-overlaps *S*, overlaps
PS-B	*T*, after-disjoint *S*, disjoint	*T*, after-disjoint *S*, disjoint	*T*, after-disjoint *S*, disjoint	*T*, after-covered by *S*, disjoint

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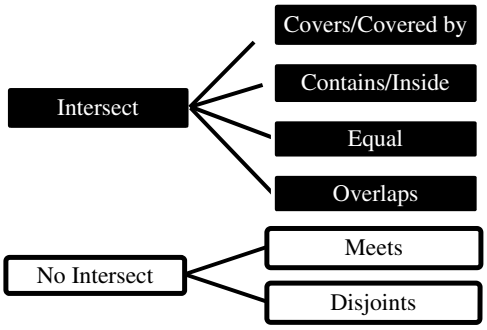

Fig. 4. Categorizing configurations for space-time conflict detection

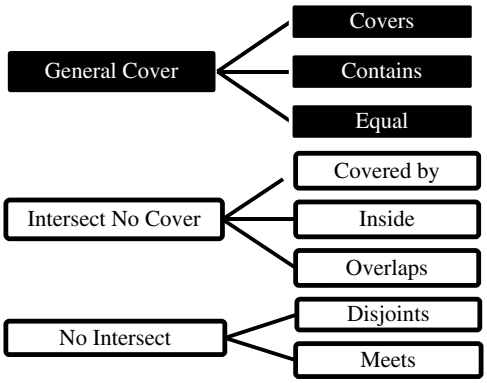

Fig. 5. Categorizing configurations for crane working range testing

configuration is represented by a value of weight as an element in the spatial or temporal matrix, (2) the second step calculates a basic 4D topological matrix by conducting an entrywise product upon the spatial matrix and the temporal matrix, and (3) the last step integrates space criticality information into the basic 4D topological matrix by conducting another entrywise product upon the 4D topological matrix and a space criticality matrix. The space criticality matrix is formed by the space criticality values of the space components.

In general, for Activities A and B, their spatial matrix is represented as

$$\begin{bmatrix} S_{SA1} \cap S_{SB1} & S_{SA2} \cap S_{SB1} & \dots & S_{\mathrm{SAn}} \cap S_{SB1} \\ S_{SA1} \cap S_{SB2} & S_{SA2} \cap S_{SB2} & \dots & S_{\mathrm{SAn}} \cap S_{SB2} \\ \dots & \dots & \dots & \dots \\ S_{SA1} \cap S_{\mathrm{SBm}} & S_{SA2} \cap S_{\mathrm{SBm}} & \dots & S_{\mathrm{SAn}} \cap S_{\mathrm{SBm}} \end{bmatrix} \tag{2}$$

Their temporal matrix is represented as

$$\begin{bmatrix} T_{SA1} \cap T_{SB1} & T_{SA2} \cap T_{SB1} & \dots & T_{\mathrm{SAn}} \cap T_{SB1} \\ T_{SA1} \cap T_{SB2} & T_{SA2} \cap T_{SB2} & \dots & T_{\mathrm{SAn}} \cap T_{SB2} \\ \dots & \dots & \dots & \dots \\ T_{SA1} \cap T_{\mathrm{SBm}} & T_{SA2} \cap T_{\mathrm{SBm}} & \dots & T_{\mathrm{SAn}} \cap T_{\mathrm{SBm}} \end{bmatrix} \tag{3}$$

The 4D topological matrix is their entrywise product

$$(3.1)°(3.2) \tag{4}$$

where SAn represents Activity A's space component n, and SBm represents Activity B's space component m.

Taking the case in Fig. 3 as an example, the 4D topological matrix is formed by applying the template of space-time conflict detection.

The spatial matrix is

$$\begin{bmatrix} S_{WSB1} \cap S_{WSA1} & S_{WSB1} \cap S_{WSA2} & S_{WSB1} \cap S_{WSA3} & S_{WSB1} \cap S_{\mathrm{PSA}} \\ S_{WSB2} \cap S_{WSA1} & S_{WSA1} \cap S_{WSA2} & S_{WSA2} \cap S_{WSA3} & S_{\mathrm{PSA}} \cap S_{\mathrm{PSA}} \\ S_{\mathrm{PSB}} \cap S_{WSA1} & S_{\mathrm{PSB}} \cap S_{WSA2} & S_{\mathrm{PSB}} \cap S_{WSA3} & S_{\mathrm{PSB}} \cap S_{\mathrm{PSA}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

The temporal matrix is

$$\begin{bmatrix} T_{WSB1} \cap T_{WSA1} & T_{WSB1} \cap T_{WSA2} & T_{WSB1} \cap T_{WSA3} & T_{WSB1} \cap T_{\mathrm{PSA}} \\ T_{WSB2} \cap T_{WSA1} & T_{WSA1} \cap T_{WSA2} & T_{WSA2} \cap T_{WSA3} & T_{\mathrm{PSA}} \cap T_{\mathrm{PSA}} \\ T_{\mathrm{PSB}} \cap T_{WSA1} & T_{\mathrm{PSB}} \cap T_{WSA2} & T_{\mathrm{PSB}} \cap T_{WSA3} & T_{\mathrm{PSB}} \cap T_{\mathrm{PSA}} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

The 4D topological matrix is

$$(3.1)°(3.2) = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

In Eq. (7), the element value 1 indicates there is a space-time conflict; the position of the element value 1 reveals what are the problematic space components.

Therefore, the last step of integrating space criticality information. This illustrating example employs a space taxonomy that includes two levels, as follows: (1) workspace, and (2) product space. The combination of the two levels generates three levels of space criticality, as follows: (1) a low level from workspace versus workspace, (2) an intermediate level from workspace versus product space, and (3) a high level from product space versus product space. Referring to Eqs. (5) and (6) in the example of Fig. 3, the related spaces are

$$\begin{bmatrix} WSA1 & WSA2 & WSA3 & PSA \\ WSA1 & WSA2 & WSA3 & PSA \\ WSA1 & WSA2 & WSA3 & PSA \end{bmatrix} \tag{8}$$

for Activity A and

$$\begin{bmatrix} WSB1 & WSB1 & WSB1 & WSB1 \\ WSB2 & WSB2 & WSB2 & WSB2 \\ PSB & PSB & PSB & PSB \end{bmatrix} \tag{9}$$

for Activity B. Based on the criticality levels of the spaces, the space criticality matrices are

$$\begin{bmatrix} 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \end{bmatrix} \tag{10}$$

for Activity A and

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 2 & 2 & 2 & 2 \end{bmatrix} \tag{11}$$

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for Activity B. In Eqs. (10) and (11), the product spaces are assigned a higher space criticality value of 2, while the workspaces have a value of 1. The space criticality matrix is obtained by conducting entrywise product on the two space criticality matrices

$$\begin{bmatrix} 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \end{bmatrix} \circ \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 2 & 2 & 2 & 2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 2 & 2 & 2 & 4 \end{bmatrix} \tag{12}$$

Each element of the resulting space criticality matrix [Eq. (12)] indicates a critical level of the space relationship that occurs between the related spaces. The value of 1 marks a low critical level that involves two workspaces. The value of 2 implies a high level that a product space and a workspace are involved. The value of 4 indicates an unacceptable design error that two products overlap. The space criticality values of 1 and 2 are arbitrarily set up in this paper to just illustrate the concept. In case a more complex space taxonomy is used, the space criticality values must be carefully designed.

The final 4D topological matrix for the example becomes Eq. (7) ° Eq. (12)

$$\begin{bmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \circ \begin{bmatrix} 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 2 & 2 & 2 & 4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 2 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{13}$$

Four-Dimensional Topological Matrix Translation

The final 4D topological matrix carries information of not only the conflicted space components but also their space types and criticality levels. The information can be translated into construction terms based on the task template and the matrix value. For instance, Eq. (13) applies the template of space-time conflict detection, and the following result can be derived according to the value and location of the nonzero element:

- Workspace congestion with low critical level by WSA2 and WSB1,
- Workspace congestion with low critical level by WSA3 and WSB1,
- Workspace congestion with low critical level by WSA3 and WSB2, and
- Conflict with high critical level by PSA and WSB2.

The previous information reveals the schedule has three workspace congestions and a critical workspace-product conflict, although the planner has realized the possibility of conflict and scheduled the two construction activities to start at different time. The workspace congestion situation may affect site productivity and safety, and the workspace-product conflict may even damage the building product. Such information will help the construction planner to prioritize the problems and take proper actions. The critical conflict requires immediate attention in planning and the workspace congestion situation, if inevitable, needs special site coordinating effort.

In summary, the construction 4D topology framework offers an efficient and flexible way to assist in construction planning by defining task templates using topology categorization. Without this rigorous topological framework to formally categorize and identify conflicts, the schedule problems will easily be missed. In addition, a template can be customized or combined with other templates to accommodate for more complicated task requirements, besides the basic template such as the one for space time conflict detection.

Implementation and Validation

The construction 4D topology framework is tested on a parking garage construction project on the Purdue University campus in Indiana (Fig. 6). It is a typical garage construction project with both concreting and prefabricated installation activities. The actual project was completed years ago, but the writers have collected all the construction planning related information (2D drawings, schedules, and site plans) and created a 4D model to validate the presented method. The 3D model of the garage in Fig. 6 is newly created, based on the 2D drawings, in a multipatch format (a typical boundary representation format) and stored in a geodatabase as the input for 4D modeling.

Four-Dimensional Model Creation

The 4D building model was created in a graphical planning system using a lifecycle workspace approach and a graphical planning method. The graphical planning system is an add-in built upon *ArcGIS 10.0* as a prototype that integrates 4D modeling and the 4D topological analysis functions. Fig. 7 displays the graphical user interface of the prototype that comprised of three parts, as follows: (1) a model viewer shows the 3D model, (2) a CPM canvas allows users to create a CPM network, and (3) an activity info window provides detailed information of each construction activity.

The prototype takes the 3D building model as input and with the 3D building model displayed in the model viewer users can create nodes of construction activity that are linked to the 3D model

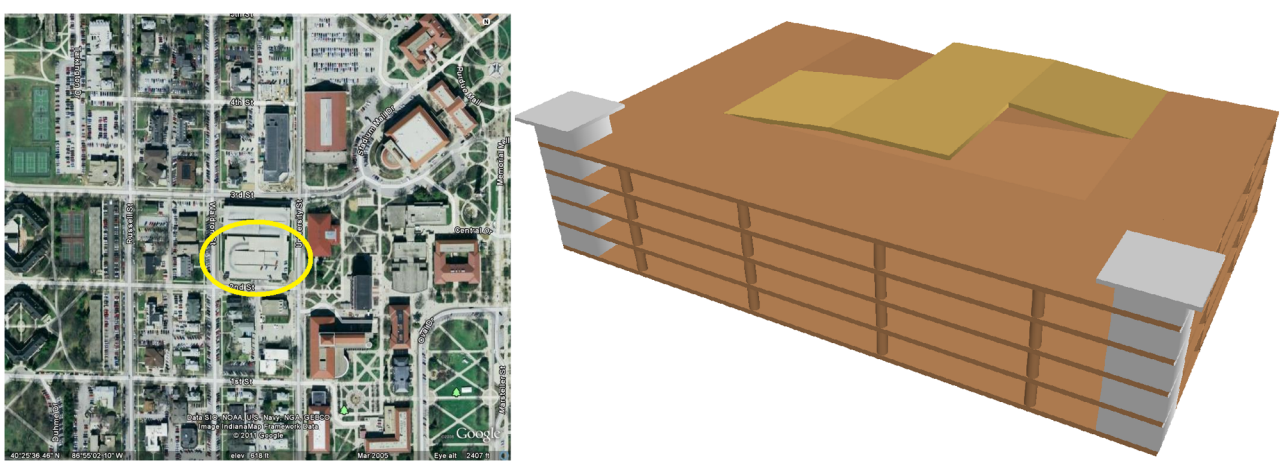

Fig. 6. Garage project model (map data © Google, Data SIO, U.S. Navy, NGA, GEBCO, image IndianaMap framework data)

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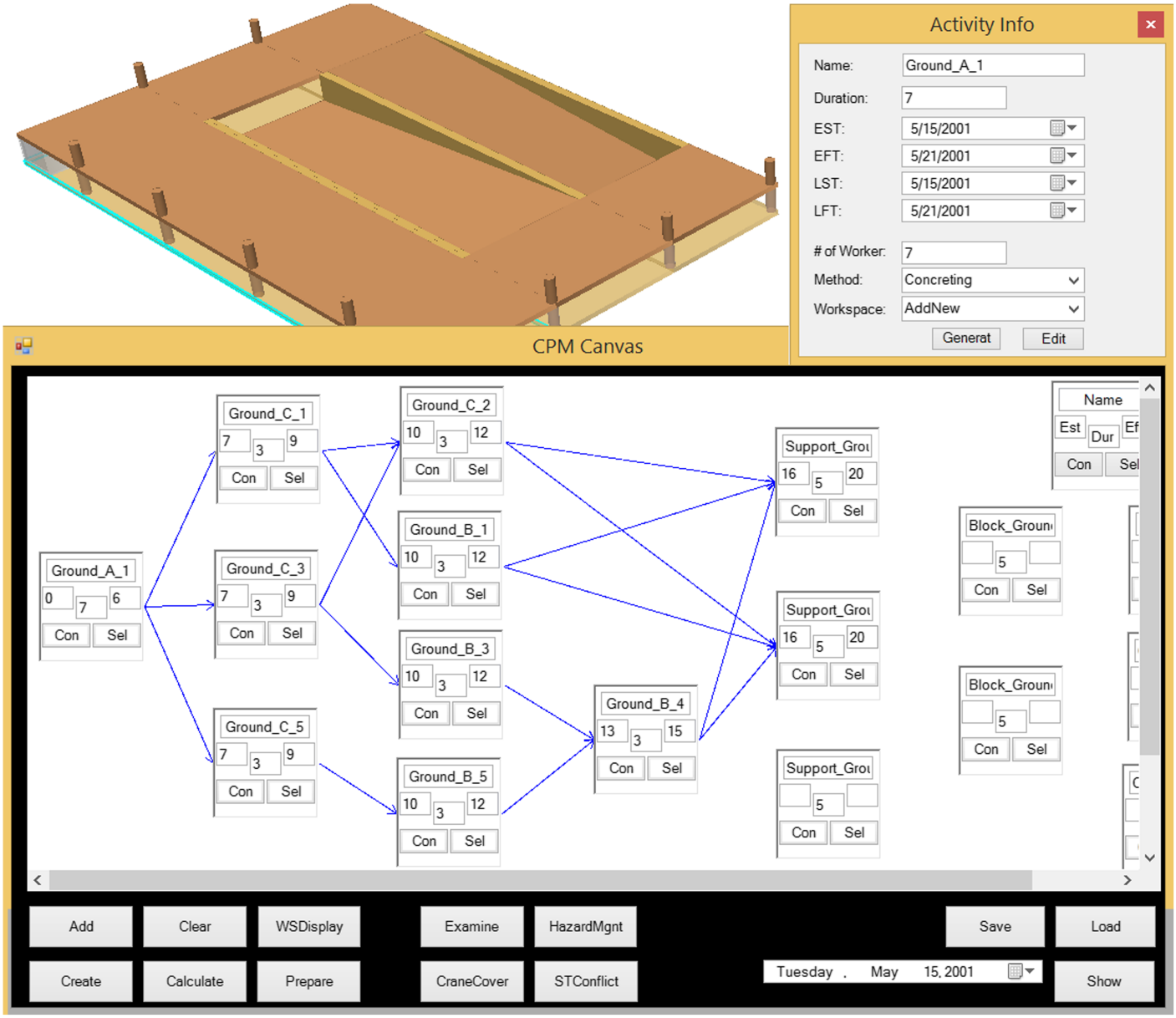

Fig. 7. Prototype screenshot

components on the CPM canvas. The 4D model was created by arranging and connecting the nodes of construction activity to form a CPM network. Workspaces of labors and equipment were also generated semiautomatically during this process, with the help of a construction professional who provides valuable information to estimate workspace dimension. With the duration of each activity and the CPM network, the temporal attributes (the start time and finish time) of each activity were calculated. The resulting 4D model has 87 construction activities with 195 space components. More details of the model creation process can be found in Su and Cai (2014a).

Task Templates and 4D Topological Analysis

This implementation test performed three tasks, as follows: (1) workspace conflict detection, (2) crane cover range test, and (3) crane's dangerous/hazardous zone management. Three modules with different task templates were devised accordingly and several planning problems were identified during the test, benefiting from the capability of 4D topological analysis. The three tools can be found on the tools panel under the CPM Canvas in Fig. 7, as follows: (1) STConflict, (2) CraneCover, and (3) HazardMgnt. Users can perform the analyses by simply clicking the button.

Space-Time Conflict Detection

The template for workspace conflict detection adopts the basic configuration illustrated in Fig. 4. The prototype identified some space-time conflicts after all the main activities have been scheduled. One of them is a conflict caused by activities of a column construction and an elevator shaft construction as shown in Fig. 8.

The excerpt of the log file that records the conflict is displayed as presented next.

Analysis finished at: 16:28, September 11th, 2014
Activity 1: Block_Second_1
Workspace_1 ID: 67
Activity 2: Col_Second_A
Workspace_1 ID: 69

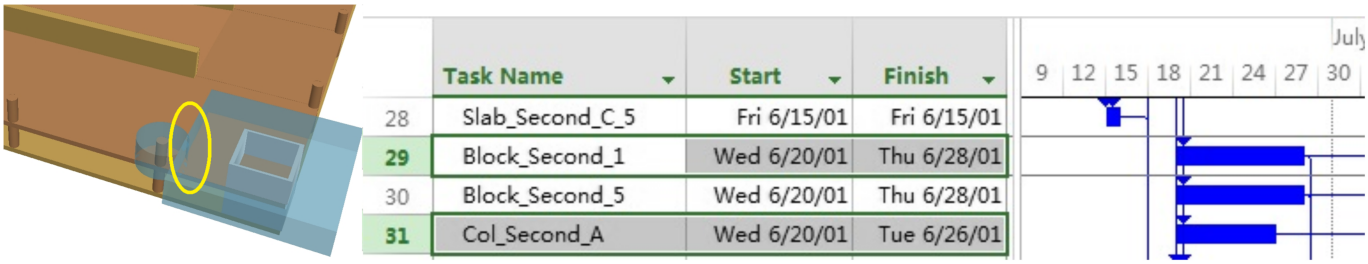

Fig. 8. Workspace conflict case

Conflict Type: workspace * workspace
Recommended Solutions:
Activities on the critical path. Adjust workspace (67), workspace (69)

This excerpt generally describes the space-time conflict. First, the name of the involved activities and their problematic space components are listed. Second, recommended solutions are provided. Because it is extremely difficult to automatically solve the conflicts and identify the optimum schedule, this system adopts an intermediate way to alleviate the problem. It first check whether there are any free slack or total slack for the related activities. Information will be given such as recommended solutions, total float of Activity 1 (Slab_Ground_C_2), 3 days, if there are any. If not, it means the activities are all on the critical path and recommendation to adjust workspaces is given as shown in this case.

It followed a detailed examination of the problematic activities. It first identified the two activities, then examined all pairs of their space components, and at last output the result in a log file. The log file information of the previous case is given describing the conflict type and the workspace details. In the meanwhile, the conflicted workspace components are highlighted in the model viewer, as presented next.

Analysis finished at: 17:01, September 11th, 2014
Workspace congestion by Workspace (67) and Workspace (69)
Activity 1: Block_Second_1
Workspace (67) ST: Day (36) Wed 06/20/2001
Workspace (67) FT: Day (42) Thu 06/28/2001
Activity 2: Col_Second_A
Workspace (69) ST: Day (36) Wed 06/20/2001
Workspace (69) ST: Day (40) Tue 06/26/2001

This case illustrates the utilization of a basic task template to help construction planners identify space time conflict. This module is able to conduct a general detection on all activities as well as a specific examination on a focused group of activities.

Crane Cover Range Test

Another problem encountered during planning is the selection of cranes. In the preconstruction planning phase in which this prototype is utilized, the crane's type and rough location must be determined, although it may not be practical to plan its detailed schedule. This module is designed for this purpose and provides convenient ways to create, visualize, and analyze a crane's workspaces.

The crane's workspace is created by specifying its maximum and minimum working range, and an example is displayed in Fig. 9. The crane is planned to assist in construction of the columns and the side slabs (scaffold is considered as part of the slabs' workspaces in this case). It will be ideal if a location can be found for the selected type of crane to cover all the targeted activities without moving.

The crane's cover range test module adopts the task template in Fig. 5 and facilitates this work by listing all construction activities in the groups of general cover, intersect no cover, and no intersect. The log file from the analysis shows that only the eight middle columns in Fig. 9 were 4D covered by the crane's workspace, but all the side slabs and four side columns were in the intersect no-cover group. This log file indicates that on one hand the crane in Fig. 9 does not fully cover the target area, and on the other hand the crane's working range has already intersected with most of the target areas. Such a result implies that all the target areas may be covered by slightly moving the crane. The problem is eventually addressed by separating the crane activity into two at different locations and durations. The combined workspace of the two crane activities covers the whole target areas.

Crane Work Zone Management

A practical problem during a crane's operation is to make sure there is no ongoing activity in the restricted area below the lift. The crane work zone management module adopts a customized and combined task template aiming to address the problem. In this task template, the spatial configurations and temporal configurations use different categorization criteria. First, all the activities must have space components intersect with the crane's workspace; and second, the space components must intersect with each other temporally. Such a template will identify all activities within the crane's cover range and with working time overlaps. Mathematically, the analysis is enabled in two steps, as follows: (1) selects the activities that have space components intersect with the crane's workspace, and (2) examines the candidate activities' temporal matrix and list those with temporal intersects in the same group.

The log file lists 21 groups of activity that meet the requirements of the task template; however, many of the activities in each group are on the same floor, similar with the situation shown in Fig. 8. The result activities yield to potential dangerous of contacting with the crane lift but further identification about what activities are in the dangerous zone below the lift cannot be achieved. The analysis

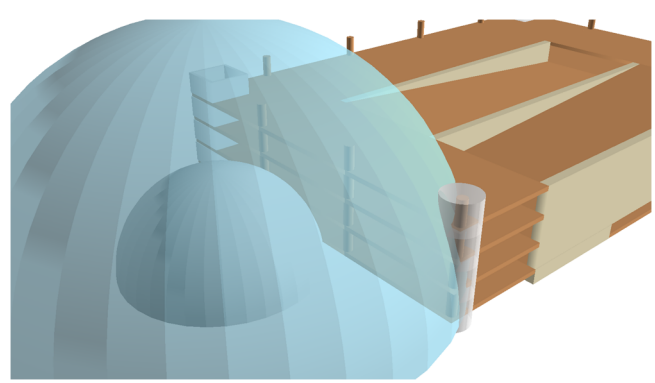

Fig. 9. Crane workspace case

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reveals a limitation of the prototype that the capability of directional analysis is missing. Without directional information, the task template that only focuses on topological relationship is not able to recognize the relationship of below or above.

Conclusions and Discussions

This paper presents a construction 4D topology framework and demonstrates its effectiveness in analyzing 4D topological relationships between construction activities to aid construction planning. The construction 4D topology framework provides a formal approach to define spatial-temporal relationships between construction activities and enables 4D topological analytics to scrutinize construction site dynamic interactions. By investigating and abstracting the nature of requirements of space-time related construction planning tasks, the framework provides a fundamental knowledge that is able to formalize requirements of a space-time related construction planning task into a template for analysis. A prototype is tested and evidences the 4D topological analysis capability of the framework. In general, the test result demonstrates great potential of creating a comprehensive construction planning system that enables a variety of 4D topological analysis functions and, in particular, a GIS-based 4D analysis tool that has a formal approach for 4D topological analysis.

The framework created in the research reported in this paper is an extension of the commonly adopted 3D topology framework. As a result, it has good compatibility in the aspects of geometric representation. Besides the GIS-based platform used to test the implementation case, the framework supports all types of geometric representation as long as the representation format has the capability to conduct 3D topological analysis and capture the eight spatial configurations. There are many published literatures regarding 3D topological analysis for different formats of geometric representation, such as solid modeling (Tilove 1981), CAD-related formats (Hans-Peter et al. 2003), industrial foundation classes (IFCs; Borrmann and Rank 2009), and boundary representation (B-rep; Borrmann et al. 2009; Su and Cai 2014b). These studies provide a solid foundation to implement the proposed framework in other than GIS-based platforms. On the other hand, the writers selected the GIS-based platform for implementation mainly because of the well-developed capability of 3D topological analysis in GIS-based software packages and the tool developed in the prototype proves the capability of the GIS-based platform to perform 4D topological analyses.

Another benefit of the research reported in this paper is that it supports spatial query languages and potentially contributes to the development of 4D query languages. The task template formalized by topology categorization functions as a query criteria and the topology configurations are like pieces of syntax of condition. It is beyond the scope of this paper, as an introduction of a framework, to elaborate all potentially useful templates. Instead, the results of the research reported in this paper contribute to a scientific basis for construction researchers to further investigate how a comprehensive 4D analysis can be achieved and can benefit the construction industry.

As a framework, there are also many limitations found during implementation. Some potential research directions include the integration of directional and metric analysis capability, the integration of complex space taxonomy, and the development of an efficient computational method. Enabling directional and metric analysis will make a remarkable step toward a comprehensive 4D analysis system for construction planning. The spatial relationships can be better described with topological, directional, and metric information.

Integrating space taxonomy will also enhance the framework. Under the pressure of short delivery, today's construction sites are usually crowded and there are always multiple construction activities being conducted at the same time. It is hard to achieve a perfectly conflict-free plan in many cases. Under this circumstance, space taxonomy becomes a critical tool for planners to rank their priority of addressing site conflicts. There are a number of studies have already made tremendous achievements in quantifying and evaluating space critical levels (Winch and North 2006; Chua et al. 2010; Moon et al. 2014). The framework can be enhanced by incorporating the existing method and the numerical matrix representation of the framework has the potential to realize it.

The analysis method of this framework involves a significant amount of computation. At the current stage, the framework employs an Octree-based partitioning method attempting to reduce the computational time. A general space-time conflict detection on all the 87 activities can be completed within 1 min on a regular desktop. However, the efficiency of the partitioning method has not been scientifically verified and there are still spaces to improve it.

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