

# A GRAPHICAL PLANNING METHOD FOR WORKSPACE-AWARE, FOUR-DIMENSIONAL MODELING TO ASSIST EFFECTIVE CONSTRUCTION PLANNING

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**SUMMARY:** *The emerging four-dimensional (4D) modeling techniques have proven benefits to effective construction planning. Still, limitations exist in the lack of an effective approach to support initial construction planning and incorporate workspace modeling in the 4D model development process. This paper presents a graphical planning method (GPM) with workspace representation to overcome the aforementioned limitations. The newly created GPM synergizes the 4D modeling process and the conventional critical path method (CPM) scheduling process with built-in workspace modeling and representation capabilities. The 4D model development process and resulting 4D models are workspace-aware; i.e., construction activities are associated with workspace requirements, and such requirements are explicitly addressed during the modeling process. GPM directly supports the initial planning rather than being just a post-plan review tool. It also forms the base for 4D analytics. By incorporating workspace requirements into the 4D modeling process, GPM is expected to enhance the effectiveness of proactive construction planning.*

**KEYWORDS:** *construction planning, 4D modeling, workspace modeling, graphical planning method*

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## 1. INTRODUCTION

A construction project involves the execution of a large number of tasks to deliver the final product. Construction planning is a fundamental activity that determines the choice of technology, defines work tasks, estimates required resources and durations for individual tasks, and identifies interactions among different work tasks (Hendrickson, 1998). Effective construction planning is critical to the success of construction projects.

A construction project includes a great number of construction activities involving a variety of resources, e.g., equipment, labor, and material. Construction activities have varying space requirements and construction duration, and interact with each other in a complex manner under a constrained space in a limited time period (Akinci et al., 2002a). Inadequate workspace planning may result in space-time conflicts that adversely affect construction productivity and site safety. Sanders et al. (Sanders et al., 1989) reported that congested workspaces and restricted access on site cause construction efficiency losses of up to 65% and 58%, respectively. Incorporating workspace consideration at the planning phase has become one of the key factors to project success and drawn significant attention from researchers. Akinci et al. (2002b) pointed out that space-time conflicts majorly hinder the performance of interfering activities. Chavada et al. (2012) highlighted the effect of activity workspace management on construction productivity and site safety issues.

Conventional planning methods such as Gantt charts, network diagrams, and Critical Path Method (CPM) lack consideration of the space needs. Time is treated as the main constraint, while space limitation and spatial-temporal conflicts are minimally incorporated. In addition, these methods lack effective means of representation and communication of workspace interferences between construction activities (Mallasi, 2006). It has been criticized that the heavy reliance on these methods has caused the planning process being seen as one-dimensional (Heesom and Mahdjoubi, 2004).

Construction four-dimensional (4D) models have emerged as a more effective tool for construction planning and control. The 4D environment integrates traditional planning aids such as two-dimensional/three-dimensional (2D/3D) drawings and CPM schedules (Mahalingam et al., 2010). It has great potential in addressing the spatial-temporal nature of construction planning challenges (Fisher and Kam, 2001). By considering both space and time together, 4D models lay a solid foundation in modeling the dynamic construction site and addressing space-time conflict problems. The early 4D modeling techniques typically combined a 3D computer-aided design (CAD) model and a one-dimensional project schedule to animate project progress graphically over time (Collier and Fischer, 1996). The resulting 4D models can display the construction sequence of activities with 3D graphics over time, functioning as an explanative communication tool that visually describes the design and construction operations (Liston et al., 2001).

Efforts were made recently to investigate other planning dimensions and to integrate them into 4D models to form information-rich 4D models or nD models (Chavada et al., 2012; Zhang and Hu, 2011). The nD modeling usually adopts Building Information Modeling (BIM) to distribute and manage semantic attributes such as labor, equipment, and cost, illustrating its potential to advance 4D models into a more comprehensive and intelligent system for construction planning. The effectiveness of construction 4D models has been evaluated within different educational and industrial settings (e.g. Mahalingam et al., 2010; Whisker et al., 2003; Pikas et al., 2013). Positive attitudes were received from many researchers and practitioners toward the development and application of 4D technologies in construction (Fischer and Kunz, 2004; Hartmann et al., 2008).

Despite the proven benefits and demonstrated potential, to date, 4D technology is not accepted on a large scale in construction management (Hartmann et al., 2008). Hartmann et al. (2008) investigated 26 cases of 3D/4D model technology implementation on construction projects. The cases revealed that engineers mainly use 3D/4D models for virtually reviewing the design of the facility, but rarely for any operation and performance analysis. Two knowledge gaps of the current construction 4D modeling technique were identified here that at least partially contribute to this scenario: (1) it lacks an effective 4D model development approach to support initial planning; and (2) it lacks a convenient approach to incorporate workspace requirements and representation into the 4D modeling process for construction analysis.

Motivated by the knowledge gaps, this paper proposes a workspace-aware Graphical Planning Method (GPM). GPM takes a 3D building model as the input, represents each construction activity related to the model as an activity node on a canvas, and generates a construction schedule by connecting the nodes to form a CPM network. The 3D building model is a semantically rich digital building model that carries basic building information. During the scheduling process, workspace of each construction activity can be conveniently created. With the assistance

of GPM, construction planners can create a workspace-aware 4D model and a schedule together without additional effort. This paper first describes related studies and then present the research contributions. Following research contributions, the method in detail is explained, including its data structure, graphical user interface, and modeling mechanism. Next, the prototype developed in this study is introduced and tested in an implementation case. At last the paper is concluded with a summary of the study, presentation of research findings/conclusions, and discussion of future research directions.

## 2. RELATED STUDIES

A *manual linking* approach is currently the most widely applied approach to create 4D models in practice (Zhou et al., 2009). The following is an example of a typical early construction scheduling and 4D model development process: first, a 2D drawing/3D model is developed early in the project design phase; next, the whole project is divided into individual activities and the baseline construction schedules are created; then, a 4D model is created by manually linking the schedule with the 3D model elements optionally through a third party software tool (Collier and Fischer, 1996; Zhou et al., 2009). Such a *manual linking* approach is widely applied and almost all commercial 4D solutions adopt this technique. However, this 4D approach considers 4D modeling and scheduling as independent processes, which results in significant deficiencies in construction planning and model development.

First, there is limited support provided to assist in the scheduling process, consequently it places a heavy burden on construction planners to mentally model the construction process over time (Heesom and Mahdjoubi, 2004). In addition, workspace is not modeled or represented during scheduling, which eliminates the possibility of automatic workspace conflict detection (Chavada et al., 2012). As a result, the 4D model created in this way serves only as a post-planning review tool without workspace consideration, providing no assistance to the initial planning. Furthermore, extensive human recognition and manual operation are required to link a huge number of building elements with their schedules for large scale construction projects, which could be error prone and time consuming (de Vries and Harink, 2007). Because workspaces are not considered during the 4D model development phase, additional efforts are needed to add workspace information to the 4D model. By this time, however, the baseline construction schedule and many other derived plans have already been completed; thus, the newly generated workspace information that could have substantially benefited the initial planning has missed the most important period to do so (Su and Cai, 2014). Recognizing the limitations in the *manual linking* approach, a number of studies have been conducted to facilitate/automate the development of construction 4D models. Dawood et al. (2005) proposed Unified Classification Methods to enable semi-automatic linkage between a 3D model and a schedule, implemented in the industrial environment. A 4D simulation can be created on an AutoCAD platform by retrieving data from a central database automatically. This method improves the linking process, but still requires a schedule and a 3D model as the input.

deVries and Harink (2007) proposed an *automatic approach* for construction planning by taking a 3D model as the input and analyzing the spatial topology among the model elements. This fully automated process completely frees the user from the burden of manual linking; however, it lacks user-system interaction and the ability to provide flexible problem solutions. When the topology rule needs to be overridden by some specific construction rules, this method may not provide appropriate results. In other words, the fully automated process makes planning a close-ended operation, therefore eliminating the possibility for the system to interact with human professionals for creative problem solving. For example, workspace conflict may occur if two columns close to each other are built at the same time, but no problem can be found in such a schedule if only building product topology is considered. Consequently, workspace conflict and constructability issues may frequently happen even if the construction sequence satisfies all topological rules.

This example also reveals an important limitation in the current practice of 4D construction modeling: workspace modeling and representation approaches are missing during the 4D modeling process. Workspaces are key resources required by construction activities, and identifying workspaces is one of the main construction planning tasks (Zhou et al., 2009). Currently, a common practice is to create a 4D digital building model without considering workspaces and then “adding” necessary workspace information to the model to make it workspace-aware. Representative works include, but are not limited to, Akinci et al.’s (2002a, c) space-loaded 4D product model, Mallasi’s (2006) Patterns Execution and Critical Analysis of Site-space Organization (PECASO), and Chavada et al.’s (2012) Activity Execution Workspace (AEW) integrated nD planning tool. These workspace-aware 4D models enable explicit workspace representation, thus significantly facilitating workspace identification and conflict detection. However, the workspace modeling process occurs after the 4D building model has been created,

providing no assistance to the initial planning. The workspace-aware 4D model, created in such a way with great effort, still only serves as a post-plan review tool.

Waly and Thabet (2003) proposed a framework of Virtual Construction Environment (VCE) as a *manual assembly* approach for 4D modeling. The proposed framework semi-automates the scheduling process at the design phase by re-assembling a 3D CAD model using drag and drop operations. The sequence of dragging and dropping determines the temporal relationship among the activities. The user is responsible for specifying concurrency, lags, and other relationships between activities. Analyzing the 3D model's repositioning and user operations leads to a 4D model. This *manual assembly* approach improves the automation of construction 4D modeling and provides a convenient 4D environment for the user to mentally identify workspaces. More importantly, it shifts the paradigm of 4D modeling from a linking process based on the input of a 3D model and a schedule to a 4D modeling-scheduling integrated process that generates a 4D model as well as a schedule from a 3D model. In this way, the 4D modeling process directly supports the initial planning to generate a baseline schedule.

However, limitations still exist in aspects of compatibility and workspace incorporation. The way of creating construction schedules using VCE is different from other traditional construction scheduling methods. It relies on a set of complex modules to translate the user's input and the dragging and dropping of operations into a construction schedule in a readable format (i.e. CPM diagram). This makes it difficult for task distribution and collaboration. In addition, workspace is not explicitly modeled and represented. Although workspace identification and conflict detection can be conducted in a comparatively convenient 3D environment, VCE still relies on a planner's mental process, eliminating the possibility of automatic space-time conflict detection.

### 3. RESEARCH CONTRIBUTIONS

The research contributes to construction 4D modeling in aspects of model development and workspace incorporation. Particular contributions include:

- (1) A CPM based graphical planning concept that improves the construction 4D modeling method by synergizing 4D modeling with the CPM scheduling process. This concept will extensively save modeling effort while still allow user-system interaction for creative problem solving. The CPM format is compatible with most of the mainstream scheduling software packages. The modeling process not only creates a 4D model as a communication or demonstration tool for post-plan reviewing, but also supports scheduling and potentially 4D analysis.
- (2) A 4D modeling method that incorporates workspace modeling at the planning phase. The timing of workspace modeling using this method further enhances the assistance to initial planning. The resulting 4D model is workspace-aware and each workspace has both spatial and temporal attributes. It enables dynamic visualization of the construction progress, thus releasing construction planners from the heavy mental burden of simulating the space usage of construction activities during initial planning.

### 4. THE GRAPHICAL PLANNING METHOD (GPM)

This section describes the technical details of GPM, including its data structure, system components, and workflow, that interactively create workspace-aware construction 4D models.

#### 4.1. Data structure

This study adopts a flexible data structure presented in (Su and Cai, 2014). As shown in Fig. 1, Activity is the root level class that represents construction activities, Workspace is the class to represent the workspace required by an activity, and Prodspace is the class to represent the space occupied by the product/building element created by an activity. In reality, a construction activity requires labor/equipment workspace to build a final product/building element. Accordingly, an Activity object is composed of at least one Workspace object and zero or one Prodspace object. An activity is allowed to have multiple workspaces because the workspace requirement of a construction activity may change over time. For example, a slab concreting activity can be roughly divided into four phases: formwork assembly, pouring concrete, curing, and formwork stripping. Each of those phases has different workspace requirements. An activity is also allowed to have no product space to accommodate activities that do not produce a final product, such as activities of temporary facilities and equipment. Each workspace (Workspace in Fig. 1) or product space (Prodspace in Fig. 1) has a "Shape" attribute to represent the geometry of its space requirement and temporal attributes "EST" (Earliest Start Time), "EFT" (Earliest Finish Time), "LST" (Latest Start Time), and "LFT" (Latest Finish Time) to specify its time of schedule. The temporal attributes of an Activity object and its Workspace and Prodspace objects are closed linked with each other. For example, an Activity

object's EST is equal to its first Workspace object's EST; its Prodspace object's EST is equal to its last Workspace object's EFT; and its EFT is equal to its Prodspace object's EFT.

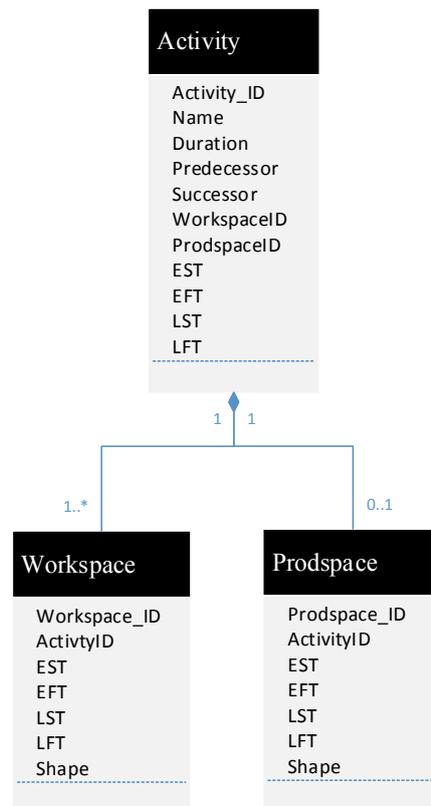


Figure 1. GPM data structure

Fig. 1 lists all necessary attributes of the classes. More attributes can be incorporated for different construction planning purposes, such as “construction method” for Activity, “Number of worker” for Workspace and “Material” for Prodspace. The composition relationship between Activity and Workspace/Prodspace indicates a strong association relationship. If an Activity is deleted, all its Workspaces and Prodspace will be deleted.

In summary, an Activity object represents a construction activity that may have different space requirements over time. This space change is represented by having one or more Workspace objects and none or one Prodspace object. A Workspace object has an unchanging space shape that only exists on site during a certain time period specified in its temporal attributes, so is a Prodspace object. GPM employs this structure and uses it as a basis for developing user interface and modeling mechanisms.

## 4.2. System Components

The newly created GPM has a Graphical User Interface (GUI) to serve as an interactive platform between the user and the system. This GUI is a reflection of the system components: a model viewer (A in Fig. 2) to display and navigate through a 3D model, a CPM canvas (B in Fig. 2) for the user to arrange and connect all CPM nodes, an activity info window (C in Fig. 2) for the user to edit construction activity information and customize workspaces, and a tools panel (D in Fig. 2) for the user to develop, visualize, and analyze workspace-aware construction 4D models.

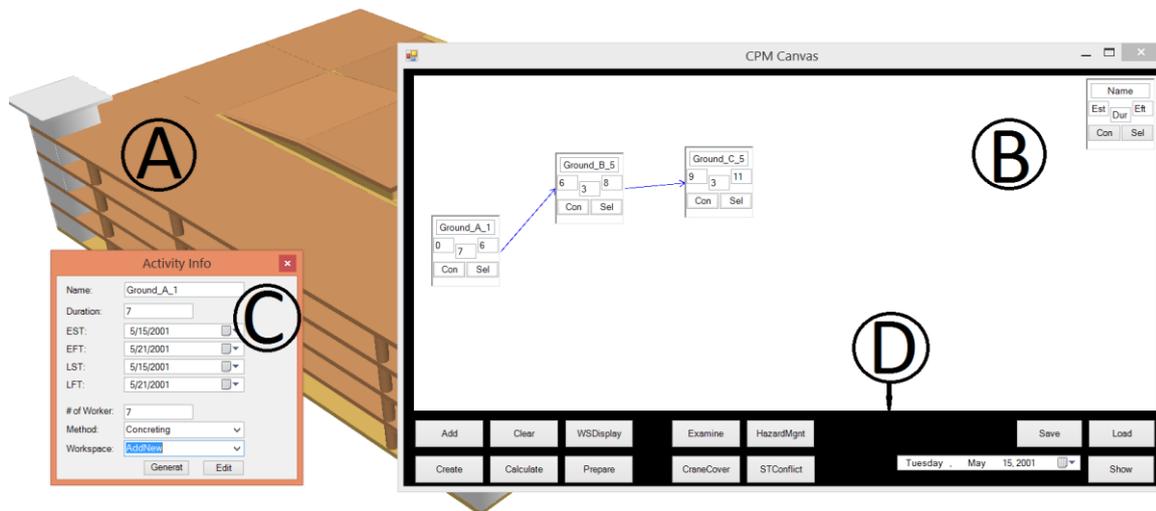


Figure 2. GPM system structure and user interface

### (A) Model viewer

The model viewer in Fig. 2 displays the main structure of a multi-floor garage building as an example. Model elements in the model viewer can have one of three visual statuses: solid, transparent, or invisible. During the model development process, all building elements start as solid geometries to indicate that they have not yet been incorporated in the schedule on the canvas (B). A building element becomes transparent when it appears as an activity node on the canvas. The differentiation between the solid and transparent visual statuses during the model development process serves as a reminder so that 1) no building element is left out in the schedule; and 2) no building element will be counted twice or more in the schedule. All workspaces are represented as transparent geometries, but in a different transparency percentage. Model elements can also be hidden to facilitate visualization and operation. During the model analysis and 4D animation processes, a building element is invisible prior to its construction, becomes a transparent workspace during construction, and is solid once its construction is complete.

### (B) CPM canvas

The CPM canvas contains CPM nodes that represent construction activities. The name of a construction activity is shown on the top of the node. The three numbers from left to right on a CPM node indicate the construction activity's EST, duration, and EFT. A sample node in the right upper corner presents the information as a reminder. The "Con" (Connecting) tool creates predecessor-successor constraints between two activities, represented by arrows connecting CPM nodes. When two CPM nodes are connected by "Con", the successor, which is an *Activity* object, will record its predecessor's *Activity\_ID* in the attribute "Predecessor", and vice versa. The EST and EFT of the CPM node that is newly added to the CPM network will be calculated and displayed. The "Sel" (selecting) tool triggers a pop-up dockable window (C in Fig. 2) that lists detailed information about the corresponding construction activity.

### (C) Activity information window

The activity information window displays an activity's name, duration, temporal attributes, assigned number of workers, related construction method, and workspace components. The workspace dropdown list is the key to create and manage workspace components. In the dropdown list, there is an item of "AddNew" beside all the existing workspace components. The "Generate" tool can be used to create a new workspace component when the "AddNew" item is selected. A *Workspace* object is created and associated with its corresponding *Activity* object. The *Activity* object's *Activity\_ID* is recorded in the *Workspace* object's attribute "Activity" and all *Workspace* objects associated with the *Activity* object are reordered chronologically so that the workspace dropdown list of an activity displays workspace components in the correct order. The "Edit" tool allows users to manually customize an existing workspace shape when the workspace component is selected in the dropdown list.

Another window for workspace creation (left picture in Fig. 3) will pop up when the "Generate" tool is used. Workspaces can be either derived from the input model elements or newly created. The "DERIVING" option offers two methods: "Offset" and "Rotate", while the "NEW CREATING" option offers methods to create new types of geometry: block, sphere, and column (right pictures in Fig. 3). The generated workspaces will be listed in

the workspace dropdown list on the dockable window following a time sequence. Utilizing the provided tools, workspaces of each activity can be created and customized to follow an evolution pattern that more realistically reflects the dynamic site space usage.

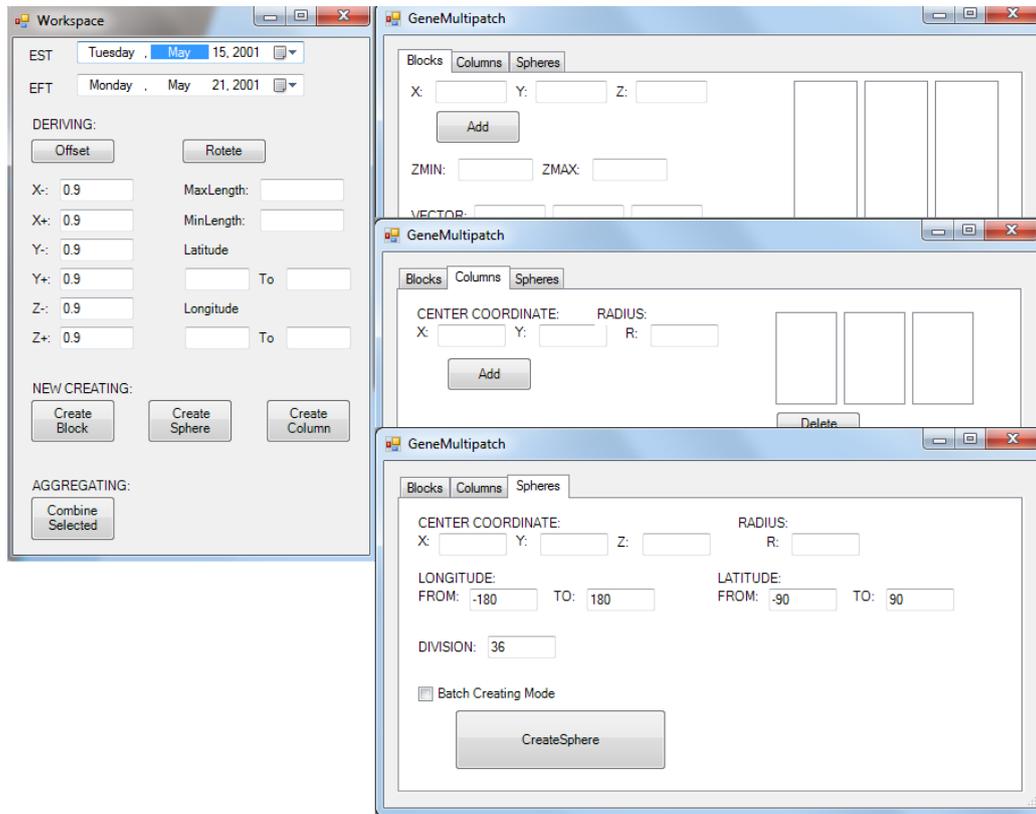


Figure 3. Graphical user interface for workspace generating

An advantage of this method exists in the timing to incorporate workspace modeling. Different from the common practice that first creates a building model and then adds workspace information to make the model workspace-aware, this method enables workspace modeling at the scheduling phase and provides visual assistance. Although estimating workspaces at the pre-construction planning phase is a challenging task, many studies have been conducted in the area and made great achievements. These studies provide insightful guidance and solid foundation to implement the presented method in practice. The details of the workspace modeling method adopted in this study can be found in (Su and Cai, 2014). Other research works of workspace modeling include but not limited to: Akinci et al.'s (2002a, c) space-loaded 4D product model, Mallasi's (2006) Approximation Envelope approach, and Kim and Teizer's (2014) geometry interpretation approach for scaffolding systems.

#### (D) Tools panel

The tools panel is located under the CPM canvas. It hosts a number of tools to assist the user in developing, analyzing, and visualizing workspace-aware 4D construction models. The tools can be categorized into three groups: model development, model analysis, and model visualization.

The model development group contains six tools on the left side: Add, Create, Clear, Calculate, WSDisplay, and Prepare. The "Add" and "Create" tool will create an *Activity* object that is displayed as CPM nodes on the CPM canvas. If "Add" is used, a *Prodspace* object for the related building product will also be created and stored by the *Activity* object's attribute "Prodspace". The created *Activity* objects can be deleted individually or in batch using the "Clear" tool. Each *Activity* object's EST and EFT are calculated as the CPM nodes are connected. The button "Calculate" is used to compute LST and LFT when the CPM network is completely or partially finished. Those time attributes are recorded, but only the EST and EFT are displayed on each CPM node. The "Activity Info" panel lists all the time attributes. The WSDisplay tool can toggle on or off the visibility of workspaces in the model viewer. The "Prepare" tool is used after the model has been completed to generate a 1D schedule and a product

animation. It triggers a process that goes through all *activity* instances and writes their attributes in a format compatible with other 1D scheduling software packages (e.g. Microsoft Project).

The model analysis group in the middle leaves interfaces with multiple tools of 4D analysis for future extension. The model visualization group on the right side contains a date selecting tool and a Show button. It allows users to view a dynamic construction progress drawing at any specified time point in the date selecting tool. The dynamic construction progress drawing displays the completed building part by solid shapes and the in-progress part by transparent workspaces.

### 4.3. The GPM Modeling Procedure

This section describes the procedure in creating workspace-aware construction 4D models via GPM. The main input needed is a semantically rich digital building model with the information of duration to construct each building element. Building information such as construction method or material for each building element can provide more assistance and facilitate the modeling process but is not required. Next, each building element is converted to a construction activity with a product space and added to the canvas as a CPM node (see top part of Fig. 4). Non-product activities such as equipment and temporary facility activities can also be created and represented by CPM nodes with no product space (see bottom part of Fig. 4). GPM offers great flexibility for users to manipulate the nodes and their connectivity. For each activity represented by a CPM node, a workspace is created during modeling (using the templates shown in Fig. 3) so that both geometry and temporal attributes are generated and assigned to the workspace. The explicit representation of workspaces can benefit users in identifying workspaces and incorporating space consideration into scheduling. A 4D model is completed after all CPM nodes are created and connected to form a CPM schedule.

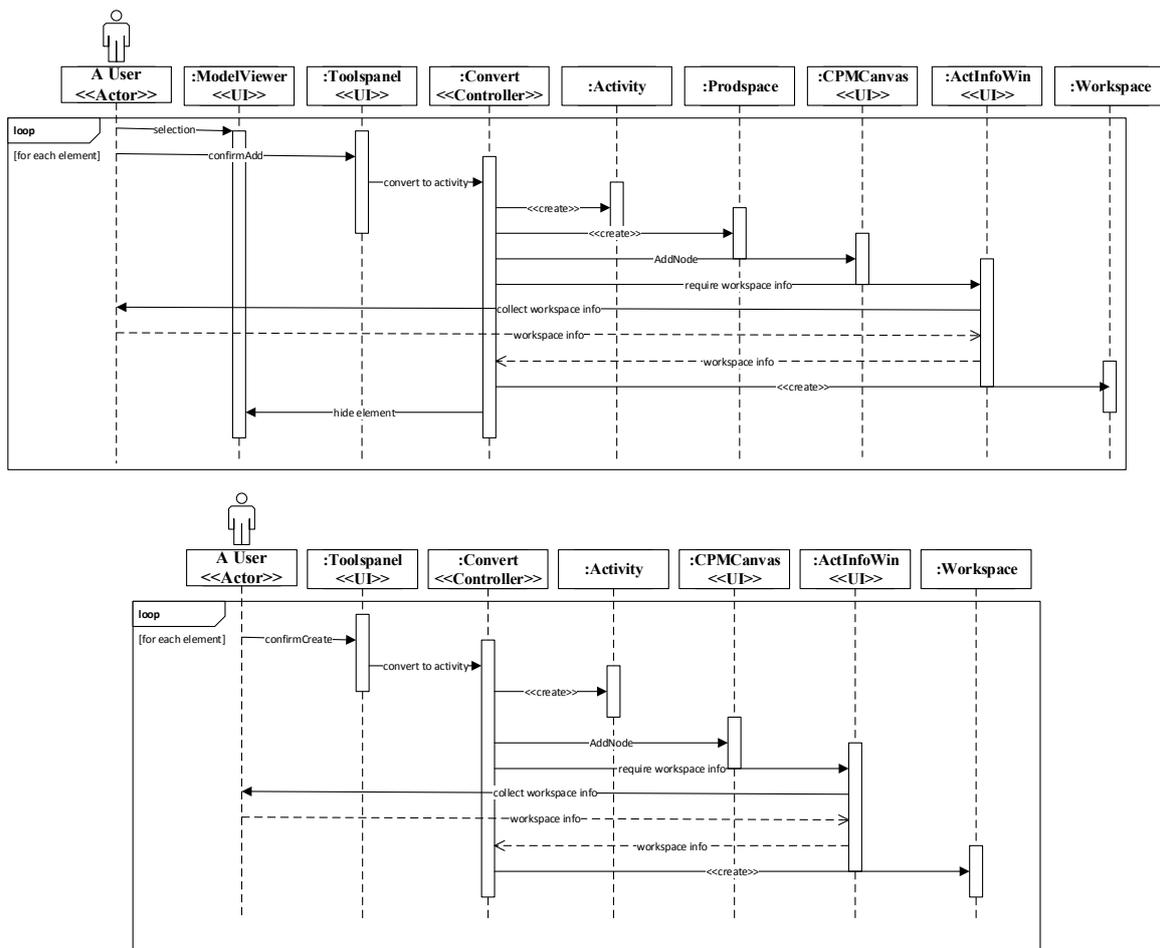


Figure 4. UML sequence diagrams of the modeling procedure

## 5. IMPLEMENTATION

This section introduces a test case that implements GPM on a garage construction project. The actual project was completed years ago on the Purdue University campus in Indiana (Fig. 5 left), but the authors collected all the construction planning documents (2D drawings, schedules, and site plans) to validate the presented method. A 3D semantically rich digital building model (Fig. 5 right) was newly created from the 2D drawings and stored in a geo-database in a typical boundary representation (B-rep) format (Multi-patch format) without losing generality.

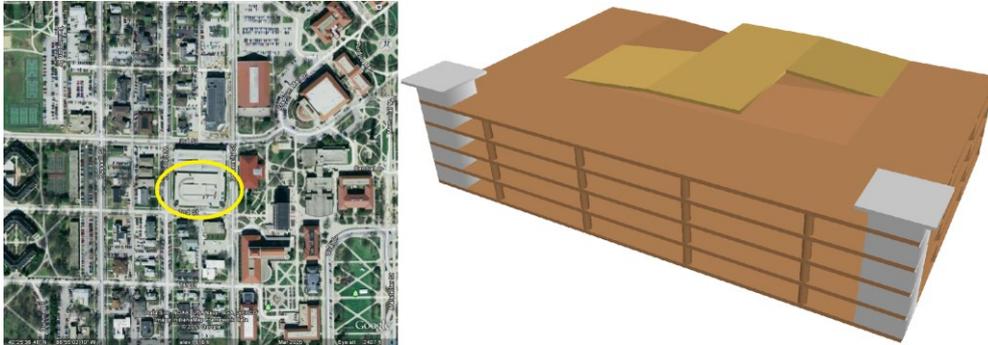


Figure 5. The garage model

The project has both concreting and pre-fabricated installation activities. The ground floor and the supporting structures adopt a cast-in-place construction method. The higher level slabs are prefabricated and installed using mobile cranes. The created building model has all the main structures including slabs, supporting walls, columns, and elevation shafts. The construction duration information of each part is stored as an attribute of the building model in the geo-database. The prototype of GPM is developed as an add-in of ArcGIS 10.1.

The authors developed a 4D workspace-aware model using the GPM prototype and the above-mentioned available sources to simulate part of the initial planning process, with the help of a construction professional who provides valuable information in scheduling and workspace planning. The rest of this section presents the findings during applying GPM to construction planning in aspects of assisting initial planning and facilitating 4D model development.

### 5.1. Initial Planning Assistance

GPM supports initial planning by providing 3D visual assistance during the CPM scheduling process. This advantage allows construction planners to conveniently take construction space into consideration during scheduling, so better decisions can be made to avoid constructability problems. Fig. 6 presents a modeling scenario using GPM. All first floor elements have been added to the canvas as CPM nodes and appear to be transparent in the viewer. The EST and EFT of the activities represented by the CPM nodes are automatically calculated. The upper floor elements are hidden to facilitate operations on the second floor. The activity info window lists detailed information of a selected node (the Ground\_A\_1 in Fig. 6). These features lead to a smooth progress of creating the CPM schedule that no activity was missed or needed to be double-checked. The newly created CPM schedule matches the original CPM schedule in the construction planning documents in terms of total duration and main milestones.

Another advantage of GPM is the presentation of not only the 3D model but also workspaces during scheduling. With workspaces incorporated, GPM facilitates the resolution of many construction planning problems. Fig. 7 illustrates two problems encountered during the implementation test. The left picture indicates a potential workspace congestion. The activity window indicates that the two involved construction activities are all on the critical path (their  $EST = LST$  and  $EFT = LFT$ ). Since such a workspace congestion problem can be alleviated by site coordination, a comment was left to remind the future construction team about the situation. The right picture depicts the process of selecting a proper type of crane. The two semi-spheres are created to represent the maximum and minimum working range of a mobile crane. The crane's working range and some critical construction activities' workspaces are displayed at the same time. At the initial planning phase, such a visual clue significantly facilitates the selection of crane types, even though the workspaces are just an estimation.

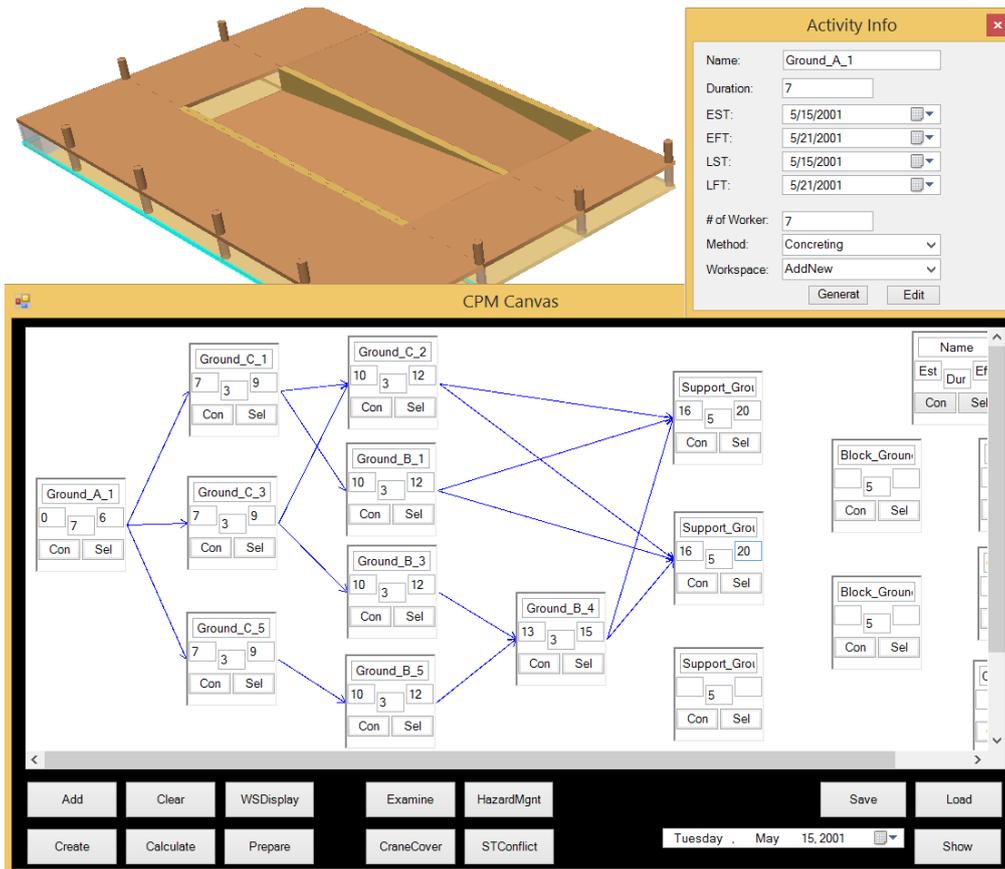


Figure 6. A screenshot during modeling

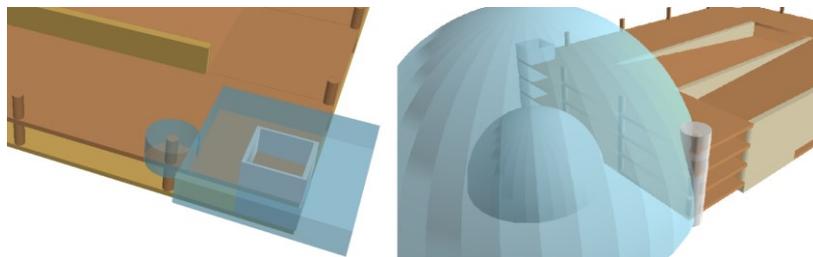


Figure 7. Construction planning problems encountered

## 5.2. 4D Model Development

GPM improves the 4D model development process by synergizing 4D modeling with CPM scheduling. By taking a 3D model as the input and conducting CPM scheduling, a 4D model can be built at the same time. The completed CPM network (Fig. 8) includes 81 CPM nodes (activities) and 190 space components. Using GPM, it takes about 6 hours for the authors to complete the modeling and scheduling work with outcomes of a workspace-aware 4D model and a conflict-free CPM schedule.

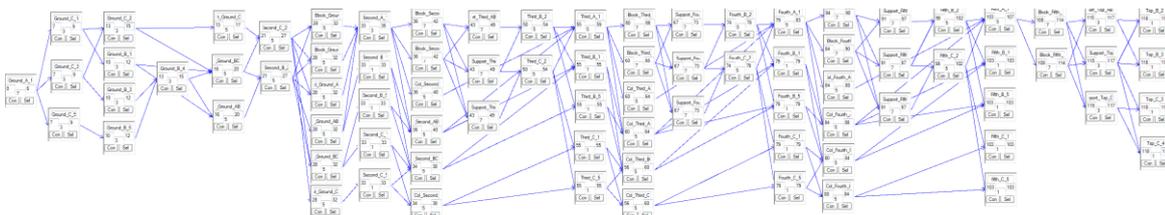


Figure 8. The CPM network

The created workspace-aware 4D model is ready for progress drawing presentation and workspace-enabled animation. These two visualization functions can better demonstrate and communicate the construction progress to and with other parties. Fig. 9 displays a construction progress drawing on a specified date. It not only displays the completed parts but also illustrates the on-going construction activities and their workspaces.

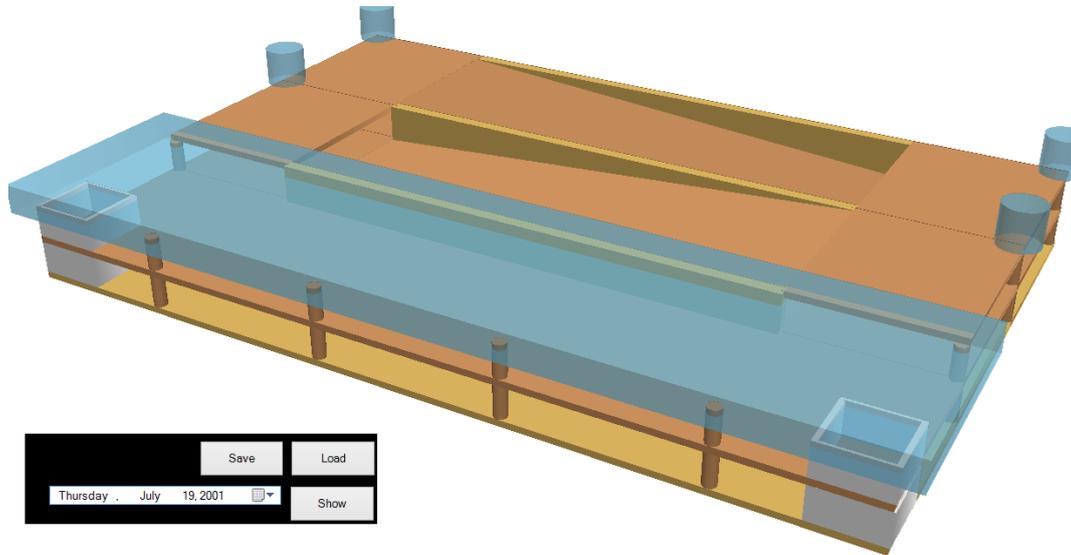


Figure 9. A progress drawing from the 4D model

Fig. 10 compares the workspace-enabled animation with the traditional product animation of the first floor slab concreting activities. Firstly, the workspace-enabled animation provides better visual effect to illustrate the construction sequencing. Secondly, it delivers information about “what spaces are needed to conduct the construction activity.” Such information is critical for construction in site planning and conflict detection.

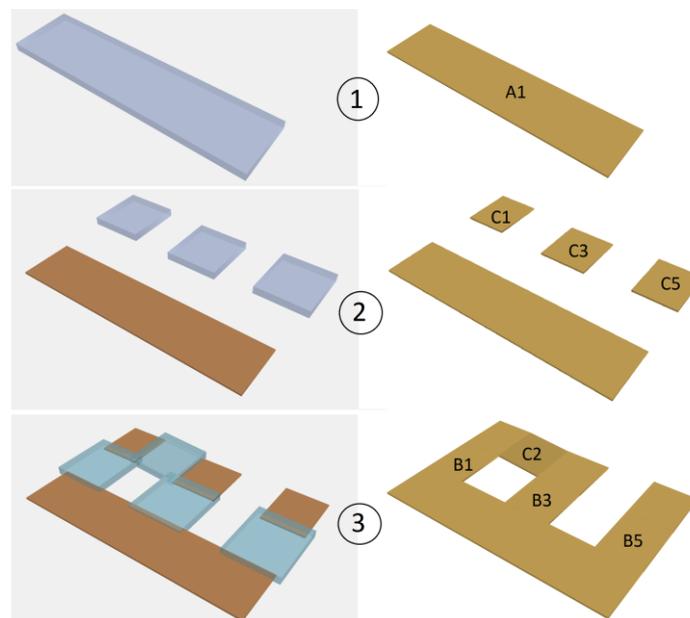


Figure 10. Workspace-enabled animation and product animation

GPM is able to export the conflict-free CPM schedule in a text format that is compatible with most traditional scheduling software packages. Fig. 11 displays an excerpt of the schedule that is imported into Microsoft Project. All the activities, attributes, and relationships are successfully maintained during the import process.

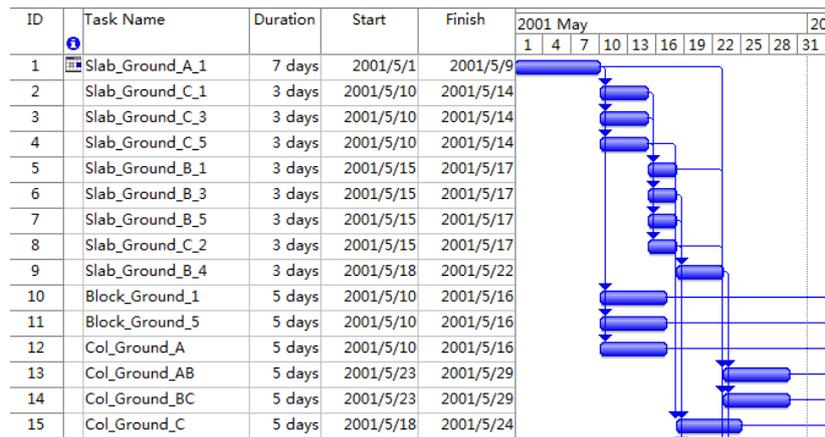


Figure 11. The CPM schedule in MS Project

## 6. DISCUSSIONS

The GPM presented in the paper is an innovative construction planning approach with good compatibility. Although the prototype for implementation was built on a GIS-based platform, neither of the concept, modeling mechanism, and procedure is software-specific. In the implementation case, the 3D model was represented in a B-rep format that is similar with most Computer Aided Design (CAD) applications and stored in a geo-database without losing generality. In addition, the data structure is able to be applied to other construction models using different 3D representation format such as Industrial Foundation Class (IFC) and CAD. The authors chose the GIS-based platform for implementation is due to the consideration that (1) the capability of extending the method to a larger scale (community or city) to promote the best use of a building model not only in the design and planning phases but also in the construction and operation phases within a community context, (2) the well-developed capability of 3D topological analysis in GIS-based software can facilitate the later-on research about construction workspace analysis, and (3) the availability of resources (e.g. city parcel models in a shapefile format).

However, the use of a GIS-based platform does bring drawbacks to the implementation case during this research. First, there are inconveniences in information management. Since this study newly designed the data structure and created most of the classes in the prototype, it requires much more effort to manage all the information than using an existing commercial or even open-source construction planning tool. Second, the Multi-patch format is more expensive in storing building information than many other formats such as LOD 2. Given the drawbacks, it would be interesting to test the method in a BIM-based platform. IFC is capable of adopting the method by creating some new space classes to implement the data structure, however, a concern exists in the capability of conducting topological analysis.

Topological analysis is critical in detecting conflicts and planning workspaces. An important future extension is to enable the workspace analysis capability of this method. Workspace planning is not only about workspace modeling but also conflict detection and resolution. Although workspaces have been modeled and visualized, the current practice of workspace conflict identification still relies on human recognition, which requires extensive effort and is error prone. On the other hand, there are many researchers have attempted to incorporate workspace analysis capabilities into construction 4D models to enable automatic workspace conflict detection (Akinci et al., 2002b; Chavada et al., 2012; Mallasi, 2006; Guo, 2002) and quantification (Chua et al., 2010), site safety analysis (Zhang et al., 2013), and site layout and equipment planning (Kim and Teizer, 2013; Irizarry and Karan, 2012). These studies all need workspace models, although with different requirements in format and level of details, as input for analysis. With GPM's workspace modeling capability, flexible data structure, and platform independency, there is great potential to integrate the workspace analysis functionalities into GPM to enable a more comprehensive tool that supports initial construction planning. Another potential research area exists in improving the automatic level of the modeling and planning process, such as enabling automatic solution after detecting workspace issues (e.g. space conflict and site safety concern) and creating a workspace database for typical construction activities to improve the automatic level of workspace modeling.

## 7. CONCLUSIONS

This paper presents a graphical planning method for workspace-aware 4D modeling and scheduling to assist in effective construction planning. While most previous 4D modeling methods necessitate CPM scheduling, building modeling, and workspace modeling as three separate tasks to build a workspace aware 4D model, GPM provides an integrated environment and synergizes the processes into one step. The integrated modeling process allows flexible user-system interaction that encourages creative scheduling solutions. When completing a CPM schedule and workspace modeling, a workspace-aware 4D model is created at the same time. More importantly, the workspace modeling is conducted during scheduling, so it directly supports initial planning to avoid workspace conflict. The workspace-aware 4D model created using GPM therefore becomes a planning tool instead of a post-plan review tool. The implementation case demonstrates the effectiveness of GPM in assisting initial planning and 4D modeling. Despite some inconveniences caused by the implementation of the prototype, GPM significantly improves the planning experience.

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