Impact of 4D Visualization on the Cognitive Process of Detecting the Logical Errors in the Construction Schedule

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Abstract

In order to understand the construction schedule, students have to read drawings, visualize the structures in mind, and link these structures with the schedule information depicted in the bar chart or CPM network. Since this is not a simple process, students studying construction scheduling sometimes hardly integrate the bar chart and the two-dimensional (2D) drawings to visualize the construction sequence in their mind. Four-dimensional (4D) visualization, which shows visually the sequence of building the structures over time using three-dimensional (3D) computer graphics, is expected to be one of the innovative methods that improve our cognitive process of understanding the construction schedule.

This paper introduces an experiment to test whether the students would better understand the construction schedule if 4D visualization is provided. For this experiment, students studying construction management at Texas A&M University were recruited and then asked to detect logical errors in the construction schedule using different levels of graphical representation. One group conducted the experiment using 4D visualization of the construction sequence, and the other group used 3D model of the constructed structure. For the experiment, an Internet instrument was developed to provide graphical representation of the construction schedule and measure the elapsed time for the students to detect logical errors in the schedule. The experiment showed that students who used 4D visualization detected more logic errors within less time than those who used 3D visualization.

I. Introduction

Construction planning requires reading the drawings, visualizing the constructed structures in mind, breaking the structures into identifiable components, and building a logical network among these components. Once the duration required for constructing each component is estimated, the computer application can identify the critical path in the network and calculate the total duration of the project using Critical Path Method (CPM). The construction schedule is then conceptually illustrated using the bar chart. The conceptual expression of the schedule has been considered effective for illustrating the entire construction schedule. However, it may take many years to develop a skill for understanding the complicated construction sequence and detecting any logical errors hidden in the construction schedule if the construction schedule is depicted using the bar chart. Undetected logical errors in the schedule could delay the entire construction project. Project engineers try to proactively detect any logical errors hidden in the construction schedule.
to finish the project on time.

The cognitive process of detecting the logical errors in the construction schedule is similar to the process of developing the construction schedule. One must read the drawings, visualize the structure in mind, break the structure into identifiable components, and then link these components with the construction schedule illustrated by the bar chart. This may be an easy process for the experienced constructors. However, the owners or the end users may have difficulties in integrating the bar chart and the 2D drawings to understand the construction schedule although they may have better knowledge of utilizing the constructed facility. Therefore it may not be reasonable to expect that they could be part of the process of making proactive decisions in construction planning. They may need comprehensive tools to understand the increasing complexity of the constructed product.

It is known that visualization may improve the human’s cognitive process of understanding the construction schedule. Murgio\textsuperscript{9} insisted that human beings obtain 83\% of their knowledge from visual observation. Johnson-Laird et al.\textsuperscript{5} empirically verified that the use of realistic materials improved performance in a deceptive reasoning problem. Pressley\textsuperscript{12} asserted that imposed pictures are almost always learned better than words.

Recent research tried to show the construction schedule visually using three-dimensional (3D) computer model\textsuperscript{1, 13, 15}. Bechtel Corporation integrated 3D Computer Aided Design (CAD) models with scheduling packages to simulate the construction operations\textsuperscript{7, 13}. Bechtel later developed 4D-Planner, a graphical simulation tool, that helps project managers, construction planners, and field engineers plan and manage their projects effectively\textsuperscript{15}. The Center for Integrated Facility Engineering (CIFE) at Stanford University also integrated 3D CAD objects with the construction schedule to show the construction sequence visually in 3D environment\textsuperscript{1}. The CIFE applied 4D CAD to the San Mateo County Rehabilitation Center campus expansion project\textsuperscript{2} and a new Walt Disney Concert Hall designed by Frank O. Gehry\textsuperscript{4}, and demonstrated that 4D visualization of the construction sequence helped project participants proactively manage their projects.

More recent research attempted a new way of distributing 4D visualization using the Internet technology. Kang\textsuperscript{6} developed a Web-based 4D visualization application using Java 3D technology. With this software, end users can update the construction schedule over the Internet and the 4D visualization model of the updated construction schedule can be displayed immediately on the Web browser.

Many construction firms, however, still hesitate to utilize 4D CAD for their project due to the initial investment of creating a 3D CAD model and lack of confidence that they could make profit from utilizing 4D CAD. It is necessary, therefore, to provide empirical evidence for the impact of 4D visualization in construction planning. This paper presents an experiment to measure the impact of 4D visualization on human’s cognitive process of understanding the construction schedule.
II. Review of 4D visualization for construction planning

Two-Dimensional (2D) drawings have been used in the architecture, engineering and construction (AEC) industry to describe a designer’s idea for the constructors. However, in order to visualize the shape of the structure in a three-dimensional (3D) world, one has to read several drawings to comprehend the spatial and volumetric aspects of the objects. This process requires a significant amount of education in the conventions of drawing and practical experience. Developing a construction schedule is even harder because one must build a structure step-by-step in mind after visualizing it in a 3D world. 3D objects can be best described by 3D visualization\textsuperscript{14}. Architects therefore have extensively used a 3D miniature model to show their design to the customers and get feedback from the customers more effectively. As 3D CAD technology became available in the AEC industry, architects learned that they can build and modify a 3D model quickly using 3D CAD, and distribute it to the project participants easily. They also noticed that they can combine additional engineering information with the 3D CAD model. Engineering, procurement and construction (EPC) firms were leaders in integrating 3D CAD with engineering information. Bechtel Corporation’s 3D modeling system for plant design (3DM), and Stone & Webster’s Construction Management Display System (CPMANDS), Fluor Daniel’s CALMA Plant Design System (PDS), and Black & Veatch’s POWERTRAK are some of examples of integrating 3D CAD with design information. These systems were used for reviewing constructibility, checking interferences, and taking off the bill of materials\textsuperscript{7}.

Bechtel Corporation expanded the use of their 3DM to simulate the construction operations and assembly sequence\textsuperscript{13}. The system includes construction equipment models and allows the planner to include temporary structures or facilities to accurately simulate the construction environment. It also provides a dynamic interference checking function to validate proposed construction flows and equipment selections\textsuperscript{7}. Bechtel Corporation also developed 4D-Planner that imports the 3D CAD model and the construction schedule from the commercial applications, such as MicroStation, Plant Design System (PDS), AutoCAD, and Primavea Project Planner, in order to merge them into a simulation file that can be reviewed interactively. The 4D-Planner is reported to help project managers, construction planners, and field engineers plan and manage their projects effectively\textsuperscript{15}.

The Center for Integrated Facility Engineering (CIFE) at Stanford University connected 3D CAD objects with the construction schedule to develop a graphical representation that shows the construction sequence\textsuperscript{1}. The CIFE and Dillingham Construction jointly demonstrated in the San Mateo County Rehabilitation Center campus expansion project that 4D CAD helped people understand a construction schedule intuitively\textsuperscript{2}. It was found that even doctors and nurses were able to understand the impact of construction plans on their department, office, and daily operations. The CIFE also utilized 4D CAD for the new Walt Disney Concert Hall construction project, which was designed by Frank O. Gehry. Using 4D CAD, the project team was able to visualize several what-if scenarios to detect conflicts before the project began, and effectively explain why certain decisions were made to the board members who were unfamiliar with the construction process\textsuperscript{4,11}.
Balfour Technologies LLC developed fourDviz which was used by the National Aviation and Transportation Center, Brookhaven, NY, and Frederic R. Harris Inc., Boston, Mass., for several projects, including the LaGuardia Airport Rail Access project and Boston's Logan Airport Modernization Program. Balfour Technologies LLC also plans to develop a 4D browser that will allow users to access a 4D portal via the Web or corporate intranet.

A design and construction of Helsinki University of Technology Auditorium Hall 600 (HUT-600) in Finland used commercially available state-of-the-art analytical and visualization tools to optimize the design, construction, and operation of the facility during early project phases. The project team was able to shorten the time for design iteration and develop a reliable budget for effective cost control. Visualization tools such as Virtual Reality-Experimental Virtual Environment (VR-EVE) fostered early communication among the end users, which eventually helped the project team capture valuable inputs from the clients and effectively utilize them for the design work. The HUT-600 demonstrated that 4D visualization could expedite the conventional design practices and promote the life-cycle consideration in the construction project.

However, some limitations of 4D CAD were revealed while using 4D CAD in the construction project, such as the necessity of a large initial investment of time and effort to create a 3D model, and limitations in updating the 4D CAD model. Kang developed a prototype of Web-based 4D visualization software using Java 3D and Java JDBC technology in order to overcome some of the limitations of current 4D CAD. This software enables end-users to modify the construction schedule over the Internet and confirm the revised construction sequence visually on a Web browser in 3D environment.

III. Experiment design

The impact of 4D visualization was mainly investigated through comparison of the level of effectiveness between two different graphic representations in helping the experiment participants detect logical errors hidden in the construction schedule. For this investigation, graduate students studying construction management at Texas A&M University were recruited. The students were randomly divided into two groups, group A and group B, which used different graphic representations for illustrating the construction schedule. The students were then asked to detect logical errors in the sequence of building wooden toy block towers with the assumptions that 1) no adhesive is used to put two blocks together and 2) the wooden blocks should be placed one-by-one using only one hand. The constructed wooden towers used in the experiment are illustrated in Figure 1. The logical errors were created by making some blocks unsupported in the building process.
In order to investigate the impact of 4D visualization, each group was provided different levels of resources. One group was provided 1) 2D drawings that illustrate the plans and elevations of the wooden towers; 2) a 3D computer model of the tower that enables the experiment participants to navigate around the tower; 3) wooden block numbers that represent the sequence of stacking up the wooden blocks to build a tower. The other group was provided 1) the same 2D drawings, and 2) the same wooden block numbers. However, this group was provided a 4D computer model so that the experiment participants can navigate not only around the tower model, but also over time to observe the construction sequence visually. Figure 2 shows the sequence of building the tower using the 4D computer model.

The experiment was implemented on the Web browser. All instructions and necessary graphic representations were provided on the Web browser. The experiment participants were asked to provide the number of logical errors they detected via the Web page, and their answers were collected in the database located in the Web server along with a time stamp. Figure 3 shows some of the Web-based instruments used in the experiment. The collected answers were then analyzed to identify the following data:

- Number of logical errors detected
- Average elapsed time to detect one logical error

The result of the experiment in this research can be easily biased due to huge individual differences between the participants. Subject A that uses a 3D computer model could finish the given task faster than subject B that uses a 4D computer model simply because subject A is more experienced in using the given resources than subject B. Therefore, the experiment was designed to have every participant use both graphic representations for problem solving. The experiment participants were asked to answer two questions. If a certain participant uses a 4D computer model in the first question, this subject is then provided a 3D computer model in the second question. If a subject starts solving the question with a 3D computer model, the subject uses a 4D computer model.
model in the second question.

Figure 2: 4D model of wooden toy tower

Figure 3: Web-based Instrument with 4D model (left) and 3D model (right)
Table 1 shows the type of graphic representations provided to each group. It is expected that participants who are particularly talented or untalented should not skew the results, as they affect both sets of statistics equally. For training purposes, one exercise problem was given to the experiment participants prior to starting the actual tasks.

Table 1: Type of graphic representations used in the experiment

<table>
<thead>
<tr>
<th>Group</th>
<th>Task 1</th>
<th>Task 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>4D model</td>
<td>3D model</td>
</tr>
<tr>
<td>Group B</td>
<td>3D model</td>
<td>4D model</td>
</tr>
</tbody>
</table>

After finishing the given tasks, the experiment participants were asked to provide their opinion about using 4D visualization for conducting the experiment. The following questions were asked in the exit survey:

1. What's your gender? (Male/Female)
2. How old are you? (21-25/26-30/31-35/36-40)
3. What's your classification? (Master/PhD)
4. Have you ever taken any construction scheduling class? (Yes/No)
5. Have you ever built a schedule for the real project? (Yes/No)
6. Have you ever taken any 3D CAD modeling class? (Yes/No)
7. When the 3D model was available during the experiment, how easy was it to understand the sequence of building the toy tower? (1: Very difficult – 10: Very easy)
8. When the 4D model was available during the experiment, how easy was it to understand the sequence of building the toy tower? (1: Very difficult – 10: Very easy)

IV. Experiment results

A total of 20 students participated in the experiment. Among 20 students 16 students finished the experiment as per the instruction. Table 2 shows the number of students in each group and the type of resources they used in the experiment. For the analysis, the measurements are reorganized by the type of graphic representation that the experiment participants used: a 3D group and 4D group. Table 3 shows the number of measurements in each task based on the new arrangement.

Table 2: Number of subjects in each group and type of graphic representation used

<table>
<thead>
<tr>
<th>Group</th>
<th>No. of Subjects</th>
<th>Graphic Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Task 1</td>
<td>Task 2</td>
</tr>
<tr>
<td>Group A</td>
<td>8</td>
<td>4D model</td>
</tr>
<tr>
<td>Group B</td>
<td>8</td>
<td>3D model</td>
</tr>
</tbody>
</table>
Table 3: Number of measurements in each task

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of measurements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Task 1</td>
<td>Task 2</td>
</tr>
<tr>
<td>3D Group</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>4D Group</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

In the experiment, all answers that the participants provided were saved in the database of the Web server with a timestamp. The following raw experiment measurements were collected in each task:

- Time that the subject started the task
- Time that the subject finished the task
- Number of logical errors that the subject detected in the task

The raw measurements were used to generate the following data in each task:

- Number of logical errors detected
  (= Number of actual logical errors that the subject detected in the task)
- Average elapsed time to detect one logical error
  (= (Time that the subject finished the task – Time that the subject started the task) / Number of logical errors that the subject detected in the task)

The results show that the students detected all logical errors when they used the 4D model. When the students used the 3D model, four students either did not detect all logical errors or made a mistake in detecting the logical errors. In general, those who used the 4D model took less time to detect the logical errors than those who used the 3D model. As shown in Figure 4, the students spent 1 minute 5 seconds to detect one logical error average when they used the 4D model in the first task. The students spent 2 minutes 36 seconds in average when they used the 3D model in the same task. In the second test, the average elapsed time spent to detect one logical error was significantly reduced regardless of graphic representations. It is assumed that elapsed time was reduced because of learning effect. In the second question, the 3D group and 4D group marked 1 minute 9 seconds and 0 minute 29 seconds respectively to detect one logical error.

Although the number of subjects is not large enough to conduct a statistical test to show if there is a significant difference between two groups, it is distinctive that the 4D group detected the logical errors faster than the 3D group in all tasks. Since this experiment is currently being conducted with more subjects, the statistical evidence is expected to be provided in the near future.

For the question of the exit survey, “When the 3D model was available during the experiment, how easy was it to understand the sequence of building the toy tower? (1: Very difficult – 10: Very easy)”, the average point of the participants marked 6.40 out of 10.
For the question, “When the 4D model was available during the experiment, how easy was it to understand the sequence of building the toy tower? (1: Very difficult – 10: Very easy)”, the average point marked 9.27 out of 10. This result clearly shows that the experiment participants felt more comfortable when they used the 4D model for detecting the logical errors in the given tasks.

V. Concluding remarks and future work

The results of the experiment demonstrated a quantitative evidence that 4D visualization helped the students understand the construction schedule. Repeating the experiment with more subjects is expected to produce a strong evidence that would convinces construction professionals to consider the utilization of 4D visualization for construction planning. The experiment also will be conducted using different population in order to secure the reliability and validity of the test and indicate sensitivity of the instrument. The impact of 4D visualization on learning is another provocative area of research. One may speculate that 4D visualization would be more effective for teaching principles of project planning and scheduling because it is less abstract than CPM networks or bar charts.

Bibliography

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