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An integrated safety management with construction management using 4D CAD model

Vacharapoom Benjaoran [a,*], Sdhabhon Bhokha [b]

[a] School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand
[b] Department of Civil Engineering, Faculty of Engineering, Ubon Ratchathani University, Ubon Ratchathani, Thailand

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ABSTRACT

This paper describes an integrated system for safety and construction management using the 4D CAD model. Safety is integrated with the construction management process throughout design, planning and control phases. Design information about building components and planning information about activities has been gathered to formulate the 4D CAD model. The rule-based system analyzes this combined information to automatically detect any working-at-height hazards and also indicates necessary safety measures in terms of activities and requirements. These safety measures are inserted into the construction schedule and visualized on the 4D CAD together with the other construction sequences. A prototype is developed and verified with a project case study. The results show that the developed system can be a collaboration tool for designers, project engineers, safety officers, and other project participants. It can raise safety awareness of the team and it leads to revisions of design and plan to be consistent with safety. Safety measures are apparently on the schedule; therefore, right resources are allocated, safety constraints are considered and alleviated ahead of time, and the safety control can explicitly refer to as well. This contributes to the success of safety management in the construction industry.

1. Introduction

Construction industry has a poor reputation of a high accident rate and hazardous activities on site. This reflects by the statistics of high accident rates in recent years in many countries (BLS, 2007; HSE, 2008; SSO, 2008). This problem causes loss of many lives, health, skilled personnel, compensation, and disrupting the production. It is a consequence of the failure of safety management on construction site.

Traditionally, safety is managed separately from the construction (Hare et al., 2006). The construction management is focusing on productivity in aspects of time and cost. Safety usually conflicts with the production work and it is to blame for hindering the production work and costing some money. Construction management which is fragmented from safety management tends to disregard safety constraints within the construction process. Unless they are well integrated, the construction project never achieves the optimum benefit of the three vital objectives i.e. cost, time, and safety.

Many research studies have addressed on the lack of integration between construction and safety (Kartam, 1997; Gambatese and Hinze, 1999; Saurin et al., 2004; Cameron et al., 2004; Chantawit et al., 2005; Navon and Kolton, 2006; Hare et al., 2006). These researchers suggested various approaches to integrate safety into the construction process including design, planning, and control phases. The issue is strongly reinforced by the Construction Design and Management Safety (CDM) Regulations (HSE, 2007) which are aimed at improving the overall management and coordination of health and safety throughout all stages of a construction project. The regulations were introduced with the intention of creating an integrated approach to health and safety through the increased involvement of clients and designers (Hare et al., 2006).

At the design phase, designers can actually play an important role in early influencing construction safety (Behm, 2005; Gambatese et al., 2007). Their designs direct the choice of construction methods. Designers must realize their privilege and be capable of identifying risks and hazards in the resulting construction methods. They then avoided or reduced any risks and hazards through safer designs (Baxendale and Jones, 2000). A design tool was developed to assist designers in identifying project-specific safety hazards and to provide best practices to eliminate the hazards. These safety design suggestions can be accumulated to form the database of knowledge (Gambatese and Hinze, 1999). In addition, a virtual reality was used to stimulate and bring back perception of hazards and safety knowledge in both explicit and implicit forms. It could assist on the design-for-safety process (Hadikusumo and Rowlinson, 2004). A study indicated that designing for

* Corresponding author.
E-mail address: vacharapoom@sut.ac.in (V. Benjaoran).

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safety is a viable intervention in construction. It just needs a new design tool that assists designers in addressing safety in the design (Gambatese et al., 2005). However, some hazards may still be inherent even in the safest designs as it is the nature of the construction work. These remaining hazards need to be handled further in the following phase.

During the planning phase, safety must be regarded as important as construction activities (Kartam, 1997). Safety and health requirements should be defined the same as the construction activities are in the work breakdown structure. These safety-related activities then must be included into the project schedule or Critical Path Method (CPM). The result is a proactive safety plan and an early involvement of safety in the project before hazards being created. The project team can be aware of the safety requirements along with their own tasks when reviewing the project schedule. Necessary resources for safety performance can also be properly allocated and procured in advance. Research studies explored planning tools for integrating health and safety in construction (Hare et al., 2006). Several tools such as safety information on drawings, a responsibility chart were attempted to cut off an amount of bureaucratic paper-work (Cameron and Hare, 2008). However, these proposed planning tools required a lot of effort and cooperation of the project team. It will be better if both construction and safety can be simultaneously planned or if a new tool can automatically give safety considerations for planners.

Finally, at the control phase, the three-levels of effective monitoring of safety performance were suggested (Saurin et al., 2004). The percentage of safe work packages was used as an indicator of this multi-level safety plan against the actual work being performed. Also, a web-based safety and health monitoring system was developed to automatically assess the actual performance and advice corrective actions required using the knowledge base (Cheung et al., 2004). Despite a large investment required, sensor and transmitter devices were installed at the guardrails to real-time monitor their existence and alert when they were misplaced (Navon and Kolton, 2006). In addition, the degree of hazard, expressing in terms of accident costs, of each construction activity is evaluated using the simulation-based model (Wang et al., 2006). The results from the simulation would specify the critical factors relating to activities and then urge management to control them in order to reduce the possibility of accidents. Although the monitoring and control are the last resort to prevent an accident, they are heavily relied on the safety plan. The safety planning is very important because we cannot control what we did not plan for. Any unidentified hazards will not be planned for safety measures and still have potential to cause harms.

It can be concluded that risks and hazards inherent in designs or construction methods must be identified as many as possible during the design and planning phases. Then, safety measures against those risks must be incorporated into the construction schedule as ordinary activities. Safety activities become visible through the project participants and have their own working time in the construction sequence. Also, necessary resources including time, responsible workers, and budget can be optimized and allocated. The planning and design phases provide a vital opportunity to eliminate hazards before they appear on the site and the ability to eliminate hazards diminishes as the project progresses (Gambatese et al., 2007). Finally, the safety performance can be properly measured and controlled.

Although some concepts and developments have already existed, an effective and comprehensive tool for the integrated safety management is still lacking. A tool is needed for collaborating between construction and safety throughout the process (Hare et al., 2006). This research, therefore, aims to develop a holistic and automatic system tool that integrates safety into design, planning and control processes. The system is supported with database that encapsulated and accumulated safety knowledge including both explicit and implicit forms. Hence, it supports an early involvement of the relevant parties, provides decisive information about budget, schedule, and training. It also improves communication, raises awareness of the parties, and can be used for allocating resources and tracking performance. This paper presents the research which includes an investigation of the current practice on construction sites in Thailand and reviews of relevant literature. The design concept, development, result and evaluation of the system are described in the following sections.

2. Safety management practice in construction

This research has conducted a survey study to realize the current practice of safety management in construction projects in Thailand. Eleven ongoing construction projects have been used for the interview sessions. These projects varied in size and type i.e. a high-rise commercial building, condominiums, academic buildings, a hospital, a metropolitan water-supply plant and mass transit infrastructures. Details of these projects are given in Table 1. These projects were purposively selected to reflect the safety problem of the industry. Project engineers and/or safety officers were asked with the series of questions regarding their current safety management process and the troubles of implementation. Role and responsibility of safety officers were also asked.

It was found that most projects did not systematically implement the safety management on site. Some projects which were a relatively small size did not have a safety officer. Project engineers took responsibility of managing safety. They were usually pressured by the work progress; hence, gave a focus on the production work. Safety instructions were inconsistently given to workers

Table 1
Descriptions of the construction project cases.

Construction project no.	Descriptions			
	Project value (million dollar)	Project type	Participant age (years)	Working experience (years)
1	0.22	Academic building	38	5
2	0.63	High-rise commercial building	27	1
3	2.71	Academic building	46	13
4	2.79	Academic building	44	15
5	3.00	Hospital building	31	6
6	3.61	Academic building	32	7
7	7.14	Condominium	29	5
8	8.34	Condominium	34	8
9	90.1	Metropolitan water-supply plant	30	8
10	129.1	Mass transit infrastructure	39	10
11	740.0	Mass transit infrastructure	42	10

during their supervision. A weekly safety talk which was a brief talk of safety concerns was also conducted. The overall site conditions were very messy and full of hazards. For example there were a lot of waste materials left on floors. Slabs at high level above ground had no guardrails. Accidents were reported as a required paper-work. People on site were overwhelmed by these hazardous conditions. This was because they did not plan for safety in advance, nor eliminate the hazards before they occurred.

The other projects which were constructed by contractors of relatively large public companies had full-time safety officers as required by the regulations. Before the construction, safety officers developed safe operating procedures (SOPs) of all hazardous construction activities such as a procedure of welding work. Hazards were identified on the complete project designs. The procedures stated safety requirements, tools, and instructions. They were related to and complied with project designs and specifications, safety regulations, and the company safety guidelines. Workers must follow these procedures when carrying out the work. During the construction, safety officers observed and inspected activities on site to ensure that all safety measures were followed. If they spotted on anything wrong, for example broken power extension, derricks with a wearing sling, workers who missed some personal protective equipment (PPE), they would order to pause that work until corrections were made. In addition, they had regular training sessions such as safety talks twice a week. Although the SOPs of activities were available and they provided details of how an activity should be carried out safely, they were separate from the construction schedule. The workers might not know or be aware of when these safety measures would be needed.

The situation similar to this not only occurred in Thailand but also somewhere else (Saurin et al., 2004; Navon and Kolton, 2006). Some studies also supported this finding that safety management in Thai construction industry was overlooked and occupational safety legislation was weakly enforced (Siriruttanapruk and Anuntakulnathi, 2004). Aksorn and Hadikusumo (2008) discovered that many factors were critical to the success of the safety program in Thai Construction. These factors were such as the management support, appropriate safety education, teamwork, and clear and realistic goals. However, when being asked about the assisting tool, they were positive that it would help them to accomplish safety tasks and to communicate with other trades and relevant parties as well.

3. Integrated system for construction and safety management

This study aims to develop an integrated system for construction and safety management. The 4D CAD model and the rule-based algorithms are used in the developed system. This development is grounded on the existing research. The prototype is created and applied to the construction working-at-height hazard. The concept and development of this system are explained in this section.

3.1. 4D CAD model

The 4D CAD model is an innovative integration tool between construction design and planning. It combines two separated information sources, a construction schedule and a 3D CAD model. It helps create explicit visual perceptions of the construction sequence and be an effective collaboration media for construction teams (Koo and Fischer, 2000). Also, it has been used to evaluate the constructability of the planned sequences. This technique has been used for many applications. For examples: 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 which can be enhanced with the 4D CAD model to improve the work-flow of construction activities. Tanyer and Aouad (2005) have extended the 4D model to the *n*D model that included the project cost dimension. Whereas the safety dimension is still not incorporated.

Also, the 4D CAD model has been applied to construction safety. Its unique ability is to represent construction activities as virtual 3D objects which can effectively convey space information. Akinci et al. (2002a,b,c) used this technique to analyze the congestion and accessibility of working space. 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. Therefore, hazard space which is generated by an activity can be analyzed using the 4D CAD model. Hadikusumo and Rowlinson (2004) pointed that the 3D or 4D visualization or/and virtual reality are more effectively used for hazard recognition than just the conventional 2D design drawings. Chantawit et al. (2005) have initiated the 4D CAD model to assist the hazard identification process. They use the safety library and plan to determine proper safety measures for the related project progress. The safety advices are given in a textual format on the resulting screen together with the 4D CAD model. However, their approaches required safety engineers to manually reveal those hazards and determine proper safety measures and the safety information is not really integrated into the 4D CAD model.

In this study, the 4D CAD model is used together with the rule-based algorithms to automatically detect spatial related hazard (working-at-height) and visualize the safety measures needed together with the construction sequence. The result is the integrated system of concurrent construction and safety management. The use of the 4D CAD model for this development brings many advantages. It accumulates various data of the construction project from design, planning, and control processes. These data related to building components and construction activities can be analyzed to specify any potential working-at-height hazards in the construction activities. Also, the 4D CAD model provides visualization of construction scenes and sequences. It can assist the manual identification of the other hazards. It can then clearly show the newly attached safety measure activities and requirements and raise awareness to all relevant parties. It can be used for reviewing the constructability of the design and schedule after the safety considerations being incorporated. The 4D CAD model is a collaboration tool for relevant parties that enable the integration of construction and safety management.

3.2. Characteristics of working-at-height hazard

A hazard is an unsafe physical condition that can cause harm. Many hazards of various kinds are associated with the construction work. Construction hazards are categorized in different ways (Hughes and Ferrett, 2005; Holt, 2005; MacCollum, 2007). Some hazard categories (such as mechanical machinery, electricity, fire, chemical and biological agents, and physical conditions) are apparently closely related to resources (materials and equipment) used in construction activities. These hazard categories are easily recognized by human. The 4D CAD-Safety developed by Chantawit et al. (2005) is an effective tool for identifying and managing these hazards. Apart from those, the working-at-height hazard is more complicated because it is related to a combination of details of building components and construction activities. It dynamically changes and relocates according to the progress of work. Factors that influence the working-at-height hazard are such as activity type, sequence, component type, dimension, placement, and space. Therefore, it requires sophisticated analyses on identification and safety visualization. This study is focused only on this hazard.

Also, the existing studies (Janicak, 1998; Huang and Hinze, 2003) pointed out that falls were the most frequently occurring types of construction accidents and resulting in fatalities or severe injuries. Fall accidents accounted for the largest percentage of all recorded accidents that is about 52%. Their findings also indicated that falls commonly occurred on small and low cost projects involving commercial buildings and residential constructions. Falls were often associated with workers on roofs, scaffolds, ladders, and floors with openings. The working-at-height hazard is the main cause of these accidents.

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. However, their approach uses the installed sensor and transmitter devices for the hazard identification. Their model cannot explicitly visualize safety measures together with the construction sequence. In this study, we use the 4D CAD model and the rule-based algorithms as tools for the hazard identification, the safety measures visualization, and the safety and construction management integration.

3.3. Functionalities

Safety management is a set of actions or procedures relating to health and safety in the workplace. It consists of three main tasks namely hazard identification, safety measure planning, and control. The developed system is designed to assist these safety management processes.

The hazard identification is the first task to be done during the construction design and planning. It is an important task because only identified hazards can be prepared for safety measures. The developed system inputs data from designs and plans to analyze each construction activity. Designs are an information source about the building components such as type, dimension, placement and working space. Plans give information about activities such as type, sequence, and materials and equipment required. These two information sources will be combined using the 4D CAD model. Rule-based algorithms are needed for analyzing these data to reveal any potential working-at-height hazards.

The second task is the safety measure planning that will automatically suggest proper safety measures to protect or prevent hazards identified from the construction activity. These safety measures are extracted from the SOPs which have already been prepared and kept separately. The SOPs are used as the database of the system and they can be continuously updated. The safety measures are defined in two forms as activities and requirements. Safety measure activities are a task to be done such as install and remove handrails and scaffoldings, and inspect them. They should be regarded the same as a construction activity. Safety measure requirements are just things that must be provided when performing construction activity such as PPE, and safeguard tools. Safety activities will be automatically inserted into the schedule therefore they can be viewed by all relevant parties and be allocated with proper resources such as time, workers, and budget. Safety requirements will be attached to a resource list of the activity. Both will also be incorporated into and visualized through the 4D CAD model.

The safety control task will be done during the construction. Actual data of accomplishment of safety activities and requirements can be collected and compared with what have been scheduled before. Safety accomplishment percentage can be quantified. A schematic concept of the integrated system is illustrated in Fig. 1. The core of the system is the rule-based algorithm which is designed to assist the safety management process as described above. The outputs of the system will be shown to the participants (designers, project engineers, or safety officers). The results may lead to a revision of construction designs or plans in order to be more efficient with safety constraints. Also, SOPs may be accumulated to provide a comprehensive safety database and knowledge for the system.

3.4. The rule-based algorithms for working-at-height hazard

Some previous research has used design drawings and virtual reality of the design to assist safety experts on the hazard identification (Gambatese and Hinze, 1999; Hadikusumo and Rowlinson, 2004). The processes were still heavily relied on human recognition. Some other research (Akinci et al., 2002b; Chantawit et al., 2005; Navon and Kolton, 2006) developed approaches to identify construction hazards, but none of them created the rule-based algorithms to enable the automation in the process.

In this study, it aims to formulate a rule-based system that automates the process. Many factors related to details of both building components and activities (i.e. component type, dimension, placement, working space, activity type, sequence, and materials and equipment) are used as input data. These factors are systematically examined to find any working-at-height hazards. After hazards being identified, the rule-based system also suggests proper safety measures including safety activities or requirements. While being implemented, the rule-based system can be updated and maintained by the safety officers. The safety measures suggested by the system can be visualized via the 4D CAD model.

The rule-based algorithms for working-at-height hazards are formulated and embedded in the 4D CAD model. Fig. 2 shows the overall programming procedure of these algorithms. The main programming procedure loops through the project timeline from the start to the completion dates. At any particular time, the program loops through a list of construction activities and examines each activity individually. The rule-based algorithms are separated into two modules namely the Hazard Explorer and the Safety Measure Advisor. The first one examines input data which are details of the activity and its related building component. The Hazard Explorer results in the activity and the placements where the working-at-height hazards are found. The latter responsively inserts safety measures into the 4D CAD model at the right placement and schedule. The programming procedures of the two modules are described separately.

The Hazard Explorer determines the performing status of the activity that are distinctively defined as not-started, in-progress, or finished. Not-started activities are neglected while only in-progress and finished activities are taken on the following steps. Given that every activity has its own associated building component (represented by 3D CAD objects); the program also determines its component type. Five component types are classified as column, beam, slab, wall, and others. The program retrieves geometric properties of the component i.e. height, top- and bottom-planes. It extracts all edges of the component and results in discrete lines. These lines are evaluated to find top and bottom levels, height, top- and bottom-plane edges of the component. Fig. 3 shows an example of geometric properties retrieved from a component.

Workers could fall from building components or scaffolds around those building components that they are working on (Huang and Hinze, 2003) where they are 2 m. high above the ground level. The placement of the working-at-height hazards can be derived from the top-plane edges of the component. Some temporary structures are required as safety measures to prevent or protect these hazards. They are such as scaffolding, guardrails,

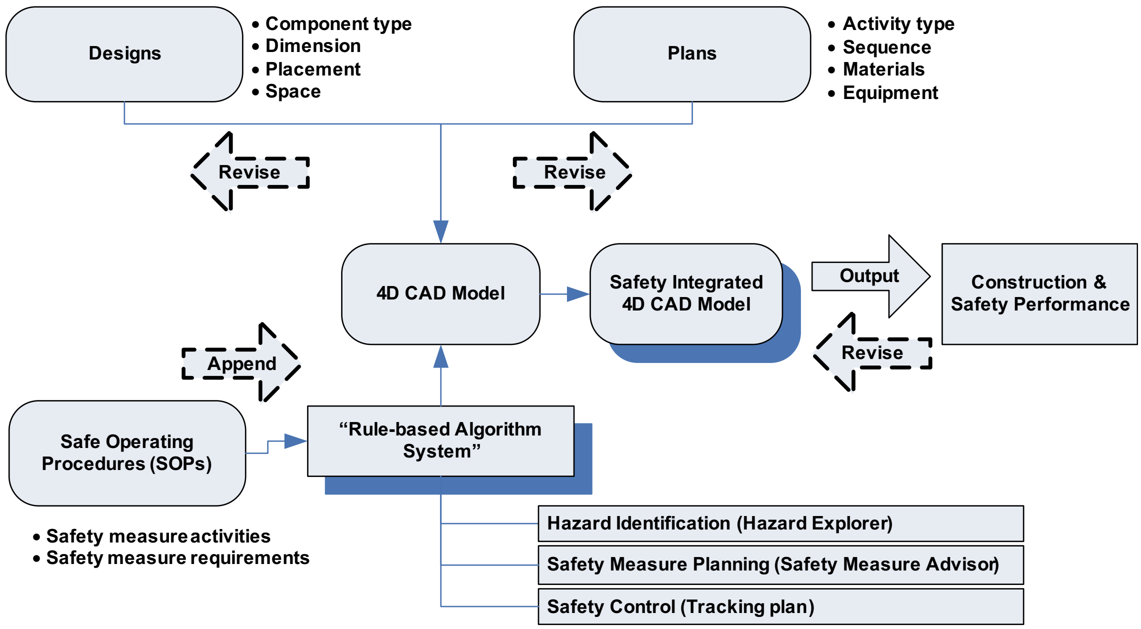

Fig. 1. The integrated system for safety and construction management.

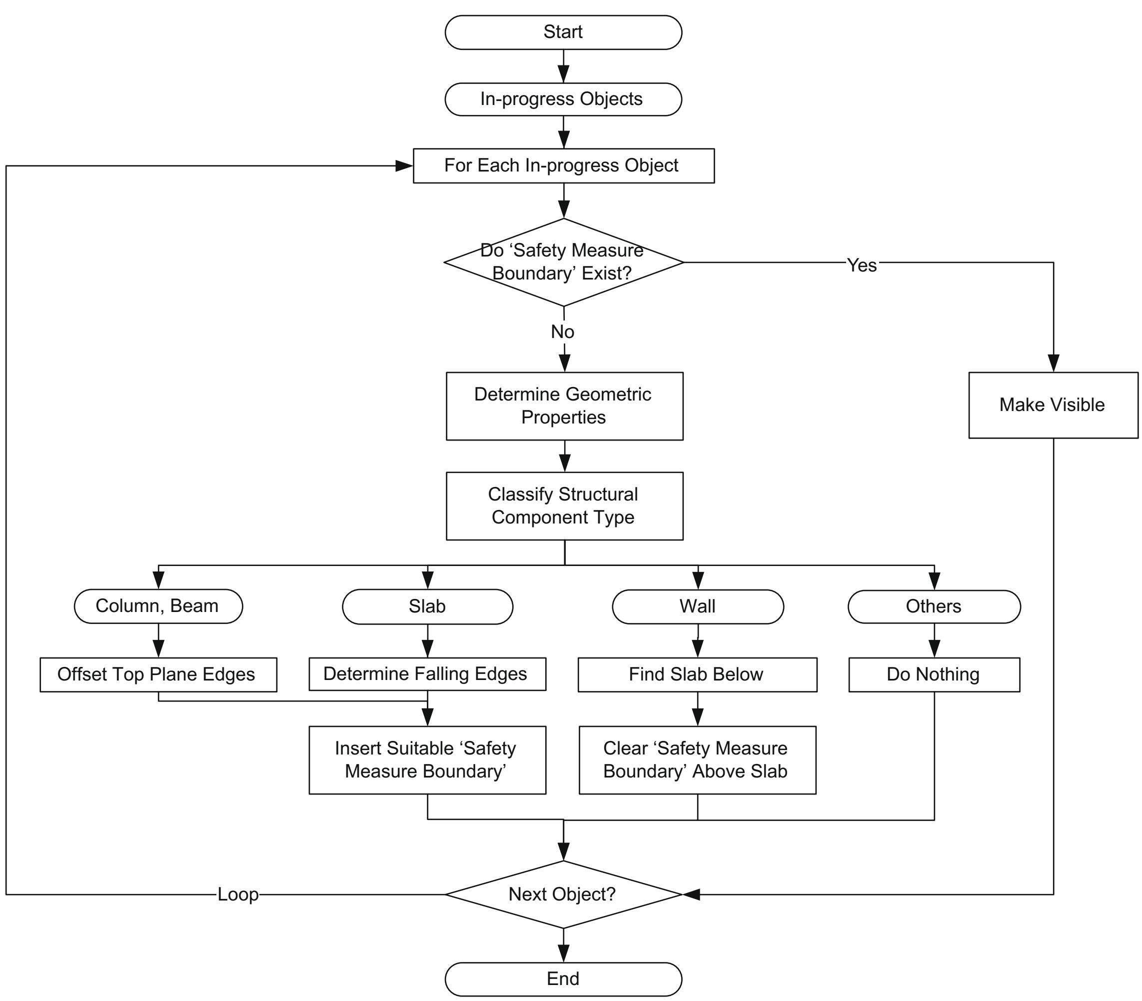

Fig. 2. The programming procedure of the rule-based algorithms for the in-progress objects.

protective partitions and cover plates. Therefore, corresponding boundaries can be delineated for these safety measures.

The other module, the Safety Measure Advisor is responsible for automatically generating (or show) and removing (or hide) proper

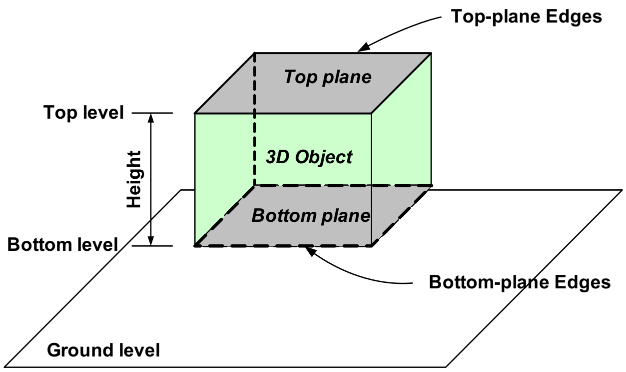

Fig. 3. Geometric properties of a 3D CAD object.

safety measures for an activity. It has different methods designed to handle different performing statuses and component types. In case of the in-progress activities, boundaries of the particular safety measures are generated depends on their component types. It is detailed as the following.

Both columns and beams are provided 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. Fig. 4 shows the boundaries generated for a typical column and beam. The program takes their top-plane edges to create a greater offset perimeter. It then vertically extrudes this perimeter downward by the column height and results with boundary surfaces around a column or a beam.

Slabs are also provided with surrounding safety-boundaries at their edges. The boundaries are separated into two portions, high and low. 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 other high boundaries are located from the top-plane of that slab upward at the height of 110 cm. These represent the guardrails around slabs during their construction. Fig. 4 shows both high and low safety-boundaries generated for a typical slab. The program extrudes the slab's bottom-plane edges downward by the column height and results in the low boundary surfaces. The other portion, high boundary surfaces result from the extrusion upward of top-plane edges by 110 cm. This program can also be applied on a slab with openings. The program finally makes these boundaries (for columns, beams, and slabs) as the safety measure activity (entitled install safety temporary structures) and associates it to the construction plan and the 4D CAD model. Also, the safety measure requirements such as scaffolds, guardrails, are attached to the resource lists of the activities.

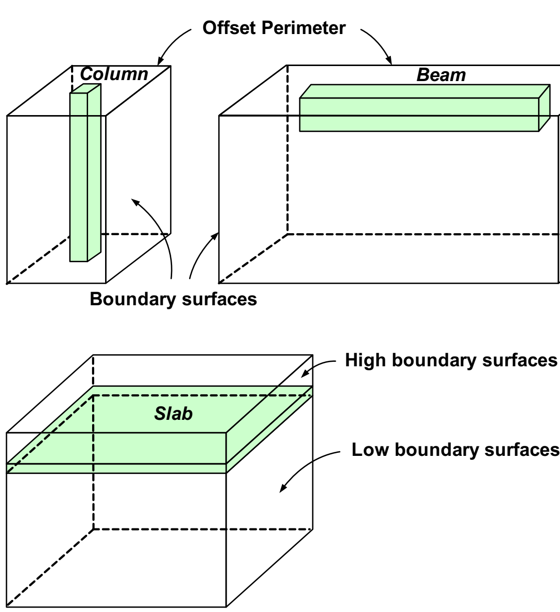

Fig. 4. Safety boundary surfaces for a column, a beam, and a slab.

Walls are different from the other component types. Walls are constructed on a slab. They can be internal or external walls. External walls, which can protect against falls and falling objects, will replace the temporary guardrails which are represented by the high safety-boundaries of the relating slabs. The wall construction will trigger the removal of these high safety-boundaries. The program makes this action as another safety activity required (entitled remove safety temporary structures) and also associates it to the construction plan and the 4D CAD model. Sophisticated geometric operations are formulated to achieve that result. The bottom-plane of the wall is assumed to be on the same level as the top-plane of its supporting slab (or the contact-plane).

All bottom-plane edges of the wall that are longer than 30 cm. are examined and their midpoints (called wall_midpoints) are determined. Then, all slabs (by their top-plane level) at this wall_midpoints' level are examined. The program refers to their high boundary surfaces (already exist). These surfaces considered one at a time. Their midpoints are also determined and called slab_midpoint. All these resulting wall_midpoints and slab_midpoints 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, the program assumes that the wall exists on that side of the slab and removes that relating surface. This midpoint operation also works on a slab with openings.

An example of this midpoint operation for a wall on a slab is shown in Fig. 5. The resulting midpoints of the wall and slab are wall_midpoints as 1, 2, 3, ..., 6; and slab_midpoints as 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 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 have 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 2. Fig. 5 also shows that the midpoint operation can work on a case of a slab with an opening.

In case of 'finished' Objects, their associated safety-boundaries are removed. This applies to columns, beams, and slabs (only for their low boundaries). Walls do not have their own safety-boundaries so that no action is 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'. After that, the program inserts the safety activity entitled removal safety temporary structures and associates it to the construction plan and the 4D CAD model.

3.5. Prototype development

The prototype is developed using AutoCAD Architecture® and Microsoft Project®. Both software supports the automation interfaces and have a Component Object Model (COM). Also, they both

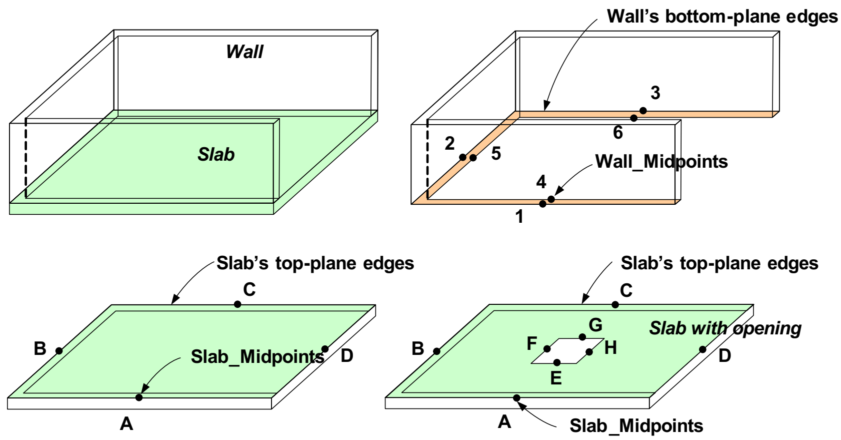

Fig. 5. The midpoint operation for a wall on a slab.

Table 2
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	Remove surface
2	B-1, B-2, B-3, B-4, B-5, B-6	B-2, B-5	Wall exists	Remove surface
3	C-1, C-2, C-3, C-4, C-5, C-6	C-3, C-6	Wall exists	Remove surface
4	D-1, D-2, D-3, D-4, D-5, D-6	-	No wall	Sustain surface

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 prototype consists of the 4D CAD model and the embedded rule-based algorithms named Hazard Explorer and Safety Measure Advisor. Some 4D CAD models (Akinci et al., 2002b; Tanyer and Aouad, 2005) were developed using the IFC or BIM compatible software; however, some others (Wang et al., 2004; Chau et al., 2005; Chantawit et al., 2005) including this research selected the commonly used software for the development. The 4D CAD model is created via linkages between 3D CAD objects (representing building components) and the corresponding construction activities. The simulation control of the 4D CAD model is developed using VBA and AutoCAD's object model. The visualization is exhibited within the AutoCAD while the corresponding schedule information is simultaneously retrieved from the MS Project through the linking keys. The details of the 4D CAD model formulation can be found in the literature so that they are excluded from this paper.

The developments of the rule-based algorithms named Hazard Explorer and Safety Measure Advisor are done on AutoCAD Architecture®. The software distinguishes many types of structural and non-structural components using the 'ObjectName' property. They are such as "AecDbSlab" for slabs; "AecDbWall" for walls; and "AecsDbMember" with 'Type' equals to "aecsMemberTypeColumn" for columns and "aecsMemberTypeBeam" for beams. The safety boundary surfaces created in the program are the 'Surface' type of CAD 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.

4. Prototype implementation and evaluation

A construction project of a three-floor hotel was used as a test case. It was an ongoing medium-sized project (at the time of validation) with the budget of 2.5 million dollars. The hotel had 45 rooms, one 700-seat convention room, and a total of area of 6650 sq.m. The 4D CAD model of the particular project and the rule-based system were formulated. Prospective users including a designer, a project engineer (planner), a site engineer and a safety officer were participated in evaluating the prototype system. This evaluation session was based on descriptive and subjective data given from the participants. The evaluation could not be conducted on a number of projects and this was a drawback of this prototype. The constraints were that the formulation of the 4D CAD model of a construction project was time-consuming and the access of the ongoing project information required full support and cooperation from the company. However, this evaluation was intended to diversify the opinions from different project participants. Criteria for evaluating the prototype were usefulness and ease of use. The usefulness was divided into hazard identification, safety measures advice, safety-integrated construction sequence, construction design and schedule verification, and safety measure control. The ease of use was divided into automation, visualization results, project independency, and 4D CAD model formulation.

4.1. Usefulness

The prototype could identify working-at-height hazards according to the progress of the construction project. Different building components were identified with the hazards at their own placements. Fig. 6 showed a resulting screenshot of the prototype system at a particular simulated time. The construction plan divided the building into two zones: A for accommodation rooms; and B for offices and a convention room. Fig. 6 showed that the project was progressing on the second floor. The in-progress activities were such as a group of columns and cast-in situ slabs in Zone A; a group of beams and long strip cast-in situ slabs in Zone B. The rule-based system could analyze these activities and identify the working-at-height hazards.

The prototype could give safety measure advices. It inserted the corresponding safety-boundaries around the related building

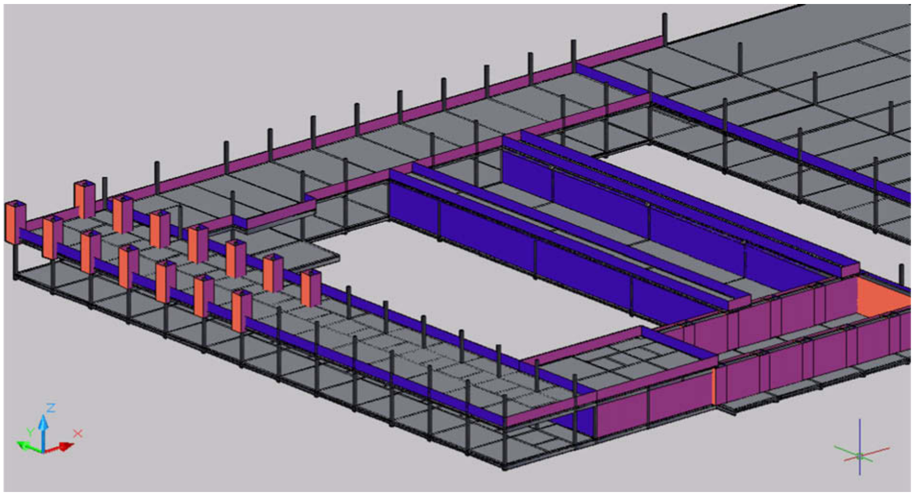

Fig. 6. A resulting screenshot of the developed prototype of the hotel project case.

components of these in-progress activities. The other boundaries were around the completed second-floor slabs. They were the high boundary surfaces which were left in place until the construction of walls on the slabs. When external walls on the second floor were constructed, their associating boundary surfaces would be removed.

The prototype could integrate safety measures into the construction schedule. The original schedule did not provide interval time for the safety activities between the formwork erection and the steel-bar placing activities. The prototype added three safety measure activities into the original schedule such as the scaffolding inspections and the guardrails installation and removal activities. Also, their associated safety measure requirements were attached to the resource list of these activities. The project engineer then revised the schedule to accommodate these added activities. Zone A was subdivided into A1 and A2 so that the carpenters and the masons, who waited for these safety measure activities, could continue their work on the other side of Zone A. Also, a contingency plan was prepared if the scaffolding failed in the inspection and had to be corrected. The safety officer pointed out that this tool could improve collaborations between the production and the safety teams. It hence motivated workers to rigorously comply with the safety measures. The prototype system was an integrated tool that could be used to check the consistency of the design, plan, and safety. It informed participants of the other necessary safety-related activities rather than only the main production activities.

The prototype led to discover some problems on the original design and schedule. In this project, the prototype revealed that a lot of guardrails would be needed according to the original schedule. The guardrails available on site were insufficient. After considering the reuses of the guardrails to keep them at a minimum, the construction sequence was revised. Activities related to the wall construction were rescheduled to follow the slab construction more closely. Also, a group of the welders were reallocated from the roof truss assembly to the guardrail installation activities. Since this project used a lot of pre-cast slabs, a tower crane was a critical sharing resource. The prospective users were notified that its slings needed to be replaced regularly. These safety measure activities needed an execution time that could halt the pre-cast slab installation activities; therefore, they were scheduled on the overtime and the next morning was spared in case they were not finished.

The prototype could support safety measure control. As the safety measures were added into the construction schedule, the progress of these activities was properly monitored. The actual data of percentage complete of the activities were regularly required to update the schedule. Any nonconformity was easily found and corrected. The prototype ensured that the necessary safety measures were accomplished in the right sequence.

4.2. Ease of use

The automation of the prototype helped reduce interactions required from the users. The construction schedule was normally prepared based on the production aspect. The rule-based algorithms could automate the safety management tasks for the users. Hazard identification, safety measures integration, and control were automatically assisted. The project engineer could then considered potential safety constraints and coordinated with the designer, the site engineer and the safety officer in advance.

The prototype system could explicitly visualize the construction scenes and sequence which looked closely to the real site (as shown in Fig. 6). The visualization of the 4D CAD model was very impressive. The safety measures were incorporated into the construction sequence and easily perceived through graphics. The safety-boundaries could help indicate the space required for temporary structures and guardrails, and the remaining space for safe work. The simulated construction sequence with safety created a clear and mutual understanding among the project team.

The rule-based algorithms were project-independent. They were designed to analyze the geometric properties of 3D CAD objects which representing building components and the schedule information. Once the rule-based algorithms were formulated and maintained, they could be applied to any construction project as this project test case. They were a programming VBA code which could be exported and re-embedded onto a new project file.

The formulation of the 4D CAD model for the construction project was a skillful and effortful task. The 3D modeling of the whole construction project was required. The modeling needed to be systematic and precise and had to use the right kind of CAD objects. The performance of the rule-based algorithms was heavily relied on the correctness of the 4D CAD model. All participants in the session stated that this model formulation task was very difficult and hindering the efficiency of the prototype. An approach to reduce this effort can be a challenge of the future research.

5. Conclusions

This research developed an integrated system for safety and construction management that early incorporates safety measures into the designs and plans. The system helps all participants consider and prepare for safety constraints before that work is actually executed. For medium and small construction projects where usually absents a full-time safety officer, this system can assist project engineers to concurrently manage safety and construction. The rule-based algorithms are formulated to help automatically identify working-at-height hazards in designs and plans, and responsively advise proper safety measures. The working-at-height which is a principal contributor to fatal construction accidents is a very complicated hazard and relates to many causal factors. These integrated safety measures are also visualized via the 4D CAD model that will clearly notify the participants. The visualization can be used to check the constructability and revise designs, plans and controls for safety. The system can facilitate the effective and successful implementation of the safety management throughout the construction process and it helps to make the construction a safe workplace. The evaluation of this prototype was conducted on a construction project. It was the drawback of the prototype generalization.

Limitations of the system are such as the effort to build up the 4D CAD model and the safety rule-based algorithms at the first implementation. Future research can alleviate this process or propose other different approaches for the holistic integration. In addition, the success of the system implementation requires project participants to value the safety as the most important issue.

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