Development of a System for Construction-Space Management and Safety Analysis Using Virtual Reality Technology in Dynamic Environment

Noppadon Jokkaw and Tanit Tongthong
Department of Civil Engineering, Chulalongkorn University
Phayathai Road Patumwan
Bangkok 10330 Thailand
Tel. 0-2218-6459
Email: *fcettt@eng.chula.ac.th*

Abstract

The objective of this paper is to present a system using the Virtual Reality (VR) technology for supporting decision making in construction-space management and safety analysis of construction processes. The proposed system provides abilities to create the virtual construction area, facilities, building components and construction machines. The proposed system is developed to express the resource movements similar to the real world construction operations and allow users to be as a part of the dynamic environment. Two construction sites with different construction operations are selected to obtain data for system development and also used as experimental cases. The proposed system assists project planners to effectively manage construction space and safety analysis by considering the selection of construction equipment, techniques of construction, sequences of construction activities, positions and paths of construction equipment and installation methods of building components. The virtual dynamic movements of equipment in construction operations allow construction managers to investigate the safety conditions of construction operations similar to when they perform in the actual construction.

1. Introduction

Accidents and space conflicts have been seen in many construction sites in Thailand. One of the causes of such problems is due to poor management in construction site operations. Construction managers normally use past experiences to deal with site layout, equipment selection, and operation sequences. Thorough planning of construction operations by the construction teams helps eliminate the problems. However, it is not an easy task to manually implement. For construction site planning, project managers should consider all limitations in the construction site in order to manage the construction activities to be smoothly performed without conflict of any resources. The construction area normally involves a lot of resources such as materials, labors and equipment. Spaces are basically required by such resources for their necessary operations, for examples, the space for material storage, the space for workers and the space for construction equipment movements. The limitations of construction site, the dimensions of building structure and equipment, and the space for construction resources' activities are the main factors for determining the construction techniques, equipment and sequences that may affect both project duration and cost. The project managers, therefore, need some tools to assist them to make a proper decision of construction site planning such as appropriate location of facilities, methods and sequences, and appropriate movement paths of resources.

For the safety analysis, normally, it is difficult for construction managers to think about safety at the state of planning. They may be able to deal with a physical situation where a certain safety procedure can be assigned. However, to do safety analysis for the resource movements at the stage of planning is quite

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difficult. This paper presents the interactive virtual system, which assists the construction managers to improve their decision-making in construction space management and safety analysis.

The proposed system, which is Virtual Reality based helps illustrate the construction activities in dynamic processes of virtual environment. The construction managers can increase their effectiveness in planning by visualizing the construction processes in all dimensions: x, y, z and time. The factory construction in Thailand is selected as a model to describe the development and applications of the system

2. The Related Research

Where as Virtual Reality (VR) refers to applications of advance technology creating virtual space for illustrating the real world in computer, Virtual Model (VM) is a part of VR and is created for illustrating the real word in computer like virtual reality but it is specifically purpose only for learning [1]. Compared with computer animation which can only show figure movement like video or movie scrip, the VM allows users to be able to observe and explore inside the virtual model, for example, walking through, rotating or flying. In the past, virtual reality was just applied in the entertainment industry but was not worldwide used for the construction because of the low computer ability and high implementation cost. Computer technology, recently, has been developed until it has high ability at low cost. The VR then can be applied to enhance effective operations of several industries such as in architectural designing and medical training including some research in construction field.

Ogata et al. (1999) [2] described the application of Virtual Reality in a map presentation. The VR model was used instead of Physical Mock Up (PMU), which was popular for creating models. This application was developed by using VR software called "Supperscape" that can be used to link between electronic map and virtual details. The user can select an interesting point on the map that needs to be observed and automatically linked to virtual details. In addition, this application can present the virtual details on Internet browser. AbouRizk (2000) [3] integrated simulation model with 3D CAD for earthmoving operation. Simulation models were automatically generated from high-level descriptions in CAD by using add-on tools to capture key information. Whyte (2000) [4] presented virtual reality techniques for housing developers to make the marketing plan and to improve the quality of newly built housing. Planners can model urban environments in 3D electronic space by using CAD and visualization techniques. Lipman and Reed (2000) [5] applied Virtual Reality language called "VRML" version 1997 to create construction model. The research was focused on creating virtual model of steel structures and construction equipment. The VRML prototype was used to create a beam object that provides a simple way to specify thousands of different types of beams with their positions. The users can walkthrough to observe several views and also control construction equipment by using control bar on Internet browser. Kamat (2001) [6] developed 3D visualizing simulated construction operation called "DCV (Dynamic Construction Visualizer)". It was the first version of a general-purposed visualization or animation system specifically designed for the earthwork operations, which involve excavation, transportation, and placement or disposal of materials. DCV was developed from computer graphic programming libraries called "Cosmo3D and OpenGL Optimizer" distributed by Silicon Graphics Inc.

For the research related to space management in construction, Tommelein et al. (1991) [7] used expert-time strategy to develop a layout tool called "SightPlan". It can create layouts over the duration of construction project by locating given temporary on-site facilities to their schedules. It places one facility at a time through a constraint satisfaction search. MovePlan Model was developed by Tommelein (1993) [8] and has been used as a decision-support tool to establish dynamic layouts. The users can apply

MovePlan to plan the position and the movement of construction resources on construction site for discrete time intervals. It can not only support users by identifying resources on site for a given time period but also, under consistent maintenance mechanisms, enforce that only consistent layouts be generated. To analyze the space conflict problem, Gue (2002) [9] applied two typical tools. AutoCAD was applied for space planning and Ms-Project was for scheduling. The CAD system was used to display the space planning result for various subcontractors. By linking to MS-project, the system can suggest a revised or updated schedule, according to the delay caused by space conflicts.

However, the research has experimented based on static models where the users can walkthrough within the static models. Or, some of them developed in animation environment where the dynamic movements are pre-set. This research generated the dynamic environment where the resources involved in the construction processes are simultaneously moving among other static models and allow users to be able to experience in the dynamic environment.

3. Virtual Reality Model Development

In this research, the CAD software was used to create the 3D static models of construction facilities and resources in scale. These models can be imported into the visualizer software, which used as an animator or visualizer to display the virtual construction-site. Programming is developed to manipulate on simultaneous movements of resources and control analysis views.

3.1 The 3D Static Models

In this research, the 3D feature in CAD software is applied to create the 3D static models. The structure of models is created in scale. The structure of model components is assigned its name by the name of layer (one component per one layer).

The 3D models in this research are classified into 3 categories, i.e., models of construction machines and equipment, models of building components, and models of temporary works and facilities, as shown in Figure1. These models are created as static models by using CAD software as shown in Figure 2.

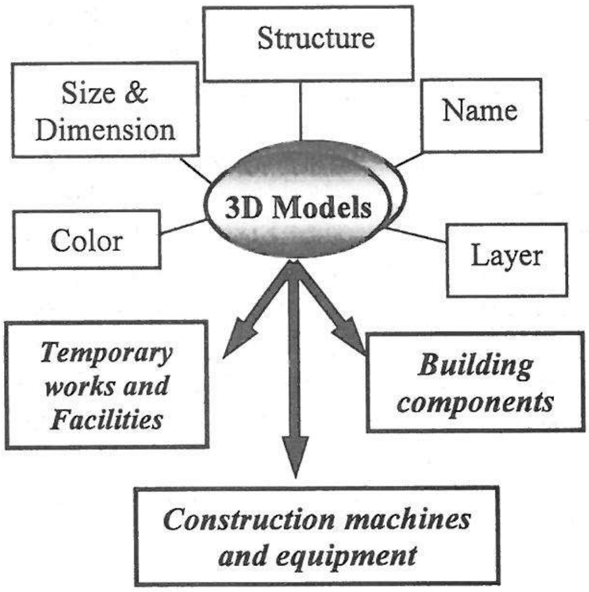

Figure 1: Virtual realty model components

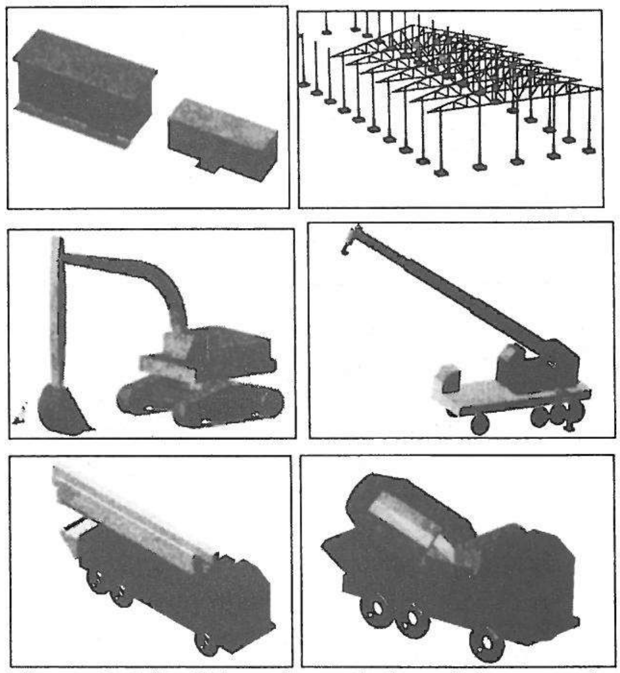

Figure 2: The 3D static scaled models created by CAD

3.2 The 3D Dynamic Models

After the static models are created by AutoCAD, they are imported into 3D visualizer in order to assign their characteristics and mechanisms. Name and color of each component must be assigned by using the command in the rollout of name and color. The important step of characteristic assignment is to assign pivot points to the components of the 3D models. Since the pivot points of the components are the important points, they are used as the center point of the components rotation and movement. These components must be linked together so that one object is superior and it can control the transformation of one or more subordinate objects or components. Object linking and building hierarchical structures are used in 3D modeling and animation as shown in Figure 3. These mechanisms are very important to express the real movements of resources, which are also key functions for space and safety analysis among various machine operations.

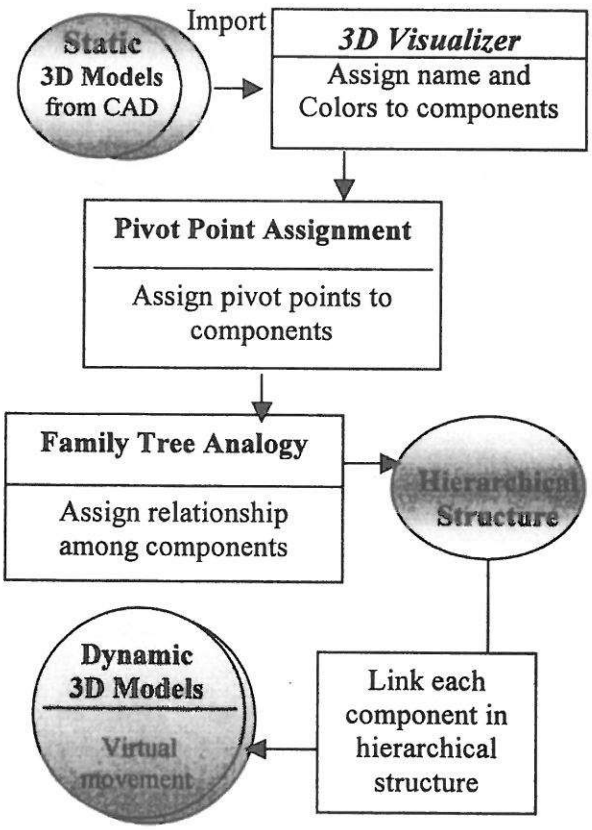

Figure 3: Flowchart of 3D dynamic model development

The examples of 3D dynamic models of equipment are illustrated in Figure 4, and Figure 5.

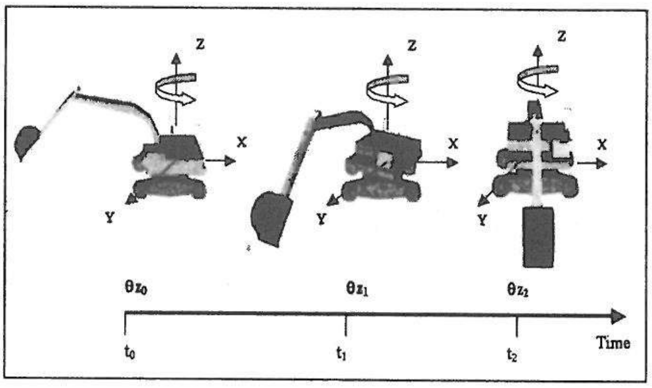

Figure 4: The 3D dynamic models of an excavator

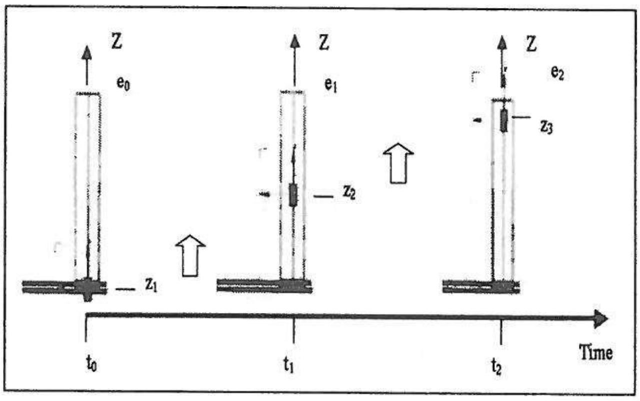

Figure 5: The 3D dynamic models of a pile-driving machine

4. Construction Space Management

Construction space management is an important task of construction project planning. Space management consists of construction-site layout and space conflict analysis. Site layout is used to manage the facilities and resources in construction site operations by determining their sizes and shapes and also locating position of the resources within the boundaries of the construction site.

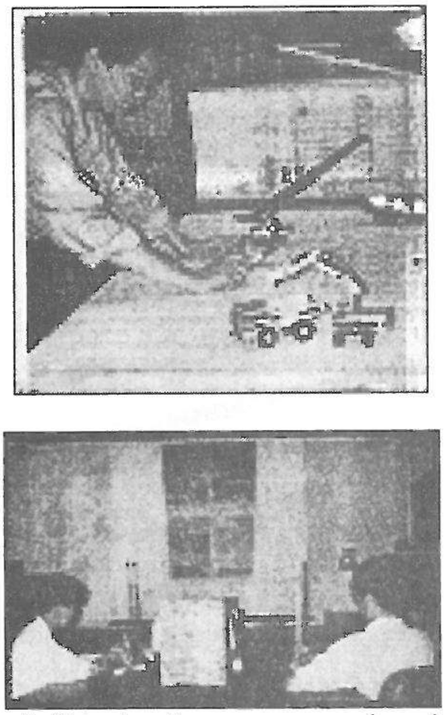

Figure 6: Construction process and equipment planning using physical models

For example, construction project planners may employ the scaled physical models and 2D drawings to experiment, analyze and manage space in construction site as shown in Figure 6. The operations of equipment and the conflict of working spaces are analyzed by construction managers to choose the suitable space management and method of work. This method is also good for communication among the parties as to let them know their responsibilities and schedules. However, if there are many resources involved and the operations consist of several steps at different times, this approach is not practical, especially, when what-if analysis is required to repeat some certain steps at a period of time.

4.1 Construction Site Layout

Construction site layout is one of the major tasks in project planning, which may lead to some space conflict, re-allocation of facility, or delay of some activities after the project starts. Site layout consists of identifying the facility and resources needed to support construction site operations, determining their sizes and shapes and also locating the position of resources within the boundaries of the construction site. The facilities allocation on site is a routine but not an easy task. For the construction of factory buildings, the facilities and resources for site layout can be classified into 3 types as follows: temporary facilities, permanent materials and construction equipment. Temporary facilities refer to construction site facilities that can be removed or demolished after construction project or construction activities completed, for examples in this case, site office, scaffolding, material storage area, maintenance and service area, prefabricating area and labor camps. Permanent materials refer to installed materials of construction components, for examples, piles, RC footing, RC column, steel column, roof structures and wall.

Construction equipment refers to the major equipment or machines for component installations, for example, mobile cranes, tower cranes, excavators and trucks. The sizes or dimensions of such equipment may affect construction operations.

In generally, project managers or project planners can use the 2D drawings to arrange construction site boundary and allocate the facilities and resources. But the limitations of 2D approach make the difficulties to visualize the construction sites in all dimensions, which may bring about the complicate problems later. The 3D or virtual reality, however, is aimed to solve such limitations. Whereas the AutoCAD is used to create the 3D CAD models of facilities and resources in scaled models, the visualizer modifies the 3D models to be active objects and is used as an animator or visualizer to display the virtual construction site. The planners can move or make changes to the types and positions of 3D models for optimizing the locations of the facilities and resources within the limited boundary to obtain more practical construction site layout, as shown in the Figure 7.

Various types of equipment can be explored and their operations and movements can also be tested to investigate their movement paths or operation areas whether they interfere other resources' activities or are obstructed by any facility components. What-if analysis of suitable set of equipment can be discovered among their real time movement via walkthrough function allowing project managers as in among the real dynamic construction environment.

observe dynamic construction operations at different locations and angles. The project managers can investigate unforeseen problems and do some prevention before these conflict operations may occur in real construction.

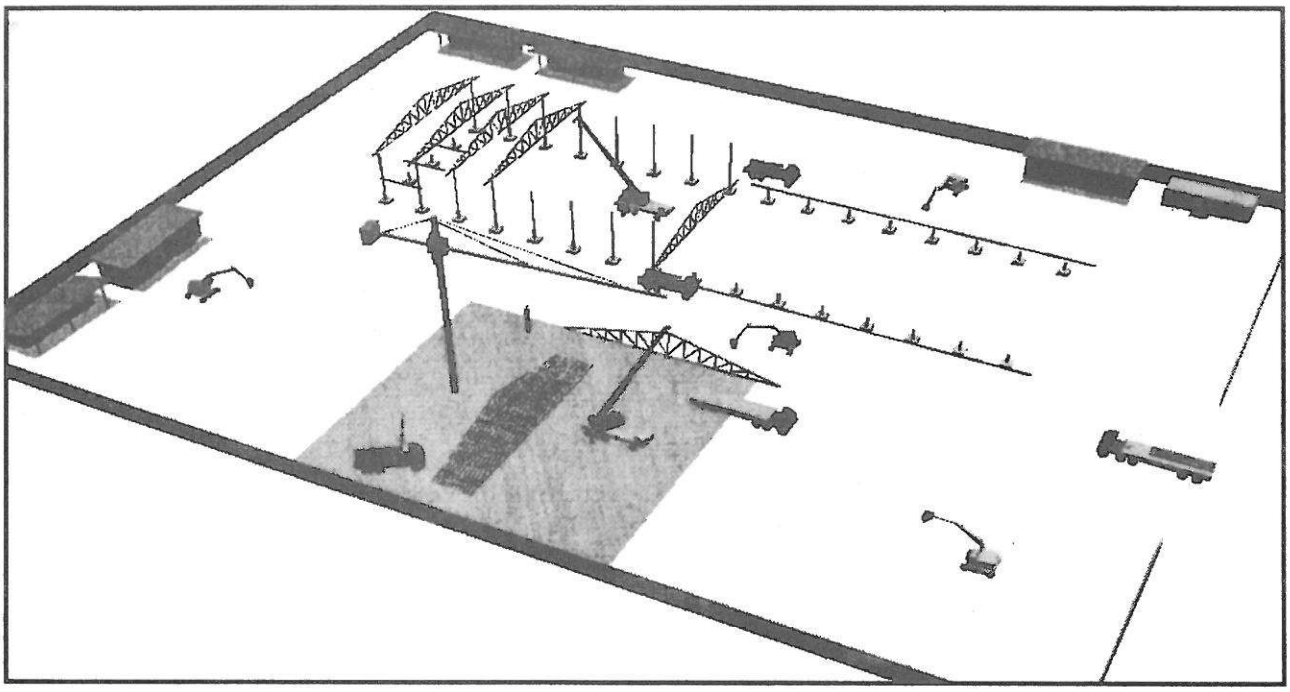

Figure 7: Construction-site layout by virtual reality approach

4.2 Space Conflict Analysis

Construction operations normally require space. Space conflict is a problem normally found in a construction site. The construction space model describes the types of construction spaces needed for construction work elements and the space occupied by completed work units. The construction space model defines two types of spaces. Areas are spaces occupied by activity work elements for a period of time and paths are spaces required for movement of materials, people, and other resources.

In this paper, the 3D CAD models and 3D visualizer are applied to analyze the space in construction site. Because of the potential of these 3D tools, which can display the construction site models in all dimensions (x, y, z, and time), the project managers can walkthrough into the virtual construction site to

According to the advantages of virtual reality, the project manager can observe and solve space conflicts effectively in all dimensions by changing some conditions of construction operation as follows:

1) Changing construction methods
2) Changing construction sequences
3) Changing resources used
4) Changing construction-site layout

These changing can be performed in a short period of time and after that the system can repeat at various specific conditions.

In Figure 8, an excavator is used to carry and move roof-trusses that will be continuously installed by a mobile-crane. The excavator operation can be simulated to determine appropriate operation paths and analyze space conflicts. In Figure 9, the excavator cannot move through rows of columns due to insufficient space. Thus, the operation path of excavator is changed by using new path outside the building instead as shown in Figure 10.

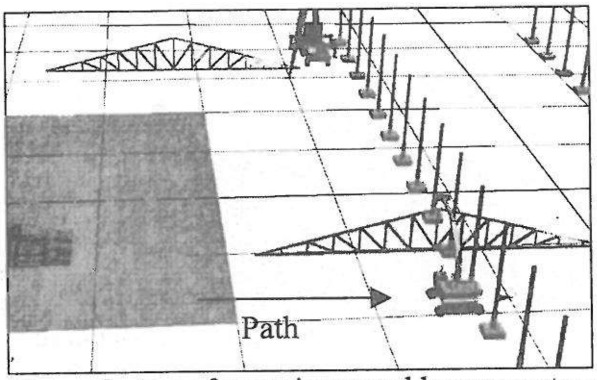

Figure 8: A roof-truss is moved by excavators

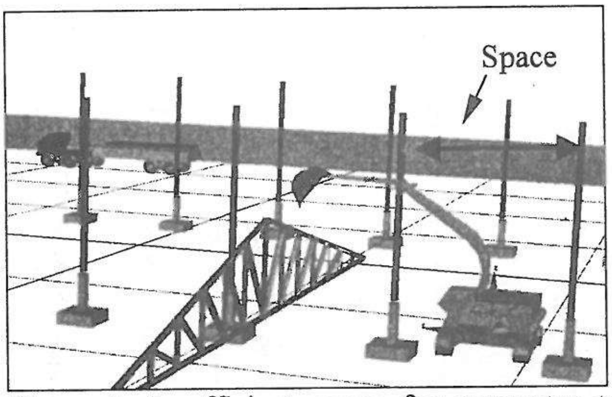

Figure 9: Insufficient space for excavator to move a roof-truss

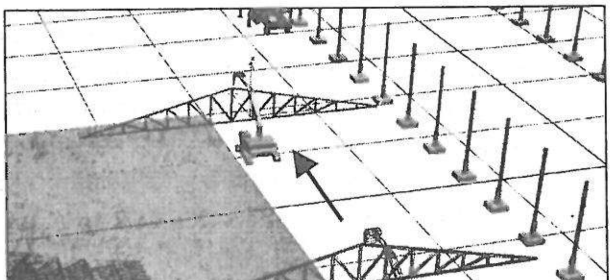
Figure 10: Alternative moving path to avoid space conflict

In Figure 11, the 3D visualizer can display that there is enough vertical space for roof-truss installation by mobile crane.

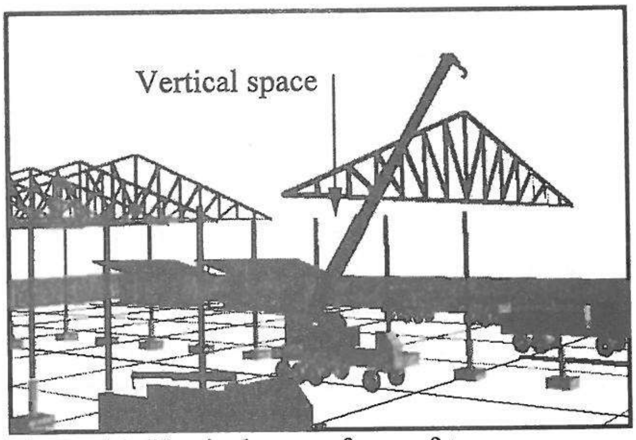

Figure 11: Vertical space for roof-truss installation

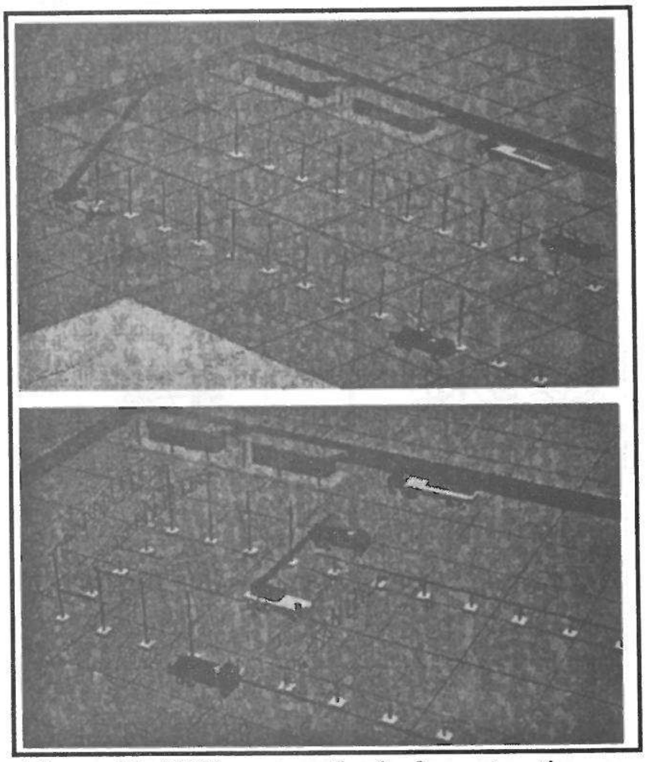
Figure 12: Different method of construction

Figure 12 presents different methods of construction, which may reduce space conflict and increase effectiveness installation of column and roof-truss.

5. Safety Analysis

As mentioned, the safety analysis on the movements of resource is beyond the thinking of construction managers due to three physical dimensions and dimension of time. The proposed system can display the construction site models in all dimensions (x, y, z, and time) and the project managers can walkthrough into the virtual construction site to observe the dangerous areas and dangerous events (time dimension). The project managers can also investigate unforeseen problems and do some prevention before these dangerous operations occur at the construction.

Figure 13 and 14 show the horizontal space conflict occurs when the mobile crane swings its arm to install a roof-truss generating a dangerous event if, at the truss-turning state, the mobile crane stands to close to installation area. Thus, the project managers can perform extensive investigation to explore the dangerous events via setting themselves as in a real situation on the virtual reality event and make some precaution to provide safety operations by changing working methods and sequences of operations or selecting different sizes of the equipment.

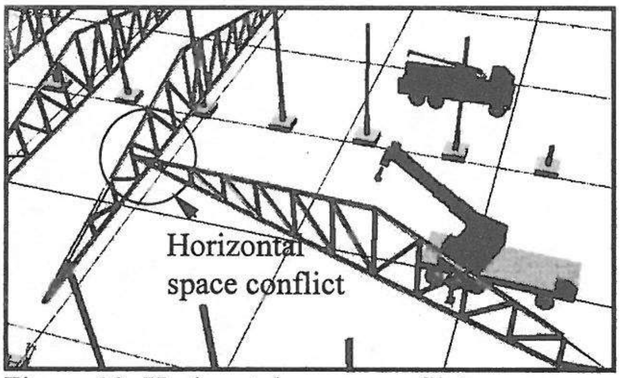

Figure 13: Horizontal space conflict area

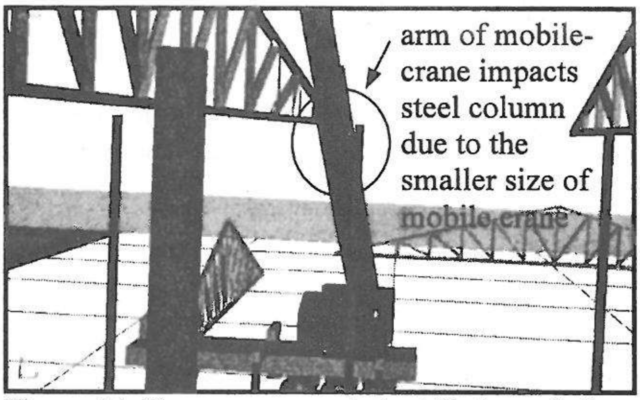

Figure 14: Dangerous event: installation of all columns and then the roof-truss

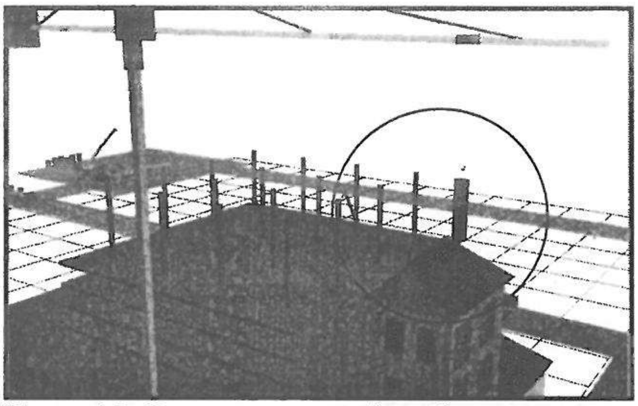
Figure 15: Dangerous operation of tower crane over a residential housing due to inappropriate tower crane location

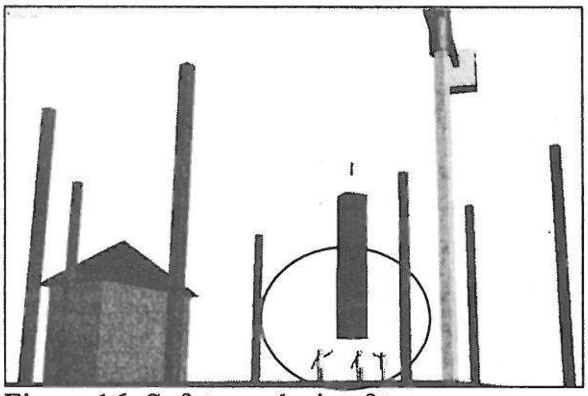
Figure 16: Safety analysis of tower crane operation over human workers

In Figure 15, tower crane operation is not safe because it is operated over the residential building due to inappropriate location of tower crane. Figure 16 shows that project managers can experiment tower crane operation among human workers for safety procedures. The proposed system can be applied to simulate various dynamic movements of construction resources, which assists project planners to investigate the safety of construction operation before they start the actual construction Managers and workers can be together to perceive the suitable procedures for their safety.

6. Conclusion

This paper presents the system developed based on Virtual Reality to assist construction managers to perform construction space management and safety analysis by placing the construction teams in the virtual environment of construction operations allowing them to explore their planned operations before hand. The system simulates the construction processes in virtual environment within four dimension of x, y, z and time.

This approach can assist project managers to generate the construction site planning, which is more flexible than experimenting by the physical scaled models. The construction managers are able to play what-if analysis on their planned operations in order to obtain the suitable equipment and methods of work.

The system helps the project planners to prepare practical construction plan to avoid and prevent space conflict, accidents, or hazard events that may occur during real construction processes.

9. References

[1] S. Ogata, "Application of Virtual Model to Achieve Consensus for Construction Project", Journal of Symposium on Civil Engineering Information Processing System, JSCE, Tokyo, 1998, pp. 81-88.

[2] S. Ogata, "Case-based Analysis for Virtual Model Application in AEC Industry" Proceedings International Conference on Information Visualization IV, London, England, 1999, pp. 566-571.

[3] S. AbouRizk, and K. Mather, "Simplifying Simulation Modeling Through Integration with 3D CAD", Journal of Construction Engineering and Management, Vol. 126, No. 6, November/December, 2000, ASCE.

[4] J. Whyte and N. M. Bouchlaghem, "Evaluating New Housing: The Potential for Developers and Planners to Use Virtual Reality Techniques" Online Planning Journal, 2000, (http://www.casa.ucl.ac.uk) (Accessed 09-07-2002).

[5] R. Lipman and K. Reed "Using VRML in Construction Industry Applications" Web3D-VRML-2000 Symposium, Monterey, 2000, CA.

[6] V. R. Kamat and J. C. Martinez, "Visualizing Simulation Construction in 3D" Journal of Computing in Civil Engineering, Vol.15, No.4, October 2001, ASCE.

[7] I. D. Tommelein, R. E. Levitt, B hayes-Roth, and T. Confrey, "SighPlan Experiment: Alternate Strategies for Site Layout Design" Journal of Computing in Civil Engineering, Vol. 5, No. 1, January, 1991, pp 42-63.

[8] I. D. Tommelein and P. P. Zouein, "Interactive Dynamic Layout Planning" Journal of Construction Engineering and Management, Vol. 119, No. 2, June 1993.

[9] S. Guo, "Identification and Resolution of Work Space Conflicts in Building Construction" Journal of Construction Engineering and Management, Vol. 128, No. 4, August, 2002, ASCE.