THE 4D CAD MODEL WITH FALL GUARD BOUNDARY VISUALIZATION

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Abstract

Safety is an essential research area in the field of construction because the construction work is very hazardous and able to kill many lives each year. The 4D CAD model has been accepted for better conceptualizing and comprehending the sequences and spatial constraints in a construction schedule. It has a potential to integrate safety into construction schedule. This research aims to create the methodology that visualizes the construction safety requirements via the 4D CAD model. Also, it develops and implements the 4D CAD model with Fall Guard Boundary Visualization (or FGB-4D model). The FGB-4D model can automatically generate boundaries for safety requirements according to an individual building component. Main types of components: namely, beams, columns, slabs, and walls are considered. The safety requirements for the fall-from-height and falling objects hazards are visualized. The size and placement of these boundaries are the results of the sophisticated geometric calculation which refers to the size and placement of a building component. The developed model can enhance the visualization of the 4D CAD model and provide a more informative construction schedule. The FGB-4D model is a proactive method of construction safety. The visualization of construction safety integrated into the technique helps project managers better comprehend and be aware of safety requirements throughout the construction. They must allocate right resources and adjust the schedule more effectively. This contributes to the accidents reduction in the construction industry.

Keywords: **Construction safety, safety requirements, 4D CAD model, visualization, construction planning**

Introduction

Construction industry has a poor reputation of a high accident rate and hazardous activities on site. Some requirements are enforced by laws to protect workers or prevent those losses. Many safety measures and devices are invented. Contractors are responsible for providing a safe working condition throughout the construction phase. Some of them perceive safety requirements

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as an extra cost and time-wasting. Research regarding safety in construction work is necessary and valuable to save people's lives.

A proactive approach to improve safety in construction is to bring safety into plans. It is to identify safety activities and/or requirements earlier during the planning phase and insert them in a proper sequence of the construction plan. Safety awareness can be achieved by the visibility of the safety requirements in the plan. This could be a cost effective way of promoting safety in construction work.

The 4D CAD model is the integration technique of construction schedules with 3D CAD models. The technique is an advanced schedule presentation method that provides great advantages such as conceptualization of construction process, and perception of space-location utilization. It is a potential tool to explicitly visualize the safety requirements. The aim of this research is to develop the 4D CAD model with Fall Guard Boundary Visualization (or FGB-4D model) that can automatically incorporate safety requirements according to the current construction progress. The focus of this paper is to describe the development and functionality of the FGB-4D model. The next sections are reviews of a safety issue in construction planning and the current development of the 4D CAD model. Then, the development process of the FGB-4D model including design, programming, and result is described.

Safety Issue in Construction Planning

Safety is an important issue in construction since the work activities are very dangerous. Both governmental agencies and professional associations put efforts to promote occupational safety and health at work. An amount of legislation is enforced mostly with contractors to perform their work safely. Also, safety professional standards are established as guidelines for their work.

Integrating Safety into Plans

Safety management includes goal setting, action details, and performance evaluation. It is a systematic implementation of required safety on the site. It must be consistent with the construction plan. However, this usually creates a conflict since safety management and construction management focus on different priorities. Many approaches have been researched to resolve this issue.

Kartam (1997) initiated the integration of safety management and construction planning. He developed the integrated knowledge-intensive system for construction safety and health performance control. He stated that the system provides a proactive safety environment and makes the team aware of safety requirements for their own tasks. Saurin *et al.* (2004) have developed an integrated planning and control model for safety and production. The model integrates safety into three hierarchical levels of production planning and control: long-, medium- and short-terms. Cheung *et al.* (2004) have developed a web-based safety and health monitoring system for construction management. Safety performance on site can be measured through integration with database, web, and expert systems.

Navon and Kolton (2006) have developed an automated model of monitoring fall hazards in building construction. It defines the areas in the building where fall-from-height hazards appear, and proposes protective activities to be integrated into the schedule. It constantly monitors the existence of the guardrails and warns when something goes wrong. Wang *et al.* (2006) have developed an innovative simulation-based model that assesses the hazard for each activity in a construction schedule. The model is an approach to manage safety and schedule simultaneously.

Hadikusumo and Rowlinson (2004) used a virtual reality to capture the safety knowledge in terms of experience in safety hazards at construction sites and accident precautions. They stated that safety engineers can be effectively stimulated by the virtual images of construction components and processes.

Previous research proposed many different methods to integrate safety requirements into construction plans. However, none could explicitly visualize safety requirements together with the construction sequence. This research adopts on the attempt to incorporate safety requirements into construction plans. It utilizes an innovative method of construction planning called the 4D CAD model. The new system is anticipated to raise the safety awareness with simulated construction scenes. Users of the system can visually see the safety requirements at the right location and (planned) time along with the other construction activities.

Spatial Location Safety

Construction hazards can be classified into many different categories (Holt, 2005). Fall-from-height and falling-objects hazards are one of the most severities that cause many casualties each year (Janicak, 1998). These hazards are related to spatial location of building components. They dynamically change and relocate as the project progresses. They can be visualized via the 4D CAD model.

Workers could fall from building components or scaffolds around building components that they are working on (Huang and Hinze, 2003). Also debris or objects could accidentally fall from these structures and hit the workers who are working below. Some temporary structures are required as safety measures to prevent these hazards. They are such as scaffolding, guardrails, protective partitions and cover plates. Therefore, corresponding boundaries can be delineated for these safety measures.

Akinci *et al.* (2002a) specified a size and a position of work spaces required for a construction activity. They classified work spaces into many different categories including a hazard space. Akinci *et al.* (2002b) established methods that automatically generate work spaces required by construction activities in three dimensions and across time. This research, however, defines safety measure boundaries for construction activities. The boundaries enclose spaces for temporary structures that prevent fall-from-height and falling-objects hazards.

4D CAD MODEL

The 4D CAD model is invented to combine two separated information sources, a construction schedule and a 3D CAD model. It helps create explicit visual perceptions of the construction sequence and it is an effective collaboration media for construction teams. Koo and Fischer (2000) stated that the 4D CAD model can be used to evaluate the constructability of the planned sequences. Many applications have been developed on this technique. For example, McKinney and Fischer (1998) has developed the 4D CAD model as a planning tool used by the project team. Their models can be used to investigate an impact of the use of time and space during construction. Wang *et al.* (2004) employed a work breakdown structure template to link with 3D CAD objects. Chau *et al.* (2005) applied it for the construction site and resources management. Ma *et al.* (2005) used it for planning site layouts at different construction stages. Jongeling and Olofsson (2007) proposed a location-based schedule method enhanced with the 4D CAD model to improve the work-flow of construction activities.

Akinci *et al.* (2002c) applied the 4D CAD model to analyze the congestion and accessibility of working space. Its unique ability is to represent construction activities as virtual 3D objects which can effectively convey space information. Winch and North (2006) introduced the concept of critical space analysis and used the 4D CAD model as a tool. Their development can optimize space allocated to tasks in relation to the critical path schedule.

Chantawit *et al.* (2005) have initiated the 4D CAD model to analyze and utilize safety measure requirements. They use the safety library and plan to determine proper safety measures for the related project progress. The safety advices are given on the resulting screen together with the 4D CAD model. It is useful to assist safety engineers; however, this safety information is given in a textual format which is not quite stimulating. It is better as if this safety information is represented in a graphical format accompanying with the 4D CAD model.

Thus this research develops the FGB-4D model that employs additional 3D CAD objects for representing safety measures required. These objects are incorporated into the 4D CAD model to simulate construction activities with safety boundaries so that the users can experience their coming works and perceive the remaining space available. The rule-based algorithms is formulated to automate the task.

The FGB-4D model

This research formulates methodology to integrate the safety requirements with the 4D CAD model. Then, a prototype called the FGB-4D model is developed and verified with a case study. The model design is described with the programming procedures and the algorithms used. The development of the prototype and its features are explained using some pictures of the program interface. The results from the implementation are also detailed.

Design

The concept of the FGB-4D model is grounded on the 4D CAD model, which loops through the project timeline. At any particular moment, the program determines the performing status of each construction activity in the plan. Three distinctive performing statuses of an individual activity are given as ‘not-started’, ‘in-progress’, or ‘finished’. The program further analyzes only the ‘in-progress’ and the ‘finished’ activities using different algorithms.

For each individual activity, the program refers to its associated building components (or groups of 3D CAD objects which are representing these components). The program determines types of these components. Five distinctive component types are classified as column, beam, slab, wall, and others. The program targets the first four types to generate/ visualize proper safety boundaries. It considers the activity’s 3D-CAD objects (or Objects) one by one and goes into two modules: the Geometric Extractor and the Safety Boundary Engine.

In the first step, the program executes the Geometric Extractor to retrieve some geometric properties of the Object i.e. height, top and bottom planes. Figure 1 shows an example of the Geometric Extractor for an Object. The Geometric Extractor is designed to work on a right-prism shaped Object because building components are typically in this shape. It determines the bounding box of the Object to obtain the top and bottom levels. Hence, the variance between the two is the height. It also makes a copy of the Object and put the copy onto a temporary Layer (“Temp” Layer). Then, it extracts all edges of this copy. The result is discrete lines representing all edges of the Object. In case of a slab with openings, all edges of openings are also included. These lines are evaluated to find their top and bottom levels, and only lines representing the top and bottom plane edges are stored. The Geometric Extractor gives results as the height, top and bottom plane edges of the Object that will be used in the next step.

In the second step, the program executes the Safety Boundary Engine to automatically

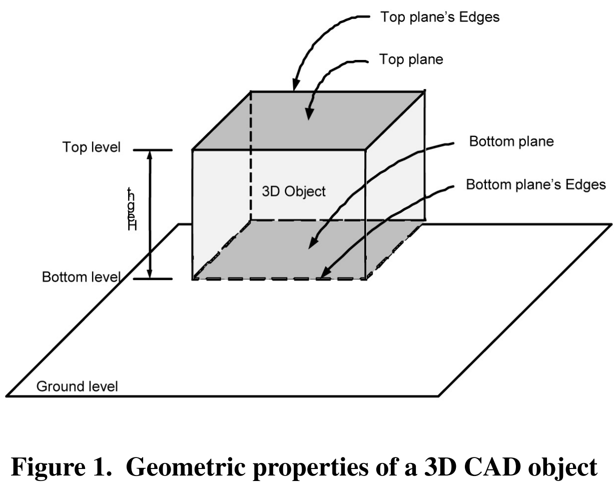

Figure 1. Geometric properties of a 3D CAD object

generate (or visualize) or remove (or hide) proper safety boundaries for the Objects. The Safety Boundary Engine is designed to distinguish the Object's performing status and type. It consists of different paths which are designed to handle different performing statuses and types of Objects. In case of 'in-progress' Objects, distinctive safety boundaries are generated (or visualized) based on the different types of the Objects.

Both columns and beams are assigned with surrounding safety boundaries at the offset distance of 100 cm. These boundaries represent the temporary supporting structures and hazardous space around columns and beams during their construction. The height of the boundaries is the same as the height of columns. Figure 2 shows the boundaries generated for a typical column and beam. The program takes their top plane edges to create a bigger offset perimeter. It then vertically extrudes this perimeter downward by the column height. The result is the surface boundary around a column or a beam. The program finally links this surface boundary to that individual column or beam.

Slabs are also assigned with surrounding safety boundaries at the edges of slabs. The boundaries are separated into two portions, the 'high' and 'low' ones. The 'low' boundaries are located from the bottom plane of that slab downward by the height of the column below. They represent the temporary supporting structures for in-situ cast slabs or the installation zone for pre-cast slabs. The 'high' boundaries are located from the top plane of that slab

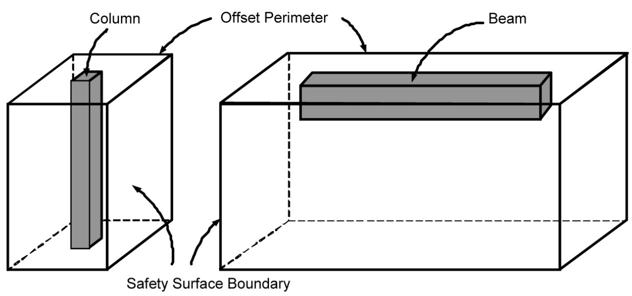

Figure 2. Safety surface boundaries for a column and a beam

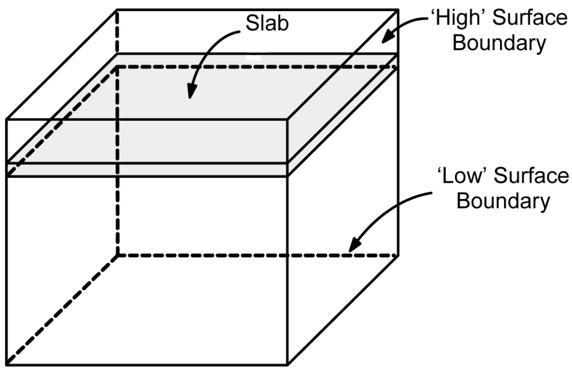

Figure 3. Safety surface boundaries for a slab

upward at the height of 110 cm. These represent the guardrails around slabs during their construction. Figure 3 shows the boundaries generated for a typical slab. The program takes bottom plane edges to extrude downward by the column height. The result is the 'low' surface boundary of that slab. For the other portion, 'high' surface boundary results from the extrusion upward of top plane edges by 110 cm. This program can also be applied on a slab with openings. Finally, the program links these both portions of generated surface boundaries to the slab.

Walls are different from the other component types. Walls are constructed on a slab. They can be internal or external walls. The construction of external walls brings an end to the 'high' safety boundaries of the relating slabs because walls can replace the temporary guardrails. They can protect workers against fall and falling objects. The wall construction triggers the removal of the 'high' safety boundaries of the relating slabs. During and after wall constructions, 'high' safety surface boundaries of the associated slabs must be removed.

Sophisticated geometric operations are formulated to achieve all above results. The program uses a complicated procedure called the Midpoint Operation to execute the task. It needs a check of the performing status of walls on the associated slabs. It is assumed that the bottom plane of a wall is on the same level as the top plane of its supporting slab (or the contact plane). It starts by taking all bottom plane edges of the wall. The edges shorter than 30 cm. are excluded but only the longer ones are considered to determine their midpoints. These midpoints are called "wall_midpoints". Then, all slabs (by their top plane level) at this wall_midpoints' level are examined. The program refers to the high surface boundaries (already exist) of these slabs. These surface boundaries are considered one at a time. A midpoint of the surface is determined and called "slab_midpoint". All these wall_midpoints and a slab_midpoint should be on the same level (the contact plane). The program evaluates the distance between every possible pair of these points. If at least one of these pairs gives the distance less than 30 cm., it can be concluded that the wall exists on that side of the slab. Hence the program hides that relating surface.

An example to illustrate the Midpoint Operation for a wall on a slab is shown in Figure 4. The example gives results of wall_midpoints that are 1, 2, 3, ..., 6; and slab_midpoints are A, B, C, and D. The program begins the first loop on a surface that gives a slab_midpoint of A. The point A can be

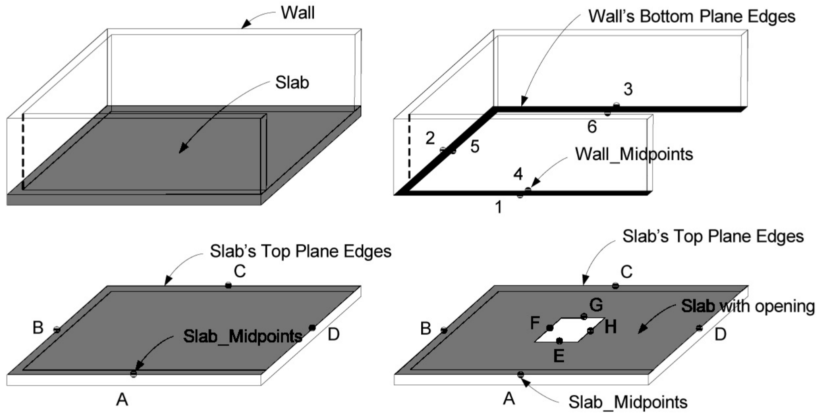

Figure 4. Midpoint Operation for a wall on a slab

possibly paired with six wall_midpoints. All distances between these six pairs are evaluated. It is found that two pairs have distances less than 30 cm. This implies that a wall has already been constructed on this side of the slab. The program then hides the relating surfaces. After that, the program goes to the next loop and repeats this procedure again and again until every surface is considered. All results from pairing and evaluation of the example are shown in Table 1. The Midpoint Operation also works on a slab with openings.

In case of 'finished' Objects, their associated safety boundaries are removed (or hidden). This applies to columns, beams, and slabs (for only their low boundaries). Walls do not have their own safety boundaries during construction and there is nothing to be done when they are finished. The programming procedure of the removal starts from tracing the linkage of an individual component and its own surface boundaries. It then changes the visibility of the associated surfaces from 'Show' to 'Hide'.

Development and Results

The FGB-4D model is developed on AutoCAD Architecture® and Microsoft Project®. Both software supports the automation interfaces and has a Component Object Model (COM). Also, they both support an embedded customized program with Visual Basic for Application (VBA). Hence, a VBA code can be programmed within AutoCAD to create ActiveX object of the MS Project application. The FGB-4D consists of the 4D CAD model embedded with the Geometric Extractor, the Safety Boundary Engine, and the Midpoint Operation. Their developments are described next.

The 4D CAD model is the integration between a 3D CAD model and a construction schedule. The 3D CAD objects (or Objects) are linked with the corresponding construction activities (or Tasks) through the linking keys. The 'Handle' property is a unique identity of an Object. The 'Text13' property is a read/write text of an individual Task. An Object that is representing a Task will have its 'Handle' recorded in 'Text13' of that Task. The result is that all Objects in AutoCAD have their own associated Task in MS Project. These linkages are a many-to-many type of relationship that is one Object can relate with more than one activity and vice versa.

The simulation control of the 4D CAD model is developed using VBA and AutoCAD's object model. The visualization is exhibited on the AutoCAD environment while the corresponding schedule information is simultaneously retrieved from the MS Project through the linking keys. Figure 5 shows the linkage concept of the FGB-4D model using objects' properties of both applications. The timeframe of the simulation is from the project start until the completion.

The developments of the Geometric Extractor, the Safety Boundary Engine and the Midpoint Operation are done on AutoCAD Architecture. The software distinguishes many types of structural and non-structural components (such as "AecDbSlab" for slabs; "AecDbWall" for walls; and "AecsDbMember" with 'Type' equals to "aecs MemberType Column" for columns and "aecsMemberType Beam" for beams) using the 'ObjectName' property. The safety surface boundaries created

Table 1. Pairing and evaluation results

Loop no.	Pair	Distance < 30 cm	Decision	Action
1	A-1, A-2, A-3, A-4, A-5, A-6	A-1, A-4	Wall exists	Hide Surface
2	B-1, B-2, B-3, B-4, B-5, B-6	B-2, B-5	Wall exists	Hide Surface
3	C-1, C-2, C-3, C-4, C-5, C-6	C-3, C-6	Wall exists	Hide Surface
4	D-1, D-2, D-3, D-4, D-5, D-6	-	No wall	Show Surface

in the program are the 'Surface' type of Objects. They are results of the 'Extrude' function of edge lines. The 'Visible' property of an Object is used to show or hide these 'Surface' Objects. The 'SetXData' is another function that is used to associate a building Object with its own safety Surfaces. The program uses the 'SetXData' function to record 'Handles' of all associated objects within the main object.

A construction project of an apartment is used as a case study. Figure 6 shows a chronological series of result screenshots of the FGB-4D model. The representations of object colors are: magenta for in-progress activity;

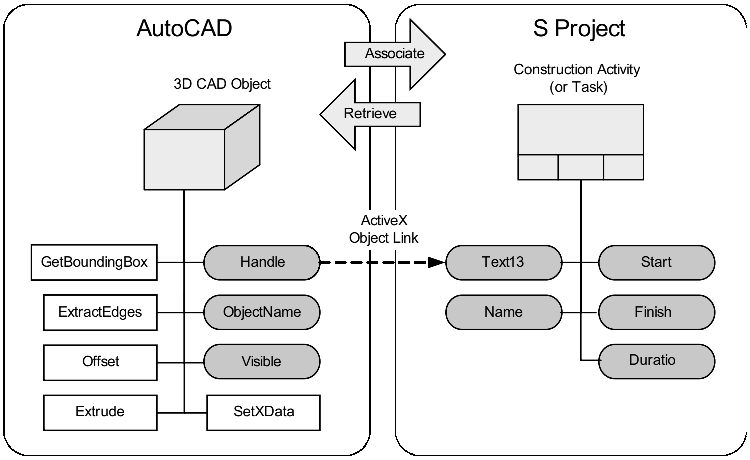

Figure 5. The integration of AutoCAD and Microsoft Project using Object's properties

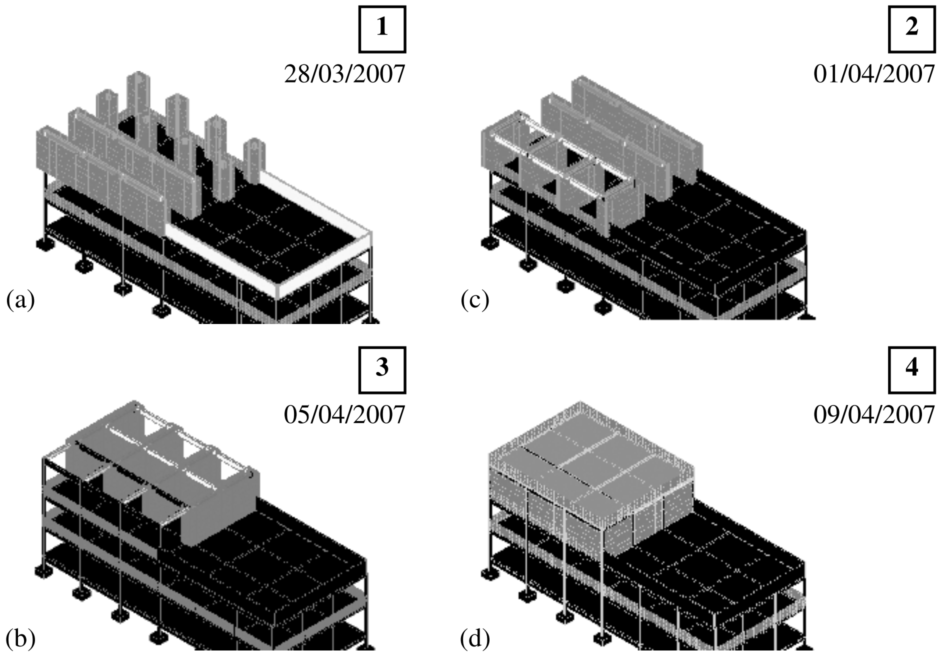

Figure 6. A series of screenshots of the FGB-4D model

yellow for predecessor of in-progress activity; black for finished activity; and red for fall guard boundary. The first screenshot shows the progress of the project on 28/03/2007. The in-progress activities are a group of beams and columns on the second floor. The FGB-4D automatically detects these activities and inserts the corresponding fall guard boundaries which are around the building components. The other fall guard boundaries are around the completed first- and second-floor slabs. They are the 'high' surface boundaries which are left in place until the construction of walls on the slabs. Some external walls on the second floor have already been constructed; therefore, their associating fall guard boundaries were removed.

The second and third screenshots show the succeeding progress on 01/04/2007 and 05/04/2007, respectively. The fall guard boundaries keep changing according to the building components. The forth screenshot shows the progress on 09/04/2007. The current activities are the construction (installation) of the third-floor slab. The FGB-4D creates the high and low surface boundaries around the slab. Figure 7 shows the screenshot of the FGB-4D model at the progress on 24/07/2007. The construction is on the seventh floor while the external walls are constructed on the lower floors. It shows that the FGB-4D model removes the high surface boundaries of the corresponding slabs when the wall construction begins.

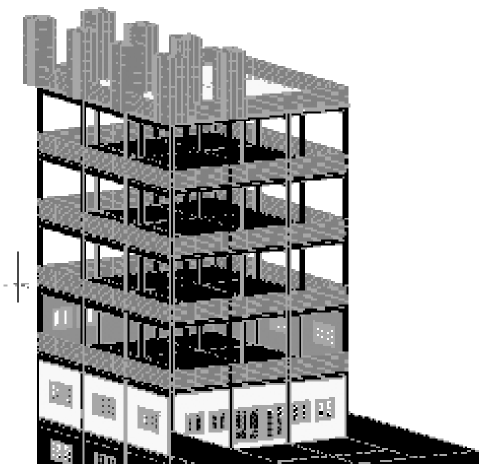

Figure 7. The screenshot of the project progress on 24/07/2007

The FGB-4D model can explicitly simulate the construction scenes and processes which look similar to the real world. The surface boundaries indicate the space used for temporary structures and fall guards and the remaining space for safe work. The FGB-4D model is a tool that integrates safety requirements with the 4D CAD technique. It informs users about other necessary supporting activities rather than only the main production activities. The FGB-4D model is an automatic and rule-based system which requires a little effort from users. However, the FGB-4D model relies on the precision and correctness of the 3D modeling practice.

Conclusions

Contractors must comply with many construction safety requirements throughout the work process. One of proactive methods of construction safety is to incorporate safety requirements into a construction plan as they are as important as other construction activities. This is to effectively prevent accidents from the work. The 4D CAD model is an innovative technique of schedule presentation. It can visualize complicated schedule information into an impressive graphical format. This research utilizes the technique to raise awareness of safety requirements. It aims to create methodology and develop the FGB-4D model to integrate safety requirements with the 4D CAD model technique. The result is that the particular safety constraints are considered and included into the plan. The FGB-4D model helps contractors clearly perceive the required spatial-location safety regarding fall-from-height and falling object hazards. These hazards are related to the size and location of building components, which have a certain placement, and so do their associated safety measures. Other kinds of hazards are different. They are related to construction workers, equipments or materials' properties which are movable and uncertain; hence, they can be visualized via the 4D CAD model. The FGB-4D model provides users with the vision of the safety requirements along with the construction sequence. It helps enhance visually the integration of safety requirements and construction schedule. It aims to caution users with the safety constraints and to prepare the schedule more effectively.

The FGB-4D model targets main components which are beams, columns, slabs and walls. These components can directly generate fall hazards. Each of them can represent many construction work packages such as formwork and rebar installment, concrete placement, formwork dismantlement and finishing. The FGB-4D model consists of complicated programming modules. Its main structure is the 4D CAD model. It is featured with the Geometric Extractor, the Safety Boundary Engine, and the Midpoint Operation. The program starts with considering one individual component at a time. The type of this component is identified so that the component is processed with a separate program designed for each type. The program analyzes the placement of the component, and automatically generates and lays proper safety boundaries at the right place. These safety boundaries are the 'Surface' type of 3D CAD objects. They are generated and/or made visible only when their associated construction activities have an 'in-progress' status. On the other statuses ('not-started', 'finished'), they are removed or hidden. The first execution of the model creates new objects of these safety boundaries but the next executions will control the visibility of these objects between 'Hide' and 'Show'.

There are some limitations of the FGB-4D model. The perfection of the FGB-4D model heavily depends on the precision and the correctness of the 3D CAD model, which is the crucial input. The 3D CAD model must be well organized. The critical aspects are the dimensions, placements, types and individuality of all components. Also, the linkages between 3D CAD components and construction activities, as a basic development task of the 4D CAD model, are critical. These demand highly-skilled personnel and effort to achieve. It is even difficult when the building design is complex. It functions correctly only on components with the right prism shape. It is an assumption of the calculating algorithms of the program. However, most building components typically are in right prism shape. The FGB-4D model considers only fall-from-height and falling objects hazards. These limitations can be challenges for the future research.

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