

INCREASING THE UNDERSTANDING OF LEAN PRINCIPLES WITH ADVANCED VISUALIZATION TECHNOLOGIES

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ABSTRACT

Advanced production management principles, like those of lean construction, have tremendous potential to improve the construction of projects. Ideas of lean construction have been proposed for more than ten years. These have had success, but they have hardly revolutionized the industry like lean production has impacted the manufacturing industry. One significant challenge facing proponents of advanced production management in construction is the ability to articulate lean construction principles in a meaningful way to new users. Advanced visualization technologies like 3D and 4D Computer Aided Design (CAD), can help managers and foremen visualize the impact and usefulness of these principles.

This paper describes an experiment performed with a graduate class to assess the use of 4D CAD for visualizing the various elements of production flow. Students were asked to assess a Critical Path Method (CPM) schedule for production flow characteristics. They were then asked to review the same sequence of work in a 4D CAD model. A large proportion of the class did not identify the flow issues in the CPM schedule, but most of them identified critical flow issues in the 4D CAD model. It was concluded that this visualization technology helped the students identify, explain and develop a deeper understanding of advanced production management principles.

KEY WORDS

Production flow, lean construction, 4D CAD modeling, visualization

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INTRODUCTION

Ideas of lean construction have been proposed now for more than ten years. The main principles include understanding construction as production, and the role that production oriented tools like the Last Planner can have on the operation of construction projects (Ballard 2000; Koskela 1992; Koskela 2000). One significant challenge facing proponents of advance production management in construction is the ability to articulate lean construction principles in a meaningful way to new users. These new users may not have much background in the theory of production management. It is desirable to have some method to present the lean construction principles directly and clearly.

Advanced visualization technologies such as 3D and 4D Computer Aided Design (CAD) can help potential new users like managers and foremen visualize the impact and usefulness of these lean construction principles. 4D CAD here refers to 3D graphical computer model plus schedule (Koo and Fischer 2000). 4D CAD modeling can animate 3D models according to the Critical Path Method (CPM) schedule. With this modeling, the construction processes can be viewed repeatedly and can be paused to analyze detailed sequencing issues.

This paper presents a method of articulating the production flow idea in lean construction through the use of 4D CAD modeling. An experiment was performed in a graduate class to examine the effectiveness of the 4D CAD model to visualize the flow of production on the project. Students were asked to examine a Critical Path Method (CPM) schedule along with a set of 2D drawings for production flow characteristics. The students were then asked to review the same construction project by viewing a 4D CAD model. Only a limited number of students were able to identify the flow issues in the CPM schedule, but a majority was able to identify them with a review of the 4D CAD model. It was concluded that this visualization technology helped the new users identify, explain, and develop a deeper understanding of advanced production management principles.

BACKGROUND

LEAN CONSTRUCTION PRINCIPLES

The idea of understanding construction as production was presented by Koskela (1992), who suggested how to integrate the Transformation, Flow and Value (TFV) model into construction. Contrary to the popular conceptualization of production in terms of transformation of inputs to outputs, the TFV concept uses the conception of production as consisting of flows of material and information through networks of specialists, and the conception of production in terms of generation of customer value (Koskela and Ballard 2003).

Construction as flow is a main concept in lean construction. There are three types of flow on a construction site, namely, material flow, location flow and assembly flow, in contrast to two types in the factory (material flow and assembly flow). Material flows in car production and site construction are compared as in Table 1. As can be seen, both the location flow and the assembly flow are highly related to the direction moving and the sequence of the specific construction trade. The location flow can be described as the movement of the specific trade through the building, while the assembly flow, the moving sequence of these trades.

Table 1: Flows in car production and site construction (Koskela 2000).

	Car production	Site construction
Material flow (Supply Chain)	A seat is assembled in the seat factory, transported to the car assembly factory, transferred to the workstation and installed.	A window is assembled in the window factory, transported to the site, transferred to the place of the installation and installed.
Location flow	The seats of one car are installed as one task at one workstation.	All window openings proceed through the installation workstation (in practice, the team moves throughout the building).
Assembly flow	The car body moves through all workstations of the assembly line.	The building proceeds through all assembly phases (like window installation, partition wall construction, etc.).

FLOW IN CONSTRUCTION

Building construction involves a large number of trades that generally work closely and interdependently. These trades may be responsible for the building's foundation, steel erection, decking, formwork, concrete reinforcing boards, concrete, dry wall, mechanical, electrical, plumbing, roofing, glazing, vertical transportation systems, fire and sprinkler systems, and environmental controls. These trades can be organized as follows (Riley and Sanvido 1997):

- *Structural Trades*: e.g. erecting structural steel (steel erector); placing and securing decking as well as welding shear studs (decking contractor); and placing rebar, then pouring and finishing concrete (concrete contractor).
- *Overhead Work Trades*: e.g. installing HVAC system (mechanical contractor), sprinkler system (fire protection contractor), emergency lighting (electrical contractor), and pipe (plumbing contractor).
- *Interior Finishes Trades*: e.g., installing wall studs, routing electrical conduit, placing insulation material, hanging drywall, and painting.
- *Perimeter Enclosure Trades*: e.g., building perimeter walls, placing windows, installing flashing, and applying sealants.

It is important to identify the reciprocal dependencies of these trade flows early in construction planning (Riley and Sanvido 1997). A Parade Game and a computer simulation are used to illustrate what impact workflow variability has on the performance of construction trades and their successors (Tommelein et al. 1998). Simulation can be very useful to understanding the nature of workflows.

INFORMATION TECHNOLOGY AND ITS APPLICATION IN LEAN CONSTRUCTION

Several approaches have used information technology to better understand the impact of lean construction. A pull-driven scheduling for pipe spool installation is tested and simulated with discrete-event simulation by Tommelein (1998). Several deterministic and probabilistic

models were tested and their buffer sizes compared. The advantage of the pull-scheduling is illustrated compared to a push-driven principle. Another approach describes the methodology of a data mining program to implement pull techniques in construction information systems (Caldas and Soibelman, 2002). A prototype and two case studies are presented to illustrate the feasibility and potential of the automated document classification methods. These uses of advanced technology have been helpful for understanding the implications of lean principles in construction project management. However, few focus on using advance technology to provide project managers and superintendents a tool for evaluating production flow in real time on a construction project.

METHODOLOGY

This research presents the comparative analysis of the use of traditional schedules against advanced visualization technology to evaluate production flow. An experiment was performed with nine students in a graduate construction management class in Architectural Engineering at Penn State University. The objective of the experiment was to develop student skills at evaluating flow in a construction operation.

Production flow is an essential concept in construction production management. Good flow refers to production flow with characteristics of work continuity, avoidance of space conflicts with other contractors or activities, and consistent work direction.

Flow continuity is one of the main characteristics for measuring production flow. The unexpected variability in pace or a pause of the production flow normally causes delay to site crews, induces double handling of material, promotes the unnecessary build up of site inventory, and impedes the start of successive trades. It is essential to understand the importance of shielding production flow from unexpected variability and to keep movement continuous (Ballard 2000).

Avoidance of space conflicts is another essential criterion to evaluate good flow. Labor, equipment, material and temporary structures from different construction trades require their own adequate work space to maximize a productive rate and minimize possible safety problems. It is desirable to coordinate the flow of these trades and manage the work space effectively to avoid potential space conflicts.

The right direction of the production flow is another distinct criterion. There are several alternatives for site managers to execute construction. Different construction flow directions lead to various effects on the flow of other trades. Take masonry wall construction for example, the masonry contractor can either build face-by-face, or construct multiple faces at the same time, or even construct the entire perimeter all at once. The face-by-face sequence may reduce the movement of the site crew and reduce the amount of the scaffold; however, the flow of interior finish trades will be disrupted. The later one might be a faster choice for the masonry trade; however, it may disrupt other perimeter enclosure trades.

Thus, good flow may have several characteristics. This paper focuses on continuity, space conflict and appropriate direction in the evaluation of flow.

EXPERIMENT DESIGN

A Primavera schedule and 4D CAD model of the Space Hangar of the National Air & Space Museum project was used for the experiment. The National Air & Space Museum is a \$150

million project in Dulles, VA that will house examples and artifacts of aviation, shown in Figure 1. This project is part of the Smithsonian Institute and will complement the current Air & Space Museum on the Washington Mall. The main hangar of the building consists of 21 arch trusses each spanning 220 feet and weighing 200 tons. This experiment focuses specifically on the Space Hangar. The space hangar was an addition to the project that will house the space shuttle and related artifacts. Its structure is a steel space frame that has a membrane roofing system.

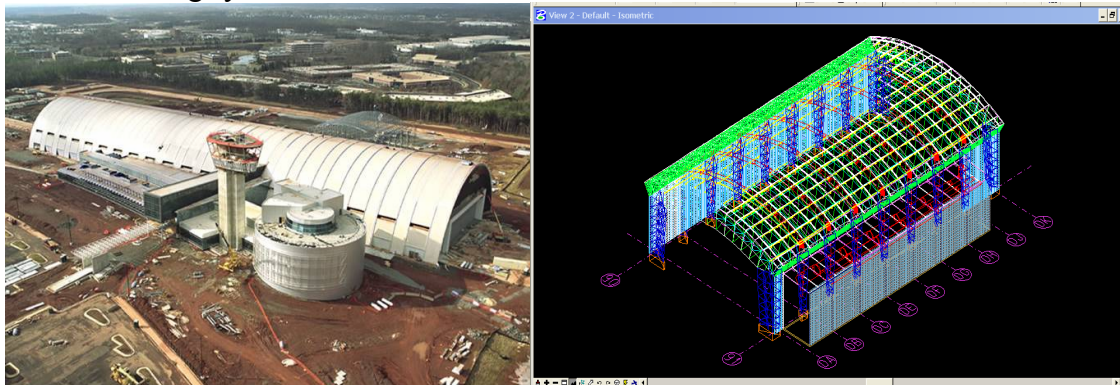


Figure 1: The National Air & Space Museum portrait and drawing. The Space Hangar is shown in the photograph at the rear of the Main Hangar, erected but unroofed.

Based on the characteristic of good flow, three flaws were intentionally placed within both the CPM schedule and the 4D model. This was done to test if the participants would identify these errors with the tools they had. These flaws include a space conflict, inappropriate flow direction, and disrupted flow. A description of each follows:

1. *Space Conflict*: A space conflict was set between the roof decking trade and the roof truss work of the steel erection contractor (see Fig. 2).
2. *Inappropriate Flow*: The fire protection trade works in the roof area in the opposite direction to the other trades (see Fig. 3). For this specific flaw, fire protection work starts at the opposite end of the building and moves in the opposite direction to other trades, like the roof truss, roof decking, and roofing, shown in Fig. 5. Normally, fire protection work is finished by the fire protection contractor or mechanical contractor, while the roofing and related work is taken by the roofing contractor.
3. *Disruption of Flow*: Both the overhead and the main supply duct work pause for about three weeks for no apparent reason (see Fig. 4).

EXPERIMENT STEPS

This experiment involved two steps: 1) examine the flow in construction using 2D drawing and the CPM schedule; and 2) inspect the construction process using the 4D CAD model. All students in the class reviewed and evaluated an electronic copy of the construction schedule and a series of 2D plan drawings, shown as in Figure 5. There were approximately 150 activities in the schedule.

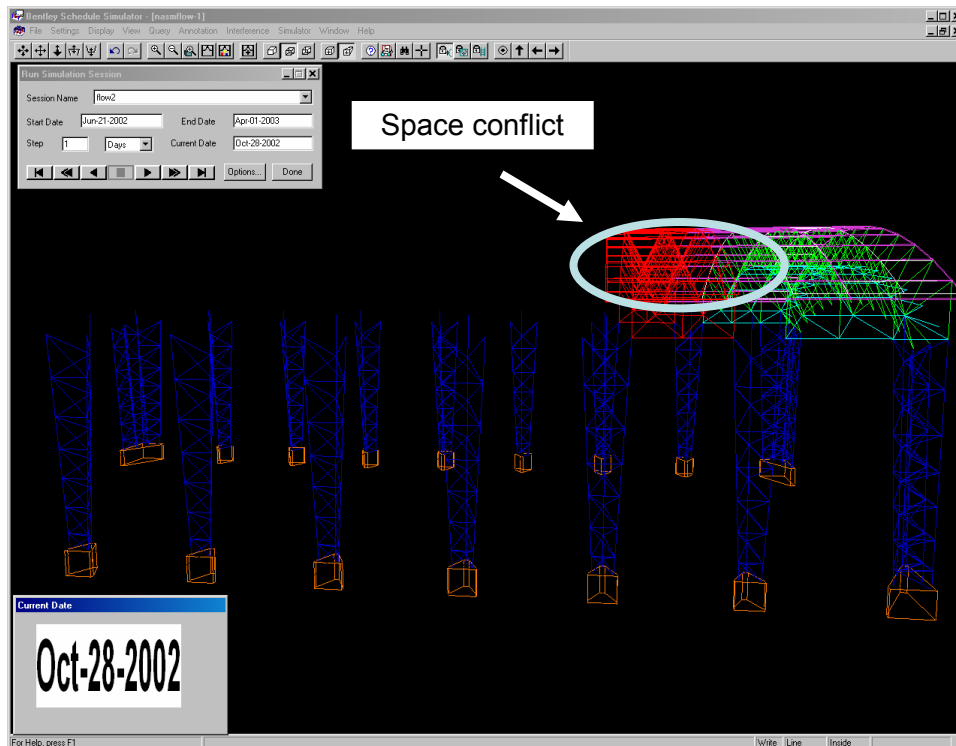


Figure 2. Space conflict between roof truss crew and roof decking crew

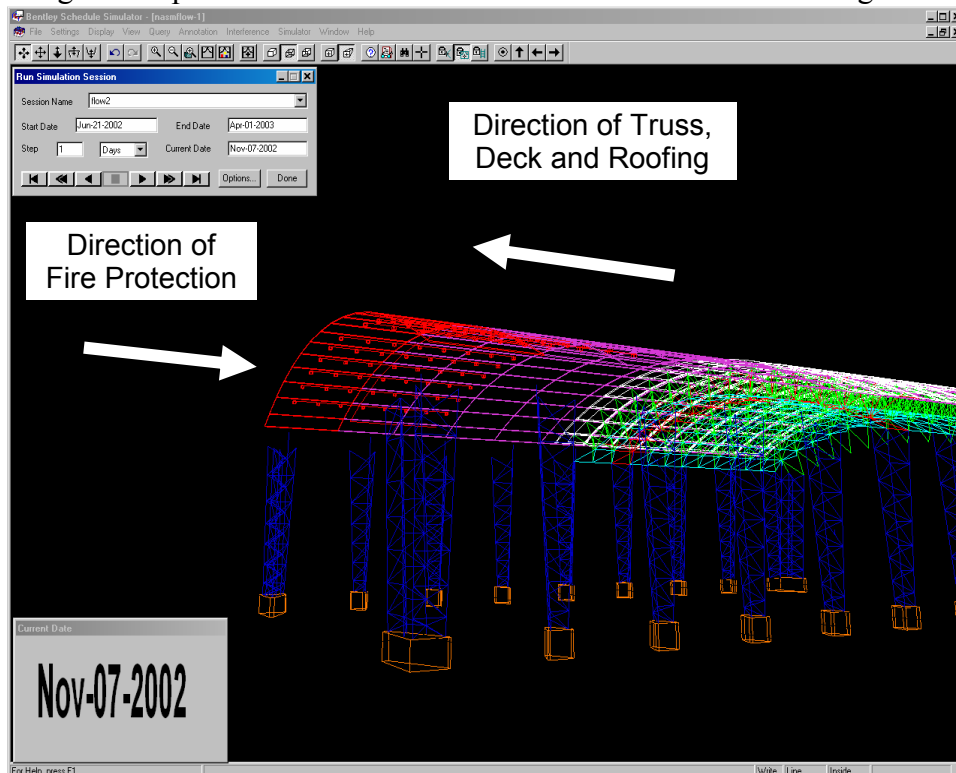


Figure 3. Direction issue in work flow

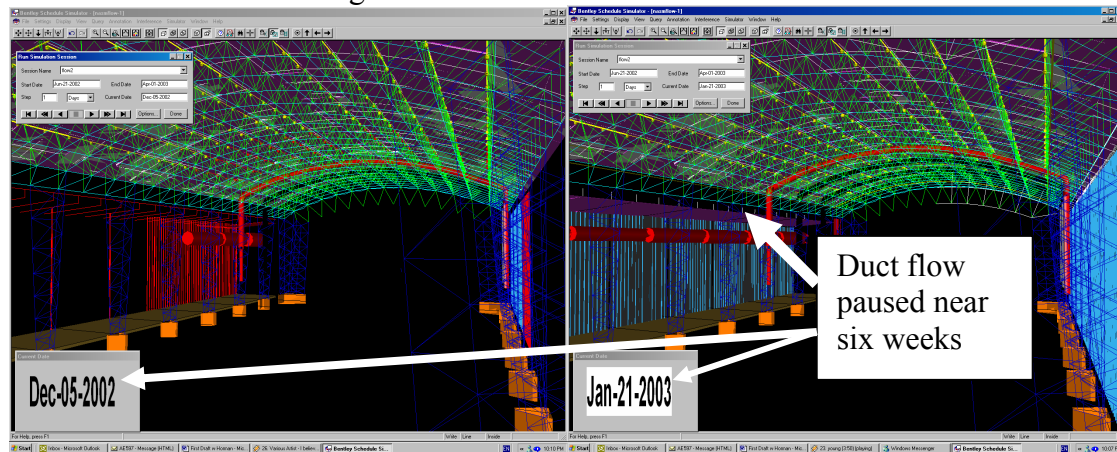


Figure 4. Disruption in work flow

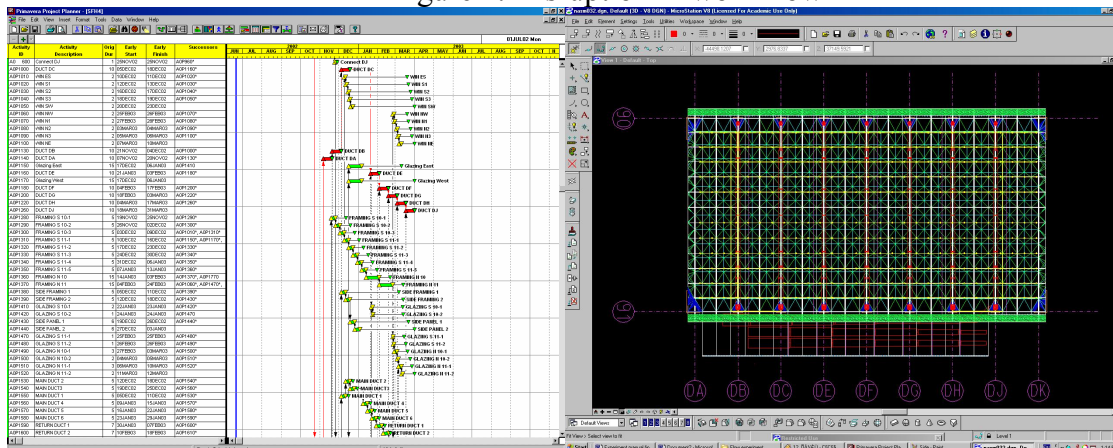


Figure 5: Schedule and plan drawing of the NASM project from the top

The participants were requested to answer the following questions after reviewing the schedule:

- Think about which contractors would do which part of the project. Connect the contractor to the work (the lists of the work and contractor are given)
- Do you see any improper construction flow? Identify these. What are the characteristics that make them poor flow?

The second part of the experiment requested the participants to review the construction process with the 4D model of the project. A detailed instruction of the 4D simulation software (*Bentley Schedule Simulator*) was provided. The participants were asked to run the model, review the model, and evaluate the construction workflow. They were asked to answer the same set of questions as in the first step. Finally, the participants were asked to evaluate which system was a better tool to evaluate the flow with a scale from 1 to 5, with 1 meaning the CPM schedule was better and 5 meaning the 4D model was better.

RESULTS & ANALYSIS

The results of both phases of the experiment were compared and used to determine if the visualization technology would improve participant ability to evaluate the important flow concepts in the construction process. These results are shown in Figure 6. It was postulated that if students found fewer flaws with the Primavera schedule and more with the 4D CAD model, this would indicate the 4D CAD model was more useful for evaluating construction flow. The experiment results provide good evidence of the effectiveness of the visualization technology, 4D CAD modeling in this project, for evaluating flow within construction.

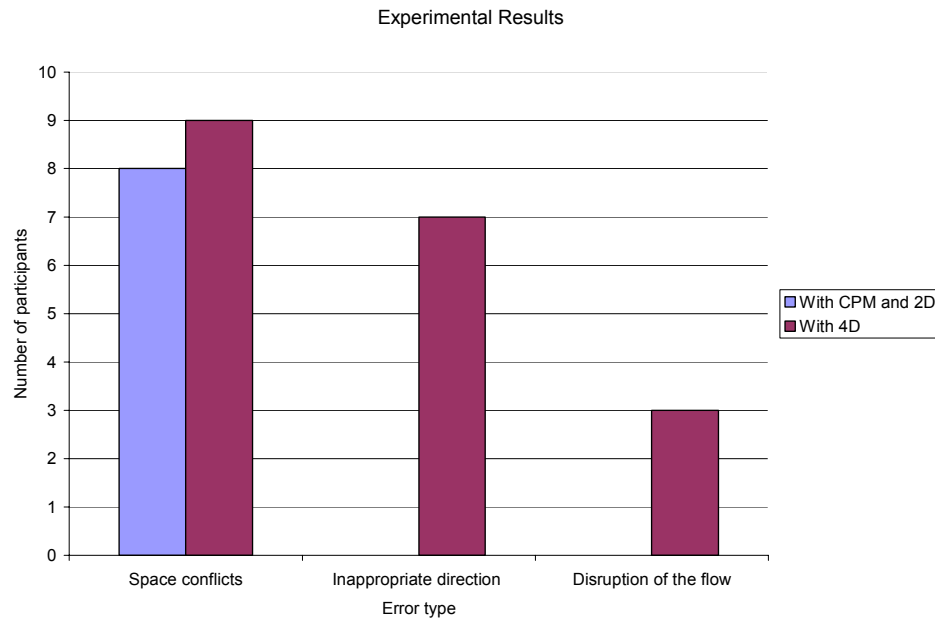


Figure 6. Experimental results

SPACE CONFLICTS

Construction trades need adequate space to perform work efficiently (Riley 1998). Space conflict may occur either between the different work in the same trade or between the work of different trades. It is comparatively easy for the planner to pay attention to potential conflicts within the same trade than between different trades. As shown in Fig. 6, eight out of nine participants in the experiment identified the potential flow space conflict between the roof truss crew and the roof decking crew using the CPM schedule, and all of them identified the same problem using 4D CAD modeling.

The CPM schedule and 2D drawings allowed a high proportion of participants to identify the space conflict. Both the roof truss work and roof decking work belong to the structural trades and this may have made it easier to identify the conflict as noted by Riley (1998) above. With the help of the linkage question, the participants understood that the roof truss and roof decking were highly interdependent already.

INAPPROPRIATE DIRECTION

The direction of the flow is another main concern in production management in construction projects. Different flow direction may lead to different demands of equipment, material storage, crew sizes, etc. Inappropriate direction of one trade may have a strong effect on the productivity of other trades.

As shown in Fig 6, none of the participants noticed the inappropriate direction of fire protection trade in the Primavera schedule; however seven out of nine identified the flow issue with the 4D CAD model. It is clear that the 4D CAD modeling was important for accurately evaluating complex flow issues like the direction of multiples trades.

DISRUPTION OF FLOW

Ballard and Howell (1998) talk about shielding production from variability. Concerning work flow, variability could refer to changes in pace or pauses in the flow of work. Using a 4D CAD model, three participants identified the pause of duct construction, while none of them did so with just CPM and 2D drawings. The results suggest the effectiveness of the 4D CAD model at presenting the dynamic characteristics of flow. The tool allows these characteristics to be visualized and analyzed with greater efficacy than a Primavera schedule.

USER COMPARISON AND EVALUATION

At the end of the experiment, the participants were asked compared the effectiveness of the two evaluation methods. The average score received was 4.6/5, indicating a very high preference for 4D CAD modeling.

What was also interesting was that four students identified two other latent flaws in the schedule logic when the construction sequence was evaluated with the 4D CAD model. One flaw related to a roofing delay between the main deck and the deck of the side gallery. The second flaw concerned a space conflict between the erection of the steel structure of the side gallery and the hanging of main ducts in that area. The schedule has both activities starting at the same time. Both flaws were embedded in the schedule and required a high level of visualization to identify them. This event provides additional evidence of the usefulness of advanced visualization technologies to evaluating and understanding advanced production management principles.

CONCLUSION

This paper reported an experiment that explored the ability of 4D CAD technologies to visualize production flow in a real-life construction schedule. It is concluded that advanced visualization technology is very useful for evaluating production flow in construction operations. This experiment was designed and performed within a graduate course, and showed that 4D modeling, an advanced visualization technology, can promote an enhanced understanding of advanced production management principles. The experimental results provide good evidence of the effectiveness of the visualization technology, 4D CAD modeling in this project, for evaluating flow in construction.

REFERENCE

- Ballard, G. and Howell, G. (1998). "Shielding Production: Essential Step in Production " *J. Constr. Engrg. and Mgmt.*, ASCE, New York, NY, 124 (1) 11-17.
- Ballard, G. (2000). *The last planner system of production control*. Ph.D. Diss_Faculty of Engineering, The University of Birmingham, Birmingham, UK, 192 pp.
- Caldas C. and Soibelman, L. (2002). "Automated Classification Methods: Supporting the Implementation of Pull Techniques for Information Flow Management " *Proceeding of the 10th International Group for Lean Construction Conference*. Gramado, Brazil, 6-8 August, 2002.
- Koo, B. and M. Fischer (2000). "Feasibility study of 4D CAD in commercial construction." *J. Constr. Engrg. and Mgmt.*, ASCE, New York, NY, 126(4), 251-260
- Koskela, L. (1992). "Application of the new production philosophy to construction" *Technical Report No. 72*, Center for Integrated Facility Engineering, Stanford University, Stanford, CA.
- Koskela, L. (2000). *An exploration towards a production theory and its application to construction*. Helsinki University of Technology, Espoo, Finland, 298 pp.
- Koskela, L. and Ballard, G. (2003). "What should we require from a production system in construction?" *Proceeding of the Construction Research Congress "Winds of Change: Integration and Innovation in Construction"*. Honolulu, Hawaii, 19-21 March, 2003.
- Riley, D. and Sanvido, V. (1997). "Space Planning for Mechanical, Electrical, Plumbing and Fire Protection Trades in Multi-story Building Construction." in Anderson, S. (ed.) *Proc. Construction Congress V*. Minneapolis, MN, ASCE, pp. 102-109.
- Tommelein, I. (1998). "Pull Driven Scheduling For Pipe-Spool Installation: Simulation of Lean Technique" *J. Constr. Engrg. and Mgmt.*, ASCE, New York, NY, 124 (4) 279-288.
- Tommelein, I. Riley, D. and Howell, G. (1998). "Parade Game: Impact of Work Flow Variability on Succeeding Trade Performance" *Proceeding of the 7th International Group for Lean Construction Conference*. Berkeley, 26 - 28 July 1999. Iris D. Tommelein (ed.). University of California (1999). 444 pp.