USING 4D MODELING TO ADVANCE CONSTRUCTION VISUALIZATION IN ENGINEERING EDUCATION

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ABSTRACT

Students in construction and engineering disciplines typically learn how to develop a building construction schedule by visualizing 2D design documents for a building project. This learning process is difficult since a student first needs to associate components in the 2D documents with their related construction activities, and then mentally visualize the construction sequence. 4D modeling technologies, visually representing the construction schedule time along with the 3D model components, has the potential to aid this learning process by providing a common visual language for students.

This research examines the value of implementing 4D modeling technologies in construction engineering education for learning how to develop building construction schedules, and the associated concepts regarding sequencing and resource utilization. This research also targeted the development of a new process for creating a 4D model which is implemented in the Virtual Construction Simulator (VCS) application. This approach allows a student to generate a construction schedule directly from a 3D model without first creating a critical path method (CPM) schedule, which is required by current commercial 4D modeling applications.

To assess the effectiveness of using 4D modeling to visualize a construction schedule, a case study research project was performed where small student groups developed a construction schedule with the aid of a 4D learning module. The 4D learning modules were developed using two different 4D modeling applications (a commercial 4D modeling application and the VCS). An experiment was conducted to assess, compare and determine the pedagogical value of the two applications.

The 4D learning modules were found to be beneficial based on quality of the resulting solutions presentation effectiveness, and the perception of the students. The VCS application was more valuable than the commercial 4D application since it encouraged more collaborative group work, engaged students, and provided a greater focus on solution development.
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Chapter 1

Introduction

When a student in design and engineering disciplines is learning to develop a construction schedule for a building, they will typically develop the schedule by interpreting 2D drawings, identifying activities and building a logic sequence network. Developing a construction schedule is difficult since one has to construct the building step-by-step in their mind after visualizing the 2D drawings. 4D modeling technologies, visually representing the construction schedule time along with the 3D model components, can provide a common visual language for students when learning how to develop construction schedules for buildings.

Benefits of 4D modeling technology used in the Architecture, Engineering and Construction (AEC) Industry have been studied and documented in recent years. 4D modeling allows project teams to visualize construction plans; identify construction consequences and space conflicts; identify safety issues; and improve communication of the project team members (Koo and Fischer 2000). While there are an increasing number of successful applications of 4D modeling in the AEC Industry, its implementation in engineering education is still limited. This research focused on the implementation of this visualization tool in construction engineering education and the quantitative assessment establishing its effectiveness.

In addition to investigating the effectiveness of the implementation of current 4D modeling tools in construction engineering education, this research also focused on
advancing the current 4D model generation process by developing a Virtual Construction Simulator (VCS) application. This VCS allows a student group to generate a construction schedule directly from a 3D model instead of first having to develop a CPM schedule for a project, and then perform an additional step to connect the schedule to the 3D model components. The educational value of the VCS in construction engineering education was assessed in comparison to a current commercial 4D modeling application.

To assess the effectiveness of using a 4D model to visualize a construction schedule, a case study research project was undertaken where small student groups developed a construction schedule with the aid of a 4D learning module. The value of the 4D model learning module was examined by investigating a small student group activity. The value was assessed by investing the groups effectiveness based on their group communication and interaction; evaluating their final activity results; and investigating the student perception of their learning experience and the impact of the technology.

This chapter introduces the current construction schedule visualization techniques used in engineering education and the current status of 4D modeling process, and describes the limitations of using these techniques and process. Then, it provides a description of this research study with a discussion of the research goal, objectives, research questions, research steps, research contributions and scope. It concludes with a discussion of the thesis organization.
1.1 Current Construction Schedule Visualization in Engineering Education

2D drawings and Critical Path Method (CPM) schedules are the traditional tools used in the construction engineering discipline to analyze a project design and plan the construction of the project. Individuals require training to interpret 2D drawings and visualize projects based on their previous experience and knowledge. With building geometry getting more and more complex, even experienced construction planners can misinterpret the designer’s intention, which can lead to poor construction plans which cause an increase in time and project cost.

To generate a CPM schedule from a set of 2D drawings, construction planners need to associate components in 2D drawings with their related construction activities and build their sequential relationships mentally. Such schedules force planners to visualize and interpret the activity sequence in their minds. Also, some planners will have different interpretations of the same schedule, which makes it difficult to communicate and discuss whether a certain problem actually existed or not. So it is difficult to conceptualize the construction process and detect problems by viewing the CPM schedule alone, especially for a novice with limited construction experience.

With recent advancements in 4D modeling technologies, it is now possible to provide our students with visual models that allow them to experience and experiment with 3D and 4D virtual models of construction projects. This advanced visual communication can significantly improve the ability of students to comprehend, learn, and gain experience with reviewing designs for constructability and planning the construction of complex building and infrastructure projects. The models can also help
students improve their visualization skills so that they will be more prepared to interpret and visualize 2D drawings in 3D.

4D model development has already been implemented in undergraduate Architectural Engineering Department at Penn State. In a previous study, the educational value of having students develop 4D models for a building project using a desktop computer monitor was assessed, and it was found that the 4D models can enhance the ability for students to understand typical planning documents (Messner et al. 2003). By using 4D models, students can visualize the built environment and gain experience and intuition related to construction method selection, construction sequencing, site planning, and site logistics.

1.2 Current 4D Model Generation Process

The current process used to develop a 4D model is:

1. Develop or obtain a 3D model;
2. Develop a construction CPM schedule;
3. Separate the 3D model into appropriate construction assemblies; and
4. Link the 3D model components with their corresponding activities specified in the CPM schedule in a 4D modeling application.

Once the 3D model and the schedule are linked, the 4D model can be viewed as a visual simulation of the construction process for the project.

One limitation of the current 4D modeling process is that it requires additional time to develop the model since a planner must first generate a schedule, and then link
the schedule to a 3D model of the project. Therefore, the 3D model and the schedule are inputs to this process, and the 4D model is the final product and used in a schedule review process. Figure 1 shows the process of a current 4D model generation process. The current method of using a CPM modeling application for generating the schedule limits the utility of the 3D model during the planning process since the planners need to first create the activities mentally, and later link them to their related 3D components in a 4D modeling application.

![Diagram of current 4D modeling process]

**Figure 1: Current 4D Modeling Process**

A Virtual Construction Simulator (VCS) prototype with a 4D CAD generation interface has been proposed, which allows a user to develop a construction schedule and a 4D CAD model by selecting objects from within a 3D model. The input to the process is only the 3D model, and the output is a CPM schedule and a 4D CAD model. Figure 2 illustrates the process of the VCS as a schedule generation tool. This is a
different approach from the current 4D CAD applications which require a CPM schedule input.

![3D Model (Input) to 4D Model (Output)](image)

Figure 2: The Virtual Construction Simulator as a Schedule Generation Tool

1.3 Description of the Research Problem

This section provides an overview of this research, which includes the research goal, objectives, approach, steps, contributions and scope.

1.3.1 Research Goal

The goal of this research is to investigate the effectiveness of 4D modeling implementation in construction engineering education for schedule visualization, and to
advance the current state of 4D modeling techniques by developing a Virtual Construction Simulator (VCS) prototype application for implementation in engineering education.

1.3.2 Objectives

To achieve the goal of this research, the following objectives were completed:

1. *Investigate the value of current 4D modeling tools used for schedule visualization in construction engineering education.* A preliminary 4D learning module was developed and implemented in an advanced project management course at Penn State to aid students in the development of a construction schedule. An initial assessment plan was used to evaluate the effectiveness of the 4D learning module in comparison to paper based schedule generation.

2. *Develop a VCS that advances the current 4D model generation process.*

The VCS was developed to allow students to interactively generate a construction schedule (in a 4D model format) directly from a 3D model. The objective is to allow rapid 4D model generation for alternative construction schedules so that the schedule can be visualized, assessed, justified and optimized in an efficient and visual manner.

3. *Assess the impact of the VCS compared to the current 4D modeling process in engineering education.* Based on the experience of implementing the preliminary 4D learning module, assessment metrics were identified and a
A detailed assessment plan was utilized to evaluate the value of the VCS compared to current 4D modeling applications used in construction engineering education. This was performed through a case study evaluation of small group effectiveness.

1.3.3 Research Approach

Since 4D model implementation in engineering education is limited, this research was first established as an exploratory investigation to study the value of 4D model implementation for schedule visualization through a case study methodology. Through this exploratory study, the value of 4D modeling and important metrics for assessing its effectiveness were identified.

In addition to exploring the educational value of current 4D modeling tools, a VCS was developed and its value in engineering education was assessed. A hypothesis testing method was used to evaluate the effectiveness of the VCS in construction engineering education in comparison to current 4D modeling applications. The hypothesis for this research is that the VCS application, when compared with a current 4D modeling application, is more effective in improving small student group communication and interaction; help students develop higher quality construction schedules, and contribute to the student enjoyment during the schedule learning experience.

The following questions were set forth for this research:
1. How effective are current 4D modeling tools for aiding students to visualize and develop construction schedules? What are the potential opportunities for improving the current 4D modeling tools?

2. What parameters should be used to examine the value of 4D modeling in construction schedule visualization?

3. What are the additional values gained by using the proposed VCS for learning scheduling in construction engineering education?

4. What is the perception of students towards 4D modeling tools?

1.3.4 Research Steps

This research aims to evaluate the value of 4D modeling used in construction schedule visualization and advance the current 4D process. The research steps are as follows:

1. Literature review: A literature review was conducted in the areas of construction schedule visualization, design and construction team communications, virtual reality, and virtual reality applications in engineering education.

2. Development, incorporation and evaluation of a preliminary 4D learning module: A preliminary 4D learning module was developed which required students to use a commercial 4D modeling application for analyzing their construction sequence solution for an assignment. This assignment was implemented in a 5th year project management course at Penn State. The
value of the learning module was assessed and student perspectives of this technique were investigated.

3. Identification of assessment parameters: By conducting the exploratory research, the researcher was able to identify critical parameters that can be used to evaluate 4D modeling learning modules used in engineering education.

4. Development, incorporation and evaluation of the VCS: The VCS was developed using a commercial 3D game engine. The interface was assessed through an experiment where 5 student groups used the VCS and 5 groups used a commercial 4D modeling application for reviewing a schedule generated in a CPM application.

5. Data collection and analysis: While performing Step 4, student group activities were observed and videotaped. A detailed content analysis was conducted to analyze the videos. Quantitative and qualitative surveys were taken to measure students’ perspectives of two different interfaces and the quality of the final schedules was assessed.

6. Documentation of conclusions and lessons learned: By conducting a preliminary study and an experiment to compare the VCS and the current 4D modeling process, the value of the VCS and the current 4D model applications used in engineering education was identified. Suggestions and recommendations for improvements were documented in the results. This will help guide future research and implementation efforts.
1.3.5 Research Contributions

The primary research contributions of this research are:

1. A VCS prototype which advances the current process of 4D model generation. Instead of focusing on improving the efficiency of developing a 4D model from a 3D model and an existing construction schedule, the VCS prototype allows a user to generate a CPM schedule and a 4D model by interacting with a 3D model of a building.

2. An assessment plan used to evaluate the effectiveness of a 4D modeling learning activity.

3. A detailed study of student group meetings which describes the frequencies/time of different categories of communications.

4. Documentation of the experiences and lessons learned from the student exercise, including students’ perceptions of 4D learning tools and suggestions for improvements.

1.3.6 Research Scope

This research focuses on understanding the value of 4D modeling in engineering education, specifically for construction schedule visualization. Two different 4D modeling interfaces: a commercial 4D modeling application and the VCS were evaluated regarding their values in aiding engineering students in the scheduling and planning process. Though the case study selected was a special repetitive scheduling method (the Short Interval Production Scheduling (SIPS) technique), the 4D model generation process
would be the same for a non-repetitive scheduling activity. It is also important to note that both interfaces have only been tested through the detailed analysis of one case study project and they have not been tested on a large scale project.

1.4 Thesis Organization

This thesis is divided into three sections. The first three chapters explain the concept and need for 4D model implementation and advancement in construction engineering education. This chapter has presented an overview of this research. Chapter Two describes the detailed research techniques used for this study. Chapter Three summarizes the existing relevant literature for this study, including literature on 4D modeling, design and construction plan communication, and virtual reality displays and applications in engineering education.

The second section of the thesis consists of Chapters Four through Seven, which focus on the development, implementation and evaluation of 4D modeling (current 4D modeling and VCS) learning modules. Chapter Four describes the case study project and the preliminary 4D learning module development and incorporation. Chapter Five presents the interface and the development process of the VCS. Chapter Six introduces the experiment conducted to evaluate the value of the VCS in comparison to a current 4D modeling tool. Chapter Seven describes the data collection and analysis process and results.
The final section of the thesis is contained in Chapter Eight. This chapter provides a summary of research results, the research limitation, and an outline for future research in this area.
Chapter 2
Research Methodology

This chapter describes the methods and techniques used for conducting this research. The basis for the selection of the research methods is also presented. This chapter concludes with a detailed description of the research process.

2.1 Research Methods Introduction

Research can be divided into three main categories: exploratory, hypothesis testing and problem solving (Phillips and Pugh 2000). The research methods designed for this research are a hybrid of exploratory and hypothesis testing approaches.

Exploratory research is often conducted because a problem has not been clearly defined as yet, or its real scope is as yet unclear at the outset of the project. It is usually used to investigate little understood problems, identify important variables or generate hypotheses for future research. This research aims to investigate the value of using 4D modeling in construction engineering education. Since limited research has been conducted in this area, an exploratory research method was extensively used in this research. Two common research strategies used in an exploratory research are field studies and case studies (Marshall and Rossman 1999). With consideration of this specific research topic, a case study method was selected.
Hypothesis testing research usually takes place in a structured environment with clear measurement criteria. A hypothesis predicts an experimental outcome and it is made without knowing whether or not it is correct. An experiment is usually performed to support or deny a hypothesis. The hypothesis for this research is that the VCS interface is more effective in improving small student group effectiveness in schedule visualization than a current 4D modeling application. To test this hypothesis, an experiment was conducted, where 5 student groups using the VCS interface and 5 groups using a current 4D modeling application generated a SIPS for a case study project.

2.2 Research Techniques

Research techniques used in the research process are detailed in the following sections. These techniques include a case study, controlled experiment, direct observations, surveys, content analysis, and reliability test.

2.2.1 Case Study

“A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” (Yin 2003). It encourages in-depth investigations of particular instances within the research subject (Fellows and Liu 2003). The case study method is very useful for exploratory research since an exploratory case study is theory-driven. A case study may be selected when it is “a representative
sample, demonstrates particular facets of the topic, or shows the spectrum of alternatives” (Yin 2003). The case study used for this research is the construction planning process for the precast concrete structure systems of the MGM Grand Hotel in Las Vegas, Nevada. Though the case study selected was a specific repetitive scheduling method (the Short Interval Production Scheduling (SIPS) technique), the 4D model generation process would be the same for a non-repetitive scheduling activity. Therefore, this case study can be stated as a representative sample of the research topic. It investigated the effectiveness of 4D modeling applications in helping students learn scheduling and the project planning process.

2.2.2 Controlled Experiment

An experiment is usually conducted to test a hypothesis about the role of the independent variable on the dependent variable. A controlled experiment generally compares the results obtained from an experimental sample against a control sample. Two or more sample groups are created at the beginning of an experiment, which are probabilistically equivalent. This equivalency is determined by the amount of variation between individuals and the number of individuals in each group. Once equivalent groups have been formed, they will be treated identically by the experimenter except for the one independent variable.

In this research, students from a senior level construction management class (AE 473) were randomly assigned to ten small groups. The groups were generated by using the “Random Team Generator” tool in ANGEL, Penn State's Course Management
Then five student groups were assigned randomly to the control group and the other five were in the experimental group. Among these ten groups, two groups consisted of 4 students each, and the other eight groups consisted of 3 students each. Due to the absence of some students, there was a 2-student group in each of the control and the experimental group. The treatment for the control group was a current 4D modeling interface which aided students to develop a construction schedule for the case study project. The treatment for the experimental group was the VCS interface which helped students to develop a construction schedule for the same project. Student group effectiveness in schedule visualization was examined to compare the impact of these two 4D modeling tools in engineering education.

### 2.2.3 Direct Observation

Direct observation is a simple method to gather data about how users interact with products (Yin 2003). It is powerful for gaining user insight. To gain maximum benefit, careful planning is needed. Without care, observation may affect what people do and bias results may produce. It is important to make the person being observed comfortable with the process. Observation can be combined with video for better data capture.

There are two types of direct observation methods: structured observation and unstructured observation (Yin 2003). A structured observation is used when the researcher determines what behaviors are to be observed before the observation starts. Usually the research uses a standard checklist or a certain theoretical framework to record
the frequency or time of the behaviors observed over a specified time period. In an unstructured observation, there is no predetermined plan about what to be observed. The researcher records behaviors as they occur and analyze them afterwards.

In the implementation of the preliminary 4D learning module, unstructured observation techniques were used to observe student presentations and discussions since no research had been done in this area and the researcher had no predetermined plan about what to be observed. When comparing the VCS and a current 4D modeling application, a theoretical framework was used to examine student group communication. Structured observation was used to observe the student group meeting process since the researcher predetermined what to be observed from the available theoretical framework.

2.2.4 Survey

A survey is a process of examining a social phenomenon involving an individual or a group, by gathering information through observation or asking (Corbetta 2003). Commonly, surveys are conducted through questionnaires and interviews (Fellows and Liu 2003).

Questions have two primary types, open and closed. Open questions are designed to allow the respondents to answer in whatever form and content they wish. This kind of questions is easy to ask but difficult to analyze the data. Closed questions have a set number of predetermined responses that respondents can choose.

Questionnaire surveys were used in this research. Closed questions were asked to measure student perceptions regarding the value of 4D learning module in the group
meeting and presentation process. These questions were measured on a Likert scale (Corbetta 2003). Open questions were designed to investigate the challenges of using 4D modeling that students encountered and suggestions for future improvements of the module.

### 2.2.5 Content Analysis

Content analysis is defined as "any technique for making inferences by objectively and systematically identifying specified characteristics of messages" (Holsti 1969). Content analysis is a widely accepted technique to systematically analyze data obtained through qualitative research. It is a phase of information processing in which communication content is transformed, through objective and systematic application of categorization rules, into data that can be summarized and compared.

A content analysis was performed for each video recorded from student group meetings. The specific method that was used to develop the content analysis was to use a video analysis application to document the frequency/time for each category that was predefined by a coding scheme. Following coding, quantitative scales were derived for further analysis.

### 2.2.6 Inter-rater Reliability Test

Inferences drawn from the content analysis need to be verified and the reliability must be tested. There are three types of reliability for content analysis (Milne et.al. 1998):
1. Stability refers to the ability of the same coder to code data the same way over time. The coder usually experiences a test-retest procedure.

2. Reproducibility (inter-rater reliability) is to measure the extent to which coding produces the same results when the content is coded by multiple coders. This type of reliability measure is usually referred to as inter-rater reliability. The measurement involves assessing the proportion of coding errors between various coders. The reliability is verified by either reporting that the discrepancies between the coders are few, or that the discrepancies have been reanalyzed or the differences have been resolved.

3. Accuracy involves assessing the coding performance of coders against a set of predetermined standard. Such a standard is set by a panel of experts, or known from previous studies.

In this study, there were 10 videos recorded, with an average duration of 3 hours for each video. The researcher coded the videos and performed a stability test. Later, an inter-rater reliability test was performed. Since each minute of the video took approximately 4 minutes to code on average, it is unrealistic to have other coders test the reliability of the entire data set. Therefore a 12-minute video was randomly identified and three other coders coded the video. Included amongst the three coders, the researcher’s academic advisor has experience in content analysis and expertise in 4D modeling and construction planning, and two graduate students in the construction engineering and management option have familiarity with 4D modeling techniques but limited experience with content analysis.
The co-agreement levels reached among coders were used to test the reliability. The measure of the co-agreement level is the coefficient of agreement or percentage of agreement. The coefficient of agreement involves calculating a ratio of coding agreements to the total number of coding decisions taken by all the coders.

Reliability is usually tested by meeting a certain standard of reliability. However, it does not necessarily require a formal calculation of reliability. If multiple coders are used on the entire data set and all the discrepancies are examined and resolved or they observe very few discrepancies, the research can feel assured that the data set is reliable for those researchers. Determining an appropriate level of inter-rater reliability should be very careful since “defining an acceptable level of acceptable level of reliability is one of the many problems in content analysis for which there is no single solution” (Holsti 1969). The reliability standards need to be answered within the context of a given research problem (Krippendorff 1980). A detailed description of the reliability test is provided in Chapter 6.

2.3 Research Process

Detailed descriptions of the major research processes for this study are introduced in this section.
2.3.1 Literature Review

To provide a background for this research, a literature review was conducted in the areas of construction schedule visualization, design and construction team communications, virtual reality, and virtual reality applications in engineering education.

2.3.2 Development, Incorporation and Evaluation of a Preliminary 4D Learning Module

An exploratory study was conducted, where a preliminary 4D learning module was developed using a current 4D modeling application and implemented into an advanced project management course (AE 473) in 2005 at Penn State. The module was used to help students learn Short Interval Production Scheduling (SIPS) for a typical floor of the MGM Grand Hotel precast structural system. Final 4D model solutions were exported into video files so that student groups could present their solutions to their classmates and the instructor.

A scoring rubric was used to compare the quality of the final solutions with the previous year’s solutions, when a paper-based 2D drawing was used to develop the schedule. Student group presentations and discussions in class were directly observed, and a preliminary survey was conducted to investigate student perspectives of the 4D learning module. The results of this module implementation are presented in Chapter 4.
2.3.3 Identification of Assessment Parameters

From the implementation of the preliminary module, the researcher was able to identify important parameters that can be used to evaluate the value of the 4D learning modules. These parameters were identified by direct observation of student group presentations and in class discussions; analysis of the survey results; and the development of a summary of lessons learned from this research.

2.3.4 Development and Implementation of the VCS

The VCS was developed using a 3D game engine. It allows students to generate a construction schedule and a 4D model by interacting with a 3D model. The VCS learning module and a 4D learning module in a current 4D application of the MGM Grand Hotel project were incorporated into the same advanced project management course in 2006. The AE 473 class was randomly divided into eight small groups of 3 and two groups of 4 students. The control group consisted of 5 student groups that used the current 4D modeling interface, and the experimental group consisted of 5 groups that used the VCS application. The experiment was conducted in the Immersive Construction (ICon) Lab where students can visualize the 3D and 4D model on a large 3-screen display system. The experiment was observed and videotaped with student permissions for further analysis.
2.3.5 Assessment of the VCS

Data were collected both during and after the experiment for examining the student group process, group product and perception towards the learning modules. The experiment for each group was observed and recorded so that the student group process could be analyzed. Initial schedules, final submitted schedules and overall SIPS assignments were documented so that their quality could be compared between the control and experimental groups. Surveys were conducted after the experiment and student presentations to gain their perceptions.

The videos were analyzed using content analysis techniques. Student group communications were coded and quantitative data were obtained by conducting frequency/time studies of different communication categories predefined by a coding scheme. Initial schedules, final submitted schedules and overall SIPS assignment were graded using scoring rubrics. Qualities were evaluated by comparing the grades. Survey results were used to examine and compare student perspectives from both control and experimental groups. The results are presented in Chapter 6.

2.3.6 Documentation of Conclusions and Lessons Learned

The benefits and limitations of the 4D learning module used in engineering education were identified through this study. Conclusions as well as lessons learned were documented. Suggestions for future improvement of learning modules were provided, and directions for further research were recommended.
Chapter 3

Literature Review

This chapter provides an overview of significant literature related to this research. Construction schedule visualization, design and construction team communications, virtual reality (VR) display system, and virtual reality applications in engineering education are covered.

3.1 Construction Schedule Visualization

To understand the value of 4D visualization technologies for schedule visualization, it is very important to know the traditional schedule visualization methods and their limitations, and background knowledge of 4D modeling. This section introduces traditional 2D and CPM scheduling methods, 3D visualization, the concept and process of 4D modeling, and the applications and values of 4D modeling in the AEC Industry.

3.1.1 Traditional 2D CAD & CPM Scheduling

2D drawings and CPM scheduling are the traditional tools used in the Architecture, Engineering and Construction (AEC) Industry to analyze project designs and plan their construction. Designers use 2D drawings to describe their ideas to other project participants. Visualization of the facility is communicated using 2D drawings
and project information is primarily exchanged via paper documents. Individuals need training to interpret 2D drawings and visualize projects based on their previous experience and knowledge. With building geometry getting more and more complex, even experienced personnel misinterpret the designer’s intention, which can lead to additional time and cost.

CPM was invented by the aerospace industry and has been adopted in the construction industry since late 1950s. Though it has been well served in this industry in many aspects, the CPM has been widely criticized in terms of its inability to cope with non-precedence constraints, difficulty to evaluate and communicate interdependencies, and inadequacy for work-face productions (Sriprasert and Dawood 2002). They use only titles to designate activities and numbers to indicate activity durations. They are separated from the visualization of the planned construction (Collier 1996).

Schedulers need to interpret the 2D drawings, identify activities and build a logical sequence network. Then they determine activity and project durations. This process results in a CPM network or a Gantt chart. Developing a construction schedule is hard since one has to build a project step-by-step in their mind after visualizing the 2D drawings.

It is difficult to conceptualize the construction process and detect problems by viewing the CPM schedule alone, especially for a novice with limited construction experience. Such schedules force users to visualize and interpret the activity sequence in their minds. Components in 2D drawings have to be associated with their related activities mentally. The processes are a sequence of events not physical objects, therefore, it is more difficult to validate and evaluate them (Retik 1993). Sometimes a
novice cannot even detect problems from a small CPM schedule. Also people have different interpretations of the same schedule, which makes it difficult to communicate and discuss whether a certain problem actually existed or not.

### 3.1.2 3D CAD Visualization

Simulation modeling and visualization are used to overcome the deficiencies of the traditional scheduling techniques. Advanced visualization techniques such as 3D visualization, 4D models and virtual reality models can be utilized for more effective generation, communication and evaluation of schedule information.

3D modeling has been around for more than three decades, and it is becoming a more useful and economically viable tool. 3D modeling can better present the physical reality of a structure than 2D drawings. 3D models have been increasingly used in a number of different areas such as automobiles, aerospace vehicles, buildings and so on. Various computer-based 3D visualization activities have been used for construction planning. Kamat et al. (2001) described a 3D visualization system for construction operations simulation. The construction system can be analyzed at the operation level of detail to plan the construction process. Interactions of various resources, such as materials, labor, equipment and temporary structures can be viewed when the building is being virtually constructed.

Thabet (2001) proposed a virtual construction model to integrate the design and construction process to improve project constructability during the pre-construction stage. The model allows the users to virtually and interactively construct 3D models of the
projects from predefined construction CAD assemblies or components. The construction process can be rehearsed, which allows the users to analyze and criticize designs as well as perform what-if scenarios.

Songer et al. (2001b) quantified the benefits of 3D models and walk-thrus for schedule development for construction projects. Completeness, reasonable activity duration and valid activity relationships were used to measure the “correctness” of a schedule. Critical path and total float, workflow and resource use were used to define “goodness”. Schedulers can generate more correct and better construction schedules by using a 3D model and a walk-thru than by using 2D plans. The walk-thru model enhanced the spatial comprehension, which enabled the schedulers to schedule concurrent activities without the fear that they were scheduling too many activities in the same area or at the same time. The walk-thru enabled experienced schedulers to develop correct schedules, as well as effectively minimized the disadvantage of inexperience.

3.1.3 4D CAD

3.1.3.1 Definition of 4D CAD

A 4D CAD model results from the linking of 3D graphical images to the fourth dimension of time (Koo and Fischer 2000). The idea of linking 3D CAD models to the construction schedules began in Bechtel Corporation in 1986-87 when they collaborated with Hitachi Ltd. to develop the Construction 4D-Planner (Smith 2001). While the
spatial and temporal dimensions of construction schedules are not effectively represented and communicated by traditional bar charts and network diagrams, a 4D model simulates the construction schedule and actually shows which pieces of projects will be constructed in what sequence (Adjei Kumi and Retik 1997). By combining 3D models with construction activities, 4D CAD animations can display the progression of construction over time, which provides the opportunity to improve the quality of construction plans and schedules (Rischmoller et al. 2001).

3.1.3.2 Development of A 4D Model

The current process used to develop a 4D model is:

1. Develop or obtain a 3D CAD model.
2. Develop a construction schedule. This information is captured from the experience and knowledge of the construction planner.
3. Separate the 3D model into appropriate construction elements or assemblies.
4. Link the components of the 3D model with their activities specified by a CPM schedule in a 4D CAD schedule. Once they are linked, the 4D model can be viewed as a simulation of the construction plan.

3.1.3.3 Benefits of 4D CAD

4D CAD models enable more people to understand a schedule quickly and identify potential problems, since it allows people to visualize the construction process as
it would be actually built before the construction starts. Koo et al. (2000) studied the effectiveness of a 4D model in conveying a construction schedule. 4D models are useful in conveying which components are being built at a certain time and location. 4D CAD is effective in:

- verifying the completeness of the schedule;
- finding inconsistencies in the level of detail among the schedule activities;
- discovering any impossible schedule sequences;
- identifying potential time-space conflicts; and
- anticipating accessibility problems.

4D models are effective in evaluating the executability of a construction schedule. They allow users to detect mistakes or potential problems prior to construction. The main benefits that a 4D model provides are as a

- visualization tool- ability to convey planning information;
- analysis tool - enhance collaboration among project participants; and
- integration medium - support users to conduct additional analyses.

4D modeling also enables the identification of potential conflicts between building elements and work spaces, safety hazards created due to proximity of construction activities, and the visualization of construction plans (McKinney et al. 1998).

Songer (2001a) quantifies the advantages of 3D/4D presentations for schedule review of construction projects. Once a schedule has been created, 4D animation is useful to review and analyze it. 4D media can improve a schedule reviewer’s ability to
identify the “correctness” and “goodness” of the schedule. With the aid of 4D CAD animation, missing activities and logic errors in the schedule are dramatically reduced, safety and overcrowding issues are easily identified, and better work flow can be achieved. 4D animation is a valuable tool for schedule analysis, especially for analyzing portions of the schedule that involve complex design drawings, which are difficult in 2D review.

4D Planning and Scheduling (4D-PS) uses 4D models to accomplish project construction planning and scheduling tasks (Rischmoller et al. 2001). It allows simulating and interacting with construction schedule through graphic display devices. The application of 4D-PS to a case study shows that 4D model reviews can help construction planners to optimize construction sequences, identify and resolve schedule conflicts, and provide feedback from construction teams to design teams. It also gives planners the ability to track and manage workers and resources. By allowing planners to make important decisions regarding deadlines, sequence and resource utilization ahead of time, 4D model reviews can dramatically improve project constructability and avoid rework.

4D CAD modeling offers the opportunity for planners to perform detailed trade sequencing and production planning (Riley 1998). Workspace congestion and inference between crews and stored materials can be predicted and minimized through visual analysis of construction sequences, so that productivity rates can be maximized.
3.1.3.4 4D CAD Applications in Construction Projects

3D and 4D models have been used on large projects and process plants. More and more companies realized the benefits and began to explore the possibilities of this tool as a means to increase their competitiveness. The Center for Integrated Facility for Engineering (CIFE) at Stanford University has lead several significant research projects related to 4D CAD in construction industry.

4D modeling was used on the Walt Disney Concert Hall Project to test the benefits and challenges of using 4D models for projects with complex geometry (Haymaker and Fischer 2001). 4D models benefited the project in the following aspects:

- Schedule creation: The GC used the 4D models to assist in planning the laydown areas for the enclosure contractor, to visualize overall project access at critical junctures in the project, to refine the interior and exterior scaffolding strategy, and to plan the installation of the complex ceiling of the main concert hall.

- Schedule analysis: The GC’s project management team used 4D models to discover several conflicts in the schedule which were not discovered in the CPM-based Gantt chart.

- Communication: The GC used the 4D models in training sessions with as many as 40 people, where subcontractors, owners, designers, and the GC reviewed the models and discussed the strategy and constraints for erecting the project
Team building: The 4D models helped the construction team find many schedule inconsistencies, resolve access, scaffolding and hoisting issues for the exterior and interior construction in a timely manner, inform more stakeholders of the approach to construction and of the schedule, and engage subcontractors in the scheduling process.

Challenges encountered in building the 4D models included:

- **Geometry issues:** Inconsistencies, lack of data, level of detail, and too much data.
- **Schedule issues:** Inconsistencies and lack of data.
- **Issues with linking of 3D model and schedule:** Inconsistencies, other data, and representation of activities with no geometry.

The documentation of the use of 4D modeling on small projects is very limited. The San Mateo County Health Center project is an example of using 4D modeling and animation on a daily basis on a small project. 4D schedule animation is a good tool in explaining the proposed construction sequence. Even people with minimal previous involvement were able to view the animation and quickly understand the impact of the planned construction on their department, office and daily operation. Video of the animation can be created and used to disseminating the construction information to a large number of people (Collier 1996).

Disney's Imagineers found tremendous value of 4D in terms of increased productivity and decreased waste on job sites. The main value is conflict resolution since 4D allows visualization of construction sequence. Another benefit is the ability to run what-if scenarios to determine optimum scheduling and resource management.
Also, all project stakeholders, from the owner to the tiling subcontractor, can see how the project is supposed to progress by using 4D.

In another case study by Staub et al. (1999), a 4D CAD model was used for the most extensive and difficult construction work of a pharmaceutical plant, leading to fewer unanticipated problems during construction. The results of using 4D on this project were:

- The piping and mechanical subcontractors fabricated all the large and expensive ducts and pipes directly from the 3D CAD model, and both reported far greater productivity and virtually no rework.
- There was only one contractor-initiated change order on the work that had been modeled in 3D.
- Requests for information were reduced by 60% percent compared with a similar project designed and built by traditional means.

The model benefited various trades on the project. It lowered the construction cost by helping subcontractors to avoid sequencing conflicts. The project manager found the 4D model valuable in coordinating construction tasks and communicating the intent of the schedule. The project designer could make modifications to one model when the design changed, whereas they had to change plans, sections, and elevations when using traditional 2D drawings.

These cases have shown that more project stakeholders can benefit from 4D models. They can understand a construction schedule more quickly and completely with 4D visualization than with the traditional construction management tools, and they have much better communication with different trades related to the project. With
successful applications of 4D CAD in the industry, it is feasible that 4D CAD may be very beneficial in construction engineering education. It can provide the opportunity to improve construction engineering education by allowing students to experience the dynamic nature of construction.

3.2 Design and Construction Team Communication

This research will investigate the value of the VCS by comparing with traditional 4D modeling tools. One critical evaluation parameter that will be used is the team communication effectiveness. This section provides a review of important work in design and construction team meeting communication.

Different criteria are available in defining communication types during design and construction team meetings. There are two main theoretical frameworks that were reviewed for this research: design team meetings by Stempfle and Badke-Schaub (2002) and construction project team meetings by Liston (2000).

Stempfle et al. (2002) discussed the four basic thinking operations (exploration, generation, comparison and selection) and analyzed design team meetings and defined six steps concerned with the communication content of a design team meeting:

1. Goal clarification: goal related communicative acts;
2. Solution generation: a solution concerning the design task;
3. Analysis: question, answer, hypothesis, exchange of information concerning a solution;
4. Evaluation: positive and negative evaluations of a proposed solution;
5. Decision: decisions for or against a solution idea; and

6. Control: Control of the implementation of a solution idea.

Stempfle’s research shows that the most frequent types used by the design teams are analysis and evaluation in a collective design process.

Rao and Kremer (2005) used the four basic thinking operations discussed by Stempfle et al. and studied design team communications by audio recording design team meetings. Recorded audio was transcribed to text and the transcriptions were categorized into one of the four basic design activities of exploration (of concepts and analysis of designs), generation (of alternate concepts and solutions), comparison (of concepts and solutions) and selection (of viable design solutions). They studied the sequence of design activities to examine how information sources were utilized. Two design team communications were analyzed and Figure 3 shows the sequences of design activities for these two groups.

One design group spent smaller amounts of time on each activity, but iterates much more frequently between the different activities. Both teams spent most of their time on comparison, then exploration, generation and selection in descending order.

Figure 3 Sequence of Design Activities for Two Design Teams during the Same Design Session

Liston (2000) analyzed the amount of time spent on different categories of communication types (descriptive, explanatory, evaluative and predictive) in a construction project team meeting.

- **Descriptive:** describing various tasks and asking questions like “who, what, when, where, how” of a project.
- **Explanatory:** explaining project decisions or schedule rationale. Questions like “why, why not” are usually discussed.
- **Evaluative:** Evaluating the project goals and checking that project requirements are met. This consists of the assessment of possible alternatives to a problem or situation.
- **Predictive:** predicting the possible consequences of a decision or estimating the value of an unknown variable during a meeting.

According to Liston’s study, it has been observed that significant time during the meetings is involved in describing various tasks (Descriptive) to other participants. 4D CAD modeling and immersive virtual environment can enhance the construction planning and plan communication process (Yerrapathruni 2003). It can also serve as an excellent tool for communication among the project participants, stakeholders and potential customers (Gopinath 2004). This fact illustrates an opportunity to introduce advanced visualization techniques and to make improvement in the way project information is communicated. A new type of Construction Information Technology (CIT) was proposed by Liston (2000) to change the time spent on the communication categories in the future Construction Information Workspaces (CIW). The current and future communication diagram by Liston is shown in Figure 4.
Figure 4: Current and Future Communication Diagram  
Source: Liston (2000)

Fard (2006) adopted Liston’s proposed framework and conducted an observational study of collaborative decision-making in order to assess the performance of project teams in design development and coordination meetings. Three different types of meetings (traditional design development meetings, value engineering meetings, and scheduling meetings) were video recorded and coded to study how the various participants in these meetings spent their time on decision-making tasks. Figure 5 shows the time study results of these three types of meetings. It shows that most of the time is spent on descriptive and explanatory tasks, and less time is spent on evaluative and predictive tasks for all these three types of meetings. This research provided a validation of the collaborative decision-making framework proposed by Liston (2000).
In this research, student group meetings were examined using Stempfle’s theoretical framework, because students were trying to develop a construction schedule for a project and they functioned more like a design team to design a process (a construction schedule). Liston’s categories were considered, but the detailed categorization of discussions of student groups performing the scheduling task was difficult.
3.3 Virtual Reality

In the experiment conducted for this research, the Immersive Construction (ICon) Lab was extensively used, which provided students a virtual environment to interact with the 3D and 4D model. This section introduces the concept of virtual reality (VR), various types of VR display systems, and the applications of VR in engineering education.

3.3.1 Definition of Virtual Reality

Virtual reality (VR) is an experience in which a person is “surrounded by a three-dimensional computer-generated representation, and is able to move around in the virtual world and see it from different angles, to reach into it, grab it, and reshape it (Rheingold 1991).” VR includes graphics applications that allow users to walk through a simulated environment and, possibly, to interact with objects in it. Interactivity means “the interaction between computer and user which takes place through changes of viewed locations, typed commands, voice commands, mouse clicks, or other means of interfacing (Shiratuddin et al. 2004).” Interactivity is the most important features of VR and relates what people see in the virtual environment to the real world. An effective virtual environment must give the user as much control as possible over their surroundings.

VR has been used in the design process and found to be more efficient to check the design solutions than the traditional media (Petric et al. 2002). VR used in construction equipment simulation provides the planners visualization of assembly sequences and real-time virtual interactive modeling of construction equipment (Bosch
and Hastak 2002). VR was also used to visualize construction plans and schedules (Waley and Thabet 2003; Whisker et al. 2003), enable architectural walk-through (Shiratuddin et al. 2004), optimize site facility layout (Tam 2002) and communicate with project teams (Haymaker and Fischer 2001).

VR can enhance the simulation by providing (Petric et al. 2002):

- Immersion: Users are completely surrounded by the environment;
- Presence: Users have the sense of being in the environment;
- Interactivity: The environment allows the participant to be involved and the result of the actions done by the participant can be visualized in the VE;
- Autonomy: Participants are neither constrained in paths nor in views preset by others. They have the freedom and autonomy to explore any single part of the environment;
- Collaboration: Multiple users are able to take part and to interact in the same VE.

### 3.3.2 Virtual Reality Display

While previous construction visualization mainly focused on the enhancement of product design, a significant amount of work has been done to develop graphic display techniques which allow users to view and interact with 3D models. The graphical interface between computers and humans has greatly improved. Virtual environments use stereo-graphics, audio and several other input devices to provide users the ability to visualize and interact with data in 3D (Nelson et al. 1999).
Non-immersive desktop VR and Immersive VR have been used to simulate the construction process (Retik 1993). A desktop monitor is used by the user to interact with a virtual model in desktop VR. For immersive VR, a large scale display or head mounted display is used to immerse the user in the virtual environment. Kasik et al. (2002) summarized 14 different displays and their characteristics.

CAVE (CAVE Automatic Virtual Environment), which was designed in 1991, was the first large immersive projection display (Cruz-Neira 1993). It is a $10' \times 10' \times 10'$ theater with three rear-projection screens for walls and a down-projection screen for the floor. A user’s head and hand are tracked with electromagnetic sensors. Stereographics’ LCD stereo shutter glasses are used to provide user 3D visual effect. CAVE and CAVE-like facilities have been successfully used in research for visualizing various complex systems. Usually these systems are used on a limited number of high-end research projects (Kalisperis et al. 2002). Due to the high cost and limited footprint of these display systems, they are not viable to be used for large scale educational purpose.

This research focuses on the use of an affordable, open footprint, three screen passive stereoscopic display system in the Immersive Construction (ICon) Lab at Penn State. Figure 6 is a rendering of the ICon Lab. The three screens, each is 6’ high by 8’ wide, provide a panoramic virtual reality environment by using rear projectors. Students can use all three screens to display a construction project to get the feeling of presence. Alternatively, they can use two screens to display the building geometry and the third screen to display construction schedule. The three screens can also be utilized
as an effective presentation system to show the audience more information than regular one screen displays.

Figure 6: ICon Lab Rendering

3.3.3 VR Used in Engineering Education

The use of immersive VR displays has primarily been limited to specialized research labs and those with large computing budgets, such as the military. Development of inexpensive hardware and software VR products in recent years has brought virtual reality within reach of the average researcher (Bell and Fogler 1995).

VR has been used in engineering education in different academic curricula. VR was used to integrate the fundamental concepts of design, analysis and manufacturing in introductory courses in Mechanical Engineering to positively impact student motivation and conceptual understanding of mechanical engineering concepts (Impelluso and
First-person simulation of lab accidents was used in undergraduate chemical engineering to address the importance of following proper lab safety procedures (Bell and Fogler 1995; Bell and Fogler 2003). VR was used to bridge the gap between classroom lecture and industrial experience. Whitman et al. (2002) used a virtual reality model of a real world manufacturing line to integrate a manufacturing engineering curriculum. The virtual reality models of the manufacturing line allows students to view the process and interrogate the process details, make changes and observe the effects, and gain a better understanding of concepts and their interrelationships. The use of a series of case studies from the real world in the curriculum enabled students to synthesize the knowledge and skills gained in different courses.

The use of VR in construction engineering education is currently very limited. Construction site visits are widely recognized as a great way for students to get first hand experience and gain a better understanding of the construction process. However, there are various difficulties of logistics and cost, such as the site is not at a specific stage of construction, large group visits to construction sites are not always welcomed, and transportation and time can be difficult to coordinate. VR allows educators to place their students in computer generated environments and present student with an educational experience difficult or impossible to achieve by using other methods. It is a useful tool to complement conventional construction site visit or site training. VR is especially beneficial as classroom substitute for field experience with hazard construction operations. Hadipriono et al. (1996) proposed the Construction Operations using Virtual Reality (COVR), which was used to educate and train undergraduate students in
performing a construction operation without subjecting them to the real on-site construction hazards.

Haque (2001) describes a 3-D animation and walkthrough integrated virtual construction site to teach reinforced concrete structure construction, which can help construction engineering and management students to better visualize the sequence of operations and design details of reinforced concrete buildings, so that they can design, manage, estimate and schedule more effectively.

Sawhney et al. (2000) proposed an Internet-based Interactive Construction Management Learning System (ICMLS) aiming at enhancing construction management education. The ICMLS uses interactive and adaptive learning environments to train students in areas of construction methods, equipment and processes, so that practical content can be incorporated into the construction curricula thus bridging the gap between the classroom and the construction site.

3.4 Summary

The effectiveness of 4D CAD has been demonstrated in real-life construction projects. 4D CAD is useful in the graphical presentation and communication of the construction schedule. It assists planners to visualize the construction process and compare different decisions made. 4D models have been used as a supporting tool, a checking tool, a communication tool, and as a parallel effort to help improve construction plans and schedules that were developed with conventional tools (Rischmoller et al. 2001). 4D models are generated by linking a 3D model and an existing construction
schedule. The 3D model and the schedule are inputs to this process, and the 4D model is the final product and used as a schedule review tool.

Traditional ways of generating a schedule limit the utilization of the 3D model and the potential benefits of the 4D model. Just like using the 2D drawing, schedulers still need to create the activities mentally, and link them to their related 3D components later. They can’t generate a schedule activity by selecting its corresponding component in a 3D model, which can translate their thinking into schedule activities directly. This research proposed to develop an interactive module, which allows students to generate a construction schedule directly from the 3D model. The output is a CPM schedule and a 4D CAD model.

VR technology has been used in construction engineering education, but has yet to achieve widespread use. There has been limited investigation of the effectiveness of visualization in engineering education in terms of student learning experience. VR technology allows two or more users, such as student project teams, to concurrently share and interact with the same VR environment. Allowing students to use 4D CAD to visualize the construction process, we may expect new forms of interaction and communication. It enabled students to work in multidisciplinary teams and to effectively communicate and understand concepts from various perspectives. This research identified the educational value and limits of allowing construction engineering students to generate 4D models in a wide format display system.
Chapter 4
Case Study and Preliminary 4D Learning Module

This chapter presents in detail the case study used for this research. A preliminary 4D learning module of the case study project was developed and provided to students. The focus of this study was to understand the impact of the 4D learning module on the student learning experience based on their use of the module.

T4.1 The Case Study Project

The case study chosen for this research was a course assignment in a senior level construction management course (AE 473) in the Architectural Engineering Department at Penn State, where students were required to develop a Short Interval Production Schedule (SIPS) for the MGM Grand Hotel Renovation.

4.1.1 SIPS Method Introduction

Short Interval Production Schedule (SIPS) is a scheduling method used to organize construction work. Different from conventional scheduling, which breaks a project into operations, SIPS breaks an operation into detailed repeatable activities. Usually the operation is a critical sequence that is repeated throughout one phase of the project and has a significant impact on the overall duration. Three major attributes that distinguish a SIPS from convention scheduling procedures are (Burkhart 1989):
1. Only one specific operation is analyzed;

2. A much higher level of detail is developed in a SIPS; and

3. Personnel involvement and commitment of everyone contributing to the operation is built into the process of developing a SIPS.

A SIPS utilizes the personnel involved in the project as part of the plan development, and the results of the SIPS process is a detailed, crew level plan for one specific operation. A SIPS applies the assembly line concept in construction and provides a productive work sequence for the project and faster learning curve for the crews. It has been used to construct buildings with highly repetitive activities. Projects with a large number of repeatable units, such as hotels, apartments, high rise office towers and prisons, can benefit from the SIPS method.

4.1.2 MGM Grand Hotel Renovation Project

The learning activity was to develop a SIPS for a typical floor of one wing of the MGM Grand Hotel Renovation in Las Vegas, Nevada. The hotel was the largest hotel in the world when it was completed in 1994. The hotel had 5,014 hotel rooms within 30 floors. It has a cross shape with a 290 ft tall core and four symmetric wings around the core (see Figure 7). The first four floors are cast-in-place reinforced concrete, with an additional 26 precast concrete floors above. The structure had a very tight schedule and needed to be finished within 9 months to meet the owner’s objectives. Since the precast concrete structure was repetitive for each floor, the construction of the structural system was a viable candidate for the SIPS method.
4.2 Previous Offering of the MGM Grand Hotel SIPS Assignment

This course assignment required students to develop a SIPS for constructing the precast concrete structural system for a typical floor of the hotel within time, crew, and equipment constraints. In previous offering of this assignment, students were given a 2D plan (see Figure 8) of a typical floor, together with some pictures taken from the construction site to visualize the structural system and develop their SIPS. Students submitted their final solutions using paper-based CPM schedules. The solutions were reviewed by the teaching assistant and the course instructor. Issues found in the solutions were addressed to the class by the instructor.
4.3 The Preliminary 4D Learning Module

In 2005, a preliminary 4D learning module was developed to aid students to develop their SIPS. The module was incorporated in the AE 473 class and the value of the learning module was assessed. Important metrics were identified for future evaluation of 4D learning modules.

4.3.1 Development of the Preliminary 4D Learning Module

The learning module consisted of a 3D model and a schedule template (Figure 9). The 3D model of a typical floor of the hotel was created using a CAD application (Autodesk VIZ). A schedule template was created using MS Project scheduling software. Both the model and the schedule template were designed so that students could manipulate and experience the model with minimal burden of technical issues.
4.3.2 Incorporation of the Preliminary 4D Learning Module

After the 4D learning module was developed, it was incorporated into AE 473 class. Students were taught how to use the NavisWorks with TimeLiner 4D CAD application (NavisWorks, 2007) prior to the SIPS assignment. They started with a simple model of an office building to learn how to import a 3D model and a schedule into the software and then link them together. This allowed students to become familiar with the software and gain the necessary skills they needed to finish the assignment.

When the students were familiar with the 4D CAD software, they started to work on their SIPS assignment. They developed a SIPS using the schedule template, and linked their schedule with the given 3D model using the 4D CAD software. The 4D CAD application allowed students to review and test their solutions. Final solutions were exported into video files for submission with the written assignment. Student groups also presented their solutions to their classmates and the instructor in the ICon Lab on a large 3-screen display system (see Figure 10).
4.3.3 Assessment of the Preliminary 4D Learning Module

The assignment provided an effective learning case study for students to learn the SIPS process, as well as an opportunity to assess the impact of the 4D learning module used in construction engineering education. SIPS final solution quality defined as the group product was compared to that of the previous year by using a standard scoring rubric. Group presentations of the SIPS were observed. Student group communication, student motivation and attitude toward 4D technology were investigated using a survey questionnaire.

4.3.3.1 Assessment of the Final Solution Quality

A scoring rubric (Goodrich-Andrade 2000) (see Appendix A) was designed and used to assess the solution quality of each student group in 2004 with the same MGM
assignment. The baseline of the group performance was measured using the traditional 2D drawing and CPM schedule. The same rubric was used to evaluate the performance of each group after the module was implemented in the fall 2005 semester. Though the average grade in year 2005 (86.75) was lower than that in 2004 (89.41), a higher overall solution quality in the schedules developed using the 4D learning module was observed. For example, 6 out of 9 student groups identified that there are some activities that can be overlapped when using the 4D model, while there were only 3 out of 9 groups that overlapped these activities in the previous year. More groups also identified that there are some activities that cannot be conducted during the night shift in 2005. The 4D model allowed students to review their solutions and helps them easily identify sequence conflicts, which were difficult to identify in the CPM schedule, so that they could revise their SIPS and determine a logical sequence for each activity. All these factors helped the student groups achieve a higher solution quality than the previous year. The course instructor felt the decrease in the average grade was due to poor written assignment quality. Students paid more attention to the 4D modeling part of the assignment. Some groups even didn’t submit a CPM schedule in their final submission. Statistical significance of comparison between the two years was not tested due to the number of the students (<30) for each year was small. It also should be noted that group equivalence through the two years was not tested when comparing the final solution quality.
4.3.3.2 Observation of the SIPS Presentation and Discussion

Student presentations and discussions were observed when student groups presented their solutions on a large, 3-screen display in the ICon Lab. In the previous year, the instructor reviewed all the solutions from student groups, and then discussed with students the most common problems they had in their solutions. With the help of the 4D model, each student group explained their SIPS to other students and the instructor in class in 2005. Since the 4D model graphically presented the SIPS, students could review the SIPS developed by other groups and experience multiple outcomes for the same project. And each group could get immediate feedback on their solution. The 4D model made the learning activity more interactive by allowing students to review and critique different solutions.

From in class discussion, it was noted that the model development improved the planning process by identifying additional issues that were not noted before. For example, the 3D model of one typical floor has two ends, and one end is connected to the core of the building. Some student groups did not notice or did not understand the impact of this and started constructing the floor from outside toward the core. This was noticed during the review process, and students started discussing issues related to the site planning and site access introduced by this problem. Other topics related to construction methods of grouting exterior wall connections were also discussed when students discovered that the necessary equipment would not be available.
4.3.3.3 Student Perceptions

After students finished the assignment and presented the solutions in the ICon Lab, they were asked to provide feedback on the 4D learning module by completing a survey. The survey investigated the value of the 4D learning module vs. 2D drawings and a CPM schedule; the communication style of the group when they worked on the assignment with the 4D module; the ease of reviewing and revising the schedule they developed; the ease of presenting solutions to the class and the instructor; and to what extent the students understood the SIPS process by using the 4D model. At the same time they were asked to state what challenges they encountered when they worked on the assignment and suggest improvements for the 4D module offered to them.

The survey results (see Figure 11) showed that students felt the 4D learning module improved their understanding of the SIPS process. The students felt that they were able to (1) communicate with their group members more efficiently; (2) easily review their developed schedule; and (3) present their solutions to the class and the instructor in a more interactive manner. It also helped them understand other groups’ solutions and learn about alternative schedules by graphically stepping through the schedules in the class. Students provided positive feedback regarding the 4D modeling activity and regarding the assignment design. While the survey showed the value of the 4D learning model, it also illustrated the difficulties that students had in fully understanding the construction plan by reviewing a traditional CPM schedule.

The researcher also conducted informal discussions with the students, the teaching assistant, and the instructor about the learning module. Informal discussions
with some students show that students were engaged by the 4D component implemented into this course. They realized the benefits of the 4D technology and would like to use this technology on their other appropriate course projects and future work. The teaching assistant (who took this course in 2003, and acted as teaching assistant in both 2004 and 2005), said the 4D videos helped him a lot in identifying which groups more clearly understand the constraints and how to use the resources to schedule the project. He identified the most valuable part of the modules as the in-class discussion, which allowed student groups to get feedback directly from their peers and the instructor.

4.4 Metrics for Future Module Assessment

In this study, the preliminary 4D learning module helped students achieve higher quality solutions, enabled schedule presentations and on time feedback, and students considered it as a beneficial and engaging tool for schedule visualization. Students also stated that the 4D learning module improved their group communication in the development of the SIPS schedule, which illustrated its potential value in improving the group process. Based on this exploratory study, a more detailed 4D learning module assessment plan was established, which examines the learning process, learning product, and student perceptions. The group process can be examined by directly observing student group meetings. For better data capture and analysis, observation can be combined with video recording the group process. The assessment plan is shown as following in Table 1:
Figure 11: Student Perception Surveys from 2005 Regarding the Benefits of 4D Modeling

Table 1: Assessment Plan for 4D Learning Module

<table>
<thead>
<tr>
<th>Assessment Metrics</th>
<th>Data Collection Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group Communication</td>
<td>Direct Observation</td>
</tr>
<tr>
<td>Group Interaction</td>
<td>Video Recording</td>
</tr>
<tr>
<td>Solution Quality</td>
<td>Scoring Rubrics</td>
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<tr>
<td>Opinion</td>
<td>Survey</td>
</tr>
</tbody>
</table>
Chapter 5

Virtual Construction Simulator

The preliminary 4D learning module illustrates the value of the development of 4D models for visualizing the construction sequence. But the current 4D modeling process requires additional time to develop the model since a planner must first generate a schedule, and then link the schedule to a 3D model of the project. A VCS application was developed, which allows a user to develop a construction schedule and a 4D CAD model by selecting objects from within a 3D model. This chapter defines the interface and the development process of the VCS prototype application.

5.1 The Interface

The VCS prototype allows for the grouping of 3D components into construction assemblies, the development of activities from within the 3D interface, and the sequencing of the activities. Following the development of the 4D schedule, the user can review and revise the activities and their sequence. It considers the process of a CPM schedule generation (create activities and sequence them), as well as the process of a traditional 4D CAD model generation (group construction assemblies and link them with the schedule). But it eliminates the linking process by allowing direct selection of the corresponding objects of an activity and its successors from within the model.
5.1.1 Basic Components

The interface consists of a number of basic components including various sets of buttons and pop up windows. Figure 12 shows the interface layout.

Figure 12: Virtual Construction Simulator Interface

A: Mode Buttons
B: Execution Button
C: Pop Up Window
D: Layer Buttons

Mode Buttons

The mode buttons allow a user to go to one specific working mode. There are 6 mode buttons: Group (create a group), Ungroup (undo a group), Create (create an activity for a group), Sequence (sequence activities), Finish (generate a CPM schedule and calculate timers) and 4D (generate and review the 4D model).
For the first four working modes, the two main functions of the mode buttons are to pop up the execution button and to make objects selectable. A selected object will change color depending on the status of the current working mode. When no mode button is selected, no execution button shows up, and the objects in the model are non-selectable. For the Finish and 4D mode buttons, no execution button will pop up when they are picked, since their mode buttons combine the function of the mode button and the execution button for that mode.

**Execution button**

The execution buttons allow the execution of the tasks under a specific working mode. There are four execution buttons: Group, Ungroup, Create and Sequence. They are named the same as their corresponding working modes. The execution buttons are designed to activate the pop up windows.

**Pop Up Window**

A pop up window consists of a number of texts, edit boxes and buttons. It allows a user to input values and save these values by clicking an OK button. There are three types of pop up windows: Group Name, Activity and Sequence. The use of these three windows will be introduced in detail in Section 5.1.2.

**Layer buttons**

A layer button is used to hide/show a set of objects in the model. Organizing the building into layers makes it easier to view, select and group similar building elements while other layers are turned off. There are five layer buttons in this interface: H/S (hide/show the background building), Frame (hide/show exterior ductile frames), Floor (hide/show floor planks), Wall (hide/show interior wall members), and Con (hide/show
cast-in-place connections between ductile frames). These buttons are specific to the MGM Grand Hotel 3D model for the prototype.

**Navigation Mode Buttons (not in the interface)**

The model can be zoomed, panned and rotated. A set of navigation mode buttons were initially created for the interface, but they did not function properly due to the limitation of the 3D game engine application. So in the final version of the VCS prototype, there is no navigation mode button. Different navigation modes are achieved by using a mouse instead of clicking buttons in the interface: holding the middle button and dragging the mouse will zoom in/out the model; holding the right button and dragging the mouse will pan the model; and holding the left button and dragging the mouse will rotate the model.

**5.1.2 Main Program Functions**

The VCS is designed to allow a user to interact with the 3D model, group building elements, create activities, sequence activities, and generate a 4D model and a CPM schedule. This section will introduce the six main functions and how they are achieved using the interface.

**Group Building Elements**

Building elements in the 3D model can be grouped into construction assemblies. Figure **13** shows the steps a user follows to group a set of ductile frames:
1. Click the “Group” mode button. This will pop up the “Group” execution button and make the objects in the model selectable.

2. Select ductile frames one by one from the 3D model. When one frame is selected, its color changes from the model color (dark green) to grey.

3. Click the “Group” execution button after selecting all the objects in the group. The “Group Name” pop up window will appear.

4. Type in the group name in the edit box on the “Group Name” pop up window. Click the OK button and a group is created.

Ungroup Building Elements

If a user changes her/his perspective about any previous grouping, the “Ungroup” function will undo the grouping. The user performs the following steps:

1. Click the “Ungroup” mode button.

2. Pick any object in a group.
3. Click the “Ungroup” execution button.

All the objects in that group will change back to their original model color. They can then be grouped into a new group later.

Create A Construction Activity

After a group is created, activities for that group can be generated using the “Create” function. Figure 14 illustrates the scenario for creating an activity for a ductile frame group:

![Figure 14: Create Function](image)

1. Click the “Create” mode button.

2. Pick the group by clicking any object in the group. The group will change color from grey to light blue.

3. Click the “Create” execution button to pop up the “Activity” window.

4. Click or input values into the edit boxes on the “Activity” window to create the activity. The current selected group name will show up by simply clicking the “Group” edit box. The first activity created will have its ID as 10. Activity ID will be increased automatically by 10 by
clicking the “ID” edit box every time. Activity name, duration, and activity type have to be input manually. Multiple activities can be created for one group. In this case, the activities for the same group should use a different activity type so that each activity will be shown in different colors in the 4D model.

Sequence Construction Activities

The sequencing is performed by defining all the successors for the current activity. Figure 15 shows the process of how to sequence two activities:

1. Click the “Sequence” mode button
2. Click the group for the activity the user want to sequence from the model.
   The group will change into a pink color when it is picked.
3. Click the “Sequence” execution button to pop up the “Sequence” window.
4. Click the “Current Activity” edit box. The current activity name will be shown in the edit box automatically.
5. Click the group for the successor activity
6. Click the “Successor” edit box. The successor activity name will be shown in the edit box automatically. There is a spinner at the end of the “Current Activity” and “Successor” edit box. When there are multiple activities for one group, the spinner can be used to look up different activities in that group.

7. If there is a lag between the two activities, the user can input the lag in the “Lag” edit box. The lag can be either a negative or positive number. A relationship between the two picked activities is created when the OK button is clicked.

An “Unsequence” button is available to undo the sequencing when necessary. The procedure is the same as that of the “Sequence” except the user must select the “Unsequence” button in step 7 instead of the “OK” button.

**Finish**

The “Finish” mode button can be clicked after the building elements are grouped and the activities are created and sequenced. When this button is clicked, the model will disappear, and the CPM schedule and timer for each activity will be generated.

Each activity has a timer. When the timer is activated for an activity, the group for that activity will appear. The timers are calculated in the “Finish” mode and activated in the “4D” mode.

The schedule can either be generated as a .txt file, or an Excel file. A final CPM schedule in Microsoft Project can be easily developed by mapping the Excel file to MS Project, or by copying individual task information from the .txt file and pasting to MS Project.
4D Model Playback

When clicking the “4D” mode button, the timer for each activity is activated (timers for concurrent activities will be activated at the same time) and the 4D model is generated to show the progress of the construction. A user can review the generated schedule by looking at the 4D model, and make changes to the schedule by creating new groups, generating new activities, and establishing new sequencing.

5.2 The Development Process

The VCS prototype is developed by using three applications: a 3D modeling software (Autodesk VIZ), a 3D game engine (Deep Creator) and a database (Microsoft SQL Server). This section will describe the process of how the prototype was developed using these applications.

5.2.1 The Modeling

The modeling was separated into two parts. One part is the 3D construction elements, and the other part is the user interface panels including buttons, windows, edit boxes and 2D texts.

The 3D construction elements were modeled in Autodesk VIZ. The model was improved from the preliminary model, which had one typical floor of the building. In 2005, students made several mistakes that may have been caused by not visualizing the overall construction environment. In 2006, new elements were added to the model to
provide students a more realistic environment and more accurate detailed model. Figure 16 is a screenshot of the 3D model. The core and four symmetrical wings of the building were modeled, with each wing showing different progress of the construction. The main construction equipment (cranes), staging area with construction materials, and the surrounding buildings were modeled by referencing the construction photos and Google Earth. The active part of the model is still one single floor. It consists of 27 ductile frames, 22 interior walls, 11 steel beams, 108 floor planks and 28 cast-in-place connections between ductile frames. The other part of the model is grouped into one element, so that it can be easily turned on and off.

![Figure 16: MGM Grand Hotel 3D Model](image)

The 3D VIZ model was converted to a .3ds file and imported into the Deep Creator game engine. 2D objects such as 2D text blit, 2D screen blit, edit box, buttons, radio buttons, and spinners were directly modeled in Deep Creator. They were put
together to form different pop up windows, or acted individually as the mode buttons, execution buttons and layer buttons.

5.2.2 The Programming

The imported 3D model and the 2D control panels were merged to form a scene in Deep Creator. To make the scene come alive, so that a user can interact with it, programs are written for Deep Creator by using the Lisp Application Programming Interface (API) (Lisp Editor). Figure 17 shows the interface of the Lisp Editor within Deep Creator. The Lisp Editor is used to add logic control to the 3D scene and edit the code for the scene and each object.

![LISP Editor](image)

**Figure 17**: Lisp Editor in Deep Creator

Two programming languages were used throughout this process: Lisp and SQL:

**LISP programs**

LISP programs were written to interface with the scene objects (codes for each object), Deep Creator parameters (global variables) and the SQL database. The main functions achieved by Lisp programs include:
1. Change predefined properties of each object, such as color, group name, status of the 3D objects, and show/hide status of the 2D objects;

2. Trigger one object animation when another object is picked, e.g., when the mode button is selected, the corresponding execution button appears;

3. Enable user input for each edit box;

4. Calculate the schedule and activate the timer for each object;

5. Write a .txt or Excel schedule file;

6. Set interface background color and navigation mode; and

7. Interface with SQL programs to query a database.

**SQL (Structured Query Language) programs**

SQL is a standard computer language for accessing and manipulating the database. The interface between the Lisp and SQL programs in the Deep Creator Lisp API allows Deep Creator to query a SQL database, so that user input in Deep Creator can be saved to the database and data needed by Deep Creator can be retrieved from the database.

### 5.2.3 The SQL Database

A SQL database was created for the VCS prototype. The database was used to store predefined properties of the 3D model objects, save user input and calculation results, and provide the access for Deep Creator to retrieve data. Four tables were used: Object table, Activity table, Sequence table and Timer table. These four tables can be queried by Deep Creator, as well as retrieve data from each other.
Object Table

The Object table is used to store the predefined properties of the 3D objects, including object ID, name, group name, status (object is under which working mode) and RGB color.

The object name and group name are the same at the beginning, so that one object can be a group by itself. Only when a user groups one object with other objects and enter a new group name from the “Group Name” pop up window, all the objects in that group will change their group name into the user defined name. In Figure 18, the object Fr11 had the group name Fr11 before it was grouped. Following the grouping with Fr12, Fr13 and Fr14, the group name for all these four objects changed to the user defined group name of Bay 6 & 7 Frame.

The Status column shows which working mode an object is currently under, so that the object can change color accordingly when it is selected. The default Status is 0, which means the object is in its original model color. When the object status is 1, it means the object is under the “Group” working mode and its color will change to grey when picked. Status 2 and 3 are for “Create” and “Sequence” mode separately, and an object will change to light blue under status 2 and pink under status 3.

The last three columns are the RGB color of the objects. When the status of an object is changed, the number in these columns will change accordingly, so that the object color is changed. These numbers are updated by the Lisp programs in Deep Creator.
Activity Table

The Activity table is used to save user entered data from the “Activity” pop up window. The information it stores includes the activity ID, name, duration, start and finish date, and activity type (see Figure 19).

The group name for the current activity will be stored in the Activity table as well by querying the Object table. The Activity table also stores the timers and successors of the current activity. The timer values are achieved by querying the Timer table, while the successor values are achieved by querying the Sequence table Successor ID column.

The Activity table is the core table, which actually queries all the other three tables and saves the data from them. When the final CPM schedule and the 4D model
are generated, the Activity table will be the only table Deep Creator needs to query to display the 4D model. Figure 19 illustrate the relationship of the four tables.

Figure 19: Activity Table of the Database
The Sequence table (see Figure 21) is used to store the user input from the “Sequence” pop up window. The information includes the current activity and its successor, the lag between them, and the successor activity ID. The Successor ID is used when the Sequence table is queried by the Activity table.
The Timer table (see Figure 21) is used to store timers for each activity. When the “Finish” radio button is clicked, the LISP program will calculate timers for each activity, then save all the timers into the Timer table. This table will be queried by the Activity table to retrieve the timer for each activity.
5.2.4 Summary of the Development Process

Figure 23 summarizes the workflow of the development process: the 3D VIZ model was imported into Deep Creator and formed a scene with the 2D control panels modeled in Deep Creator. Lisp codes were written for the scene and each object to achieve the functions of the prototype, while SQL codes were used to save user input and retrieve data from the database. A SQL database was created with four data tables for Deep Creator to query data.
Figure 23: Workflow of the VCS Development Process
Chapter 6

Assessment of the Virtual Construction Simulator

An experiment was performed to assess the potential value gained by using the VCS prototype. The experiment was designed to compare the VCS prototype with a traditional 4D CAD interface by examining the student learning process (student communications, interactions, use of the 3D model), learning product (the quality of generated construction schedules) and student perspectives when they used the two different interfaces to develop a SIPS schedule for the MGM Grand Hotel project. This chapter describes the experiment details, data collection, data analysis and results.

6.1 The Experiment

6.1.1 Display Systems

The experiment was conducted by using the 3-screen display system and a SMART Board interactive whiteboard as the fourth display in the ICon Lab at Penn State. Figure 24 shows the display systems.
The three screens (each is 6’ high by 8’ wide) provide a panoramic virtual reality environment by using rear projectors. Students can use all three screens to display a construction project to get the feeling of immersion and presence. Alternatively, they can use two screens to display the building geometry and the third screen to display a construction schedule.

The SMART Board is a touch-sensitive display which connects a computer and a digital projector to show the image from the computer. It is an interactive white board which allows a user to control computer applications directly from the display. In this experiment, the SMART Board was set up to allow a user to interact with either a Microsoft Project CPM schedule (the control group) or a SQL database (the experimental group).
6.1.2 Experiment Procedures

Students in the AE 473 class were randomly assigned to 10 small student groups (see section 2.2.2 for details), where 5 student groups used the VCS 4D model generation tool (the experimental group) and 5 groups used a current 4D CAD application (NavisWorks with Timeliner) for reviewing a schedule generated in a CPM application (MS Project) (the control group).

Each student group was assigned a 4 hour time period to finish the assignment in the ICon Lab. A training session prior to the experiment was offered to each group to show them how to use the interface and the SMART Board. On-site technical support was also provided to help students whenever they encountered technical problems. Reference materials such as construction cost data and construction pictures were also made available for students to use when they were performing their activity.

The control group used MS Project displayed on the SMART Board to generate the project activities and sequence the activities. The 3D model was available to the group throughout the exercise to visualize the project on the 3-screen display system. Figure 25 shows a control group developing their initial schedule in the ICon Lab. The initial schedule they developed was documented for analysis and saved after the group decided that they had finished. Then the schedule was loaded into NavisWorks with Timeliner, which already included the 3D model of the project. The students linked their schedule activities to the appropriate objects in the 3D model in NavisWorks. When complete, they reviewed their schedule by viewing the 4D model. Once they visualized the 4D model, they were able to revise their original schedule on the SMART
Board and then update their schedule (using the update function in NavisWorks) so that they could see the revisions. The final schedule and the 4D model were saved and provided to the student group for future use in completing the class assignment.

Figure 25: One Control Group

The experimental group used the Deep Creator game engine prototype for grouping 3D elements, developing the activities, sequencing the activities, and visualizing the 4D model. They had the 3D model on the three large screen display system. They were able to pick 3D objects in the model and group them. They were also able to generate activities and sequence them from within the 3D model. Data from using the VCS was saved to the SQL database (SQL Management Studio) and displayed on the SMART Board, which allowed the group to review the activities and the sequence they generated. Figure 26 shows students in an experimental student group discussing sequencing alternatives when they were developing their initial schedule. After developing their initial sequence, the group was able to review the 4D model using the
VCS prototype. The initial schedule that they developed (e.g., the first time that they selected the “Finish” mode button) was documented for further analysis. Then they were able to visualize the 4D model and revise their schedule. They received a schedule and a 4D model after they went through this process. Since the NavisWorks application is a more mature commercial application than the self-developed VCS prototype, a 4D model was developed for each experimental group based on the final schedule they developed using the game engine interface, so that they had the opportunity to revise their schedule in NavisWorks for final submission.

Each student group presented their 4D model to the class and the instructor in the ICon Lab after their final submission. The instructor and the class asked questions, provided comments and discussed alternatives regarding each specific 4D model. Figure 27 is a picture of one group presenting their 4D model to the class.
6.2 Data Collection

Various types of data were collected during and after the experiment. This section introduces the data collection process.

6.2.1 Data for Measuring Group Process

One objective of this experiment was to examine the group process for both the control group and the experimental group. To achieve this objective, group activities and communications were observed and videotaped when student groups were working on the project in the ICon Lab. A video analysis software (Studiocode) was used to live capture the observations. The videos were captured and saved directly onto an Apple Macintosh computer hard drive. Since the communications of the students would be analyzed, it was very important to get high quality audio during the capture. A pair of
Pressure Zone Microphones (PZM) was used to accurately record audio. They were put on the flat surface table that students sit around and picked sound from the entire room with good accuracy. Figure 28 shows the audio and video capture equipment and the Macintosh computer used in the experiment.
Figure 28: Audio & Video Recording Equipment
6.2.2 Data for Measuring Group Product

Three types of group product data were collected: the initial schedule, the final schedule, and the SIPS assignment. Initial schedules of both groups were documented, so that the quality of the initial schedules that were developed using different interfaces could be compared. For the control groups, they used MS Project to develop the schedules. When a group decided they had finished developing the schedule, they were asked to save two copies of the schedule. One copy was for research purpose and saved as the initial schedule, and another copy was used to develop the 4D model in NavisWorks. For the experimental groups, the initial schedule was generated automatically when they clicked the “Finish” mode button. The initial schedule in an Excel file was documented by the researcher. Then the group could proceed to revise the schedule after they reviewed the 4D model they developed.

The quality of the initial schedules was evaluated by the course teaching assistant using a standard schedule evaluation form (See Appendix B). The researcher created 4D models using the initial schedule that each group generated, so that it was easier for the teaching assistant to review the schedules and evaluate their quality. Since the researcher created 4D models for the control group in NavisWorks 4D modeling tool, and the experimental group had the 4D models in Deep Creator, the grading was not blind. The teaching assistant felt that the experimental group had better planning than the control group.

The grading was blind for both the final schedule and the SIPS assignment. The teaching assistant did not know which group the assignment was from. Data showing
the quality of the final schedule were obtained from the teaching assistant who graded the assignment using a standard scoring rubric. The average scores of the final schedule portion of the control group and the experimental group were calculated to compare the quality of the final schedule.

The final scores of the SIPS assignment for each group were obtained from the teaching assistant as well. The average scores for the SIPS assignment for the control group and the experimental group were also calculated to compare the quality of the overall SIPS assignment.

6.2.3 Data for Measuring Student Perspectives

Surveys were conducted after the experiment (See Appendix C-Survey I) and following the SIPS in class presentation (See Appendix D-Survey II) to obtain perceptions of the students from both experiment groups. The survey questions consisted of both quantitative and qualitative questions.

The quantitative data in the surveys consisted of the responses of the participants to several questions on a Likert scale of 1 to 5 (1-strongly disagree to 5-strongly agree). For Survey I, all 16 students in the control group returned the questionnaire, which made the response rate 100%; 16 out of 18 students from the experimental group returned the questionnaire at a response rate of 89%. For Survey II, 14 out of 16 students returned the questionnaire, which made the response rate 87.5%; and 16 out of 18 students from the experimental group returned the questionnaire, which made the response rate 89%. Table 2 shows the response rate of each group.
Table 2: Survey Response Rate for the Control and Experimental Groups

<table>
<thead>
<tr>
<th></th>
<th>Control Group (16 Students)</th>
<th>Experimental Group (18 Students)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Returned</td>
<td>Response Rate</td>
</tr>
<tr>
<td>Survey I</td>
<td>16</td>
<td>100%</td>
</tr>
<tr>
<td>Survey II</td>
<td>14</td>
<td>87.5%</td>
</tr>
</tbody>
</table>

The qualitative data included questions asking students the challenges they encountered, what they liked about the experience, and comments and suggestions for future improvement of the assignment.

6.3 Data Analysis & Results

6.3.1 Video Analysis & Results

The videos were analyzed by using Studiocode to examine student group process. The video analysis results are presented in this section.

6.3.1.1 Coding Scheme

A multi-level coding scheme was developed to code the time spent on different categories when students were developing their SIPS in the ICon Lab. Figure 29 shows the coding scheme. The coding scheme examines student group communications and interactions.
The group communication portion of the scheme was adopted from a theoretical framework used in examining group communications in the design process (Stempfle et al., 2002). When used in this research, the communication categories were defined according to project related content, technical content and others. Details are in the following section:

1. Project content related communications

**Goal Clarification:** Questions, answers, or statements which clarify the goals and objectives which the group needs to achieve along with the requirements which they need to fulfill. Examples taken from the experiment include:

“So, we are doing the entire building, right? No, just one wing, one floor.”

“First we are going to figure out how long the ductile frames will take.”

“Our final goal was 4.23 days, wasn’t it?”
Solution Generation: Questions or statements which propose potential solutions or new ideas that were not proposed previously within the group’s discussion. Some solutions could be more detailed solutions of the previous ones. As long as it is not exactly the same as the previous one, it is counted as a new solution generation. These solutions can be related to meeting any of the goals within the project, including activity duration, division of work, resource utilization, or activity sequencing. Examples taken from the experiment include:

"I think we need to work around the clock”

“Are we going to put up the two walls, then put up the connecting piece?”

“Do you want to break them up into two bays a time?”

Analysis: Questions, answers or statements which clarify, explain, or develop additional information regarding a proposed solution. Examples taken from the experiment include:

- Clarification Questions for a proposed solution: For example, if a student says, “I think we should construct the walls by bays” (a Solution Generation statement), then a student may follow this with a question such as “Are we going to perform the construction by two bays or three bays?” (An Analysis question)

- Explanation of one’s solution idea when others ask questions about the idea

- Clarify the given piece of information in the assignment or in the model. For example, “There’s one crane for each wing. So for our purpose, we really only have one crane to work with.”
Calculations of durations for activities

“If we did like a bay, we almost have less than a half day per bay.”

“There will be more frames in the group C, so we need to leave more time for this group”

Hypothesis:

“So, we are going to assume 7 work days?”

**Evaluation:** Questions, answers or statements which provide or seek a value judgment related to a proposed solution or a comparison of multiple solutions. When students had different evaluations on one specific solution, even if they happened at the same time, they should be counted as two instances. Examples taken from the experiment include:

- **Questioning the proposed ideas:**
  
  For example, “Are you sure we can work on weekends?”

- **Comparison of multiple alternatives**

- **Positive evaluation:**
  
  For example, “That looks good”

- **Negative evaluation:**
  
  For example, “I would rather do it in one direction rather than going back and forth”

- **Expression of uncertainty:**
  
  “I’m not sure if we can do it in this way”
**Decision**: Statements related to conclusive decisions for or against a solution. The decision should be a final decision agreed upon by the entire group. It is noted throughout the communication that in many cases, one student will express the decision and others will silently agree. This has to be decided by looking at if the group had additional discussion about the current topic or finally executed it or not. If the group finally didn’t do it in this way, it should be an evaluation instance instead of a decision instance. An example taken from the experiment includes:

“Ok, we are going to pick this element first.” (There was not additional discussion from the group)

2. Technical communications: Questions, answers or statements which focus on the use of the technology tools and applications. Technology such as the SMART Board, Microsoft Project and 4D CAD applications (NavisWorks with Timeliner and the Deep Creator Game Engine module) were used in this experiment. Students were not familiar with the technology. Even though they were provided a brief training session before they started the experiment, they were still confronted with different technology issues when they used the tools. Students talked among themselves about these technical issues, as well as asked for assistance from the on-site technical support personnel. Communications related to these issues are categorized as technical communication. Students are not supposed to asked questions about the project. In very few cases, when some groups ask project related questions, it was counted in this category as well, since the assistant usually would not answer those questions.
3. Other: All other communications not included in the previously defined categories. For example, students may discuss unrelated topics such as the weather or unrelated course information. Note that silence was excluded from all categories so there is no categorization of silence. Natural brief silence in the flow of communication is counted into the same category of the flow.

The group interaction was also examined since the researcher observed differences in the interactions between the control groups and experimental groups in the experiment. In the coding scheme, two types of group interaction are defined as:

1. Collaborative Interaction: Mutual engagement of students in a coordinated effort to solve a problem.

2. Cooperative Interaction: Division of labor so that different people are responsible for portions of the work.

The hypothesis for this research is that a collaborative process produces a more effective group learning experience since in collaborative interaction, all members in the group focus on the same topic and all of them learn more about that topic at the same time through discussions. In cooperative learning, each individual focuses on their own task, it is an effective way to finish a task faster, but it may not allow all members in a group to achieve a maximum learning experience.

Though not shown in Figure 29, the average time of using the 3D model during the overall schedule generation time was also coded.
6.3.1.2 Reliability Test

A stability test and an inter-rater reliability test were performed to verify the video analysis results. The researcher performed a stability test by recoding the videos until she agreed with herself. Later, an inter-rater reliability test was performed to measure the extent to which coding produces the same results when the video was coded by multiple coders. A 12-minute video was randomly identified, and the researcher’s advisor and two graduate students in the construction engineering and management option coded the video. Each of them was provided basic training for using Studiocode. Then a copy of the coding scheme description was made available to them. They coded the video by referencing the description in the coding scheme. During this process, no questions related to the coding scheme were answered, and the researcher only provided technical support for using Studiocode. The coders had to code the video based on their understanding of the descriptions in the coding scheme.

When the coders finished coding the video, their video analysis results were compared with that of the researcher. A discussion was conducted to examine and resolve the discrepancies. The co-agreement level was measured by calculating the percentage of agreement between different coders. The percentage of agreement involved calculating the ratio of coding agreement durations to the total duration of the video. The agreement level is 93% on average among the 4 coders after the discussion. Figure 30 shows the extent to which the 4 coders agree with each other after the discussion.
6.3.1.3 Video Analysis Results

In this research, only the project related communications were analyzed. The content analysis results of the group communications is shown in Table 3 and Table 4. Table 3 shows the time percentages of different communication categories, and Table 4 shows frequency percentages of the different categories. Data shown in the tables are the average for five groups in the experimental and control group.

The time percentage table shows that the experimental group who used the VCS interface spent more time on clarifying their goals, generating solutions, evaluating proposed solutions and making decisions over the whole communication process. On the other hand, they spent less time in explaining proposed solutions or developing additional information in order to solve the problem. The frequency percentage table
shows that the experimental group was able to generate more solutions, evaluate them and make decisions.

Table 3: Time Percentages of Each Communication Categories

<table>
<thead>
<tr>
<th></th>
<th>Experimental Group</th>
<th>Control Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal Clarification</td>
<td>5.09%</td>
<td>4.53%</td>
</tr>
<tr>
<td>Solution Generation</td>
<td>17.84%</td>
<td>11.12%</td>
</tr>
<tr>
<td>Analysis</td>
<td>65.73%</td>
<td>79.58%</td>
</tr>
<tr>
<td>Evaluation</td>
<td>7.92%</td>
<td>3.13%</td>
</tr>
<tr>
<td>Decision</td>
<td>3.42%</td>
<td>1.64%</td>
</tr>
</tbody>
</table>

Table 4: Frequency Percentages of Each Communication Categories

<table>
<thead>
<tr>
<th></th>
<th>Experimental Group</th>
<th>Control Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal Clarification</td>
<td>6%</td>
<td>8%</td>
</tr>
<tr>
<td>Solution Generation</td>
<td>25%</td>
<td>21%</td>
</tr>
<tr>
<td>Analysis</td>
<td>46%</td>
<td>57%</td>
</tr>
<tr>
<td>Evaluation</td>
<td>14%</td>
<td>8%</td>
</tr>
<tr>
<td>Decision</td>
<td>9%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 5 shows the time percentage each group spent on collaborative and cooperative interactions. Group 1 to Group 5 is the control group and Group 6 to Group 10 is the experimental group. It was observed that three out of five groups in the control
group had cooperative interactions throughout the process. One group spent a significant amount of time using cooperative interaction (56% of the overall process). Though the other two groups did not have large amounts of cooperative interaction, it was still important to note that no cooperative interaction was observed in any of the experimental groups.

Table 5: Collaborative vs. Cooperative Interaction Time Percentages

<table>
<thead>
<tr>
<th>Group</th>
<th>Control Group (NavisWorks) (%)</th>
<th>Experimental Group (VCS) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G1</td>
<td>G2</td>
</tr>
<tr>
<td></td>
<td>Collaborative</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Cooperative</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Group Size</td>
<td>4</td>
</tr>
</tbody>
</table>

6.3.2 Quality of the Initial Schedule, Final Schedule and SIPS Assignment

Quality of the initial schedules, the final submitted schedules and the SIPS assignment were evaluated. Table 6 summarizes the results of the quality comparison between the control group and the experimental group. Since the amount of students in each group was small (16 and 18 separately), no statistical test was conducted. The average score was compared between the two groups. Based on a 30-point scale, the average score for the control group was a 20.80, and the average score for the experimental group was a 21.16. The quality of the final submitted schedule was compared between the two groups as well. Based on a 30-point scale, the average score
of the final SIPS for the control group was a 24.3, and the average score for the experimental group was a 24.5. And the SIPS assignment scores were 82.4 and 82.75 on a 100-point scale for the control and experimental group. The difference in overall quality indicated a small average improvement using the VCS.

### Table 6: Comparison of the initial schedule, Final Schedule and SIPS Assignment

<table>
<thead>
<tr>
<th></th>
<th>Control Group (Current 4D)</th>
<th>Experimental Group (VCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Schedule (30)</td>
<td>20.8</td>
<td>21.16</td>
</tr>
<tr>
<td>Final Schedule (30)</td>
<td>24.3</td>
<td>24.5</td>
</tr>
<tr>
<td>SIPS Assignment (100)</td>
<td>82.4</td>
<td>82.75</td>
</tr>
</tbody>
</table>

### 6.3.3 Survey Results

Survey I was mainly used to compare students’ perspectives of the two different applications during the experiment. The average score was calculated for each survey question for both groups and was summarized in the following Table 7. Though there were 8 (<30) groups of paired data, the difference of the means between the two groups was tested and might come from a normal distribution. So a paired T-test was conducted by using Minitab to test the significance level of the difference of the average scores of the two groups. The hypothesis was that the average score of the experimental group was higher than that of the control group. At a significance level of 5%, the T-value=0.011<1.98 (critical value at significance level of 5%). So the hypothesis
could not be rejected, and the average score of the experimental group was higher than that of a control group, and the difference was significant.

Table 7: Summary of Survey I Results

<table>
<thead>
<tr>
<th>Survey Questions</th>
<th>NavisWorks</th>
<th>VCS</th>
<th>Difference (VCS-NW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. It was valuable to have a large scale 3D model when developing our schedule</td>
<td>4.13</td>
<td>4.69</td>
<td>0.56</td>
</tr>
<tr>
<td>2. Our group adequately utilized the 3D model when developing our schedule</td>
<td>3.31</td>
<td>4.19</td>
<td>0.88</td>
</tr>
<tr>
<td>3. The 3D model helped me in generating ideas and evaluating other people’s ideas</td>
<td>3.81</td>
<td>4.31</td>
<td>0.50</td>
</tr>
<tr>
<td>4. The 3D model provided a common media to keep the whole group focused throughout the process of developing the schedule</td>
<td>3.94</td>
<td>4.25</td>
<td>0.31</td>
</tr>
<tr>
<td>5. The 4D model made it easier for me to communicate with my team members when we worked on the assignment.</td>
<td>4.14</td>
<td>4.25</td>
<td>0.11</td>
</tr>
<tr>
<td>6. The 4D model in the ICon Lab was helpful for examining the schedule we developed.</td>
<td>4.56</td>
<td>4.44</td>
<td>-0.13</td>
</tr>
<tr>
<td>7. I felt more confident in our schedule after reviewing the 4D model.</td>
<td>4.06</td>
<td>4.00</td>
<td>-0.06</td>
</tr>
<tr>
<td>8. The 4D modeling activity helped me gain a better understanding of the SIPS process.</td>
<td>4.06</td>
<td>3.94</td>
<td>-0.13</td>
</tr>
</tbody>
</table>

Some detailed results from Survey I are included in the following figures. These results show that students using the VCS (experimental group) feel that the 3D model is more valuable (Figure 31) and fully utilized (Figure 32) in helping them develop the
schedule than students using the traditional 4D interface. A much larger percentage of students in the experimental group stated that the 3D model helped them generate ideas and evaluate other group members’ ideas (Figure 33), improved the team communication (Figure 34) and kept student group members focused on the same topic (Figure 35). These two interfaces have similar effects in making students feel confident about their initial schedules (Figure 36), and helping them examine their schedules (Figure 37). And, students using the VCS enjoyed their experience more than students using the traditional 4D CAD interface (Figure 38). Overall, comparison of students’ perceptions between these two groups shows that the VCS had additional values in helping them generate a construction schedule and enjoying the experience.

![3D Model Value](image)

**Figure 31:** Comparison of the 3D Model Value
Our group adequately utilized the 3D model when developing our schedule.

Figure 32: Comparison of the 3D Model Utilization

The 3D model helped me in generating ideas and evaluating other people’s ideas.

Figure 33: Comparison of Idea Generation
The 4D model made it easier for me to communicate with my team members.

Figure 34: Comparison of the Group Communication

The 3D model provided a common media to keep the group focused throughout the schedule development.

Figure 35: Comparison of the Group Common Focus
I felt confident in the initial schedule that we developed before reviewing the 4D model in the ICon Lab.

Figure 36: Comparison of the Initial Confidence

The 4D model in the ICon Lab was helpful for examining the schedule we developed.

Figure 37: Comparison of effectiveness of the Schedule Review
Figure 38: Comparison of the Extent Students Enjoyed the Schedule Development Process

Survey II was used to investigate the value of the 4D model in aiding student presentations and in class discussions. Since students in both groups finished their final 4D model using NavisWorks following the experiment and developed it into a video file, they were using the same tool for the presentations and discussions. So there was no comparison between the two groups. Figure 39, Figure 40 and Figure 41 show that 4D modeling was considered a very effective tool in helping students present their solutions, understand alternatives, and understand the overall SIPS planning process.

Figure 39: Ease of Presenting Solutions
Students also provided some additional comments, showing they were in favor of using 4D CAD in presentations and discussions. Some quotes from the students include:

- “It (4D modeling) is a good learning tool and made understanding of other people’s ideas easier.”
• “Good to see other approaches to the same problem and the actual solution.”
• “Really found it helpful to see all the different models. It demonstrated many issues about the construction that our team did not initially think about.”

6.3.4 Summary of the Experiment Results

4D learning modules using two different 4D processes were compared in the experiment. The VCS showed additional value beyond the current 4D CAD application. When comparing the commercial 4D modeling module to the VCS module, it was noted that:

1. The video analysis results showed that the experimental group who used the VCS spent more time on generating solutions, evaluating proposed solutions and making decisions throughout the entire communication process. On the other hand, they spent less time in explaining proposed solutions or develop additional information to solve the problem. Though there was no established theory to assess the effectiveness of the group process based on the communication categories used in this research, the researcher felt that the experimental group had more effective group communications than the control group in the problem solving process based on her experience of observing 10 student group communications.
2. Both the quality of the initial schedule and the final schedule developed using the VCS interface were slightly higher than using a traditional 4D modeling application. Though the differences were small, it was important that students could develop a higher quality construction schedule at the beginning of the project.

3. Significant differences were found in student perceptions towards these two applications. Students using the VCS interface felt that they were able to generate more solution ideas, focused on the common topic more easily with other group members, and had better communications with their group members. It was important that the VCS groups enjoyed this experience more than the groups using the current 4D application. They had more fun when performing the exercise using the VCS, and achieved the same or higher quality schedules.
Chapter 7
Conclusions

This chapter first provides a summary of this research. Then, it introduces the contributions and limitations of this research. A discussion of future research in the application of 4D learning modules in construction engineering education is presented. Finally, concluding remarks are provided.

7.1 Research Summary

This research aimed to investigate the effectiveness of 4D modeling used in construction engineering education for schedule visualization. A longitudinal study was conducted to examine the value of 4D learning modules in aiding students to develop a construction schedule.

At the outset of this research, an exploratory study was performed to investigate the value of a preliminary 4D learning module developed using a current 4D modeling application (NavisWorks with Timeliner). An initial assessment plan was used to evaluate the value of the preliminary learning module. The preliminary learning module improved the schedule quality, enabled interactive schedule presentation and discussion, and was deemed by the students as a beneficial and engaging tool.

Later, a VCS prototype application was developed, which advanced the current 4D model generation process by allowing the generation of a 4D model and a
construction schedule by directly interacting with a 3D model. An experiment was conducted to examine the value of the VCS prototype by comparing it with the current 4D modeling process. The experiment results showed that the VCS helped students develop a slightly higher quality schedule on average, and students enjoyed the learning experience more using this application compared to the current 4D modeling process.

Therefore, both 4D learning modules are an effective learning aid for schedule visualization in engineering education, and the VCS 4D modeling process has additional values beyond the current 4D modeling generation process.

7.2 Research Contributions

Various contributions of this research are discussed below.

7.2.1 Identification of the Value of 4D Learning Modules in Engineering Education

While there are an increasing number of successful applications of 4D modeling in the AEC Industry, its implementation in engineering education is currently limited. This research implemented this visualization tool in construction engineering education and conducted quantitative and qualitative assessment to identify its value in engineering education. At the same time, an assessment plan was identified to evaluate the effectiveness of 4D learning modules.
7.2.2 Advancement of the Current 4D Model Generation Process

The current 4D modeling process mainly functions as a schedule review tool. It still requires a person to generate a CPM schedule first. The current method of using a CPM application for generating the schedule limits the utility of the 3D model during the planning process since the planners need to first create the activities mentally, and later link them to their related 3D components in a 4D modeling application. From the experiment, it was found that the average 3D model use was 21% during the overall schedule generation time when using the current 4D model generation process.

The developed VCS is a schedule generation and review tool. It allows the generation of a 4D model and a construction schedule by directly interacting with a 3D model. It eliminates both the mental linking process, and the manual linking process of 3D model objects and schedule activities. This process makes it possible to better utilize the 3D model. From the experiment, we found an average 3D model use was 75% during the overall schedule generation time when using the VCS 4D generation process.

7.2.3 Time Study of Group Communications for Two Different 4D Generation Processes

A content analysis was conducted to analyze the student group communications for each recorded video. The time percentages of different types of communications (goal clarification, solution generation, analysis, evaluation, and decision) were documented for both 4D generation processes when students were planning the
construction process and generating a schedule. Though there was no established theory to evaluate the effectiveness of the group communication based on the communication categories used in this research, the documentations of the time percentages of different communication categories for this case study has started to build a knowledge base for future research in this area.

7.3 Limitations

The limitations of the research are described in this section.

7.3.1 Limited Case Study Application

This research presents the results from the study performed on one case study project. There is little research in this area, so the researcher conducted an exploratory study on one detailed case study before implementing a large scale investigation. The case study selected may be an inadequate representation of diversity. Different case studies may result in different results. Therefore, the findings from this single case study may not be generalized.

Another limitation of this case study was that the 4D module was developed when the research started. Since we wanted all the students to have the opportunity to work on their schedule using the 4D learning module, there was no chance to compare the group process between the more traditional paper-based scheduling process and 4D scheduling process.
7.3.2 VCS Prototype Limitations

The developed VCS prototype has several limitations:

- Each object in the 3D model has to be coded to achieve all the required functions. This limited the large scale implementation of the VCS due to the time needed to develop larger simulation.

- User entered data was stored in a SQL database. Users needed to check the database from time to time to retrieve needed information, and the SQL database interface is not very user friendly.

- The user interface had some limitations due to the game engine implementation.

At the same time, these limitations increased the time spent on technical communications.

7.4 Future Research

Suggestions for future research related to the use of 4D modeling in engineering education are presented in this section.

7.4.1 An Improved VCS

To make the interface more valuable and smooth, the VCS needs to be improved:

- Other 3D game engines, which can define a global parameter for all objects in the 3D model, could be used to develop a similar application, so
that there is no need to code each single object in the model and make large scale implementation easier;

- Use a more user friendly database for the application, so that students can easily manipulate the interface without onsite technical support;
- Find a way to map the construction schedule from the database to Microsoft Project directly;
- Automate the sequencing process. The current sequencing process is to find the successor of a current activity. An improved VCS could make this process automatic by sequencing activities automatically according to the order in which they were selected.
- Add resource components into the VCS, such as crews and cranes, so that students can pick the resources from the module and assign the resources to specific construction tasks. This could then allow for the visualization of the resource loading.

7.4.2 Paper-based Scheduling Process Communication

This research compares the group process of using two different 4D interfaces. It would be valuable to obtain the paper-based scheduling process data as a baseline. In the case study project used in this research, we intended to have all students try the 4D learning module, so there was no paper based group process data. Other courses that have scheduling assignment but do not use a 4D learning module yet, could be considered as candidates to measure the paper-based group process data.
7.4.3 Effect of the 3-Screen Display System

The 3-screen display system provides students a one to one large scale model, which makes students have the feeling of presence of a real construction site. The effect of the large 3-screen display system vs. desktop monitor on student group process could be investigated.

7.4.4 Construction Plan Communication

From the video analysis, the time percentages of different communication categories defined in the coding scheme were obtained. But currently there is no established theory existing to measure the effectiveness of the communications by looking at the percentage of these communication categories. We need to develop a more detailed understanding of construction plan communication and we still have much to learn in this area.

7.4.5 Implementation of the VCS on Complex Projects

In this research, the VCS was used on a relatively simple project, and no significant differences were found when comparing the developed construction schedule quality. Currently the developed VCS limited large scale implementation since each object in the 3D model has to be coded to achieve all the required functions. If this limitation is addressed and the VCS is implemented on a more complex project, bigger differences in schedule quality may be observed.
7.5 Concluding Remarks

Students in engineering disciplines usually work in small groups to solve problems. When students are solving their problems, instructors usually are not present, which makes it difficult to coach student group problem solving competences. Visualization technology enables students to walk through a construction projects and obtain a better understanding of the building system. It provides a common language, which can help students achieve better communication. 4D modeling also allows students to experience the dynamic nature of the construction by showing the progress of a construction project. 4D modeling is a valuable tool to aid students in their problem solving process and is important for supporting their learning. More 4D learning modules could be created to aid engineering students to learn engineering concept.
Bibliography


Camp, G. (1996). "Problem-Based Learning: A Paradigm Shift or a Passing Fad?"


Smith, S. (2001). "4D CAD Goes Beyond Mere Representation, "4D is far ahead of where most of the construction industry is willing to think"-Dr. Joel Orr."


### MGM Grand Hotel SIPS
#### Assignment 2

**Student(s):**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Definition of Excellence</th>
<th>Score (0 to 1)</th>
<th>Weight (0 to 100)</th>
<th>Total</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zones Identified</td>
<td>Logic separation of zones&lt;br&gt;Clearly noted on plan</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activities defined</td>
<td>Logic breakdown&lt;br&gt;Includes activity, production quantities &amp; time&lt;br&gt;Clearly presented&lt;br&gt;Logic production rates</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIPS for Typ Wing</td>
<td>Appropriate level of detail&lt;br&gt;Logical flow and sequence&lt;br&gt;Considers resource constr&lt;br&gt;Considers other project factors</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4D Presentation</td>
<td>Clearly illustrates you plan&lt;br&gt;Professional presentation</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-30 Activity Schedule</td>
<td>Clearly shows building flow&lt;br&gt;Logical breakdown of building</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discussion Questions</td>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Written Document/Professional Presentation</td>
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</tbody>
</table>
## Appendix B

### Schedule Evaluation Sheet

<table>
<thead>
<tr>
<th>Evaluation Parameters</th>
<th>Weight</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correctness</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Completeness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reasonable Duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logic Sequence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goodness</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Minimized Critical Path</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smooth Work Flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Creativeness</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Creative Sequence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
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</tr>
</tbody>
</table>

### MGM Grand Hotel Schedule Evaluation Sheet

<table>
<thead>
<tr>
<th>Evaluation Parameters</th>
<th>Weight</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correctness</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Completeness</td>
<td></td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>Creative Sequence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Correctness**: Have all required activities with appropriate level.
- **Completeness**: Durations should be based on logic production rate.
- **Reasonable Duration**: Ductile frames go before the floor planks. A wall sits between two adjacent floor plank bays, so the wall should go after both bays finish. All grout should occur at once. Grout cannot go over night. Start from the core toward outside.
- **Goodness**: More concurrent activities with consideration of available space. No overcrowding.
- **Minimized Critical Path**: No possible discontinuity of the work flow due to worker or equipment availability or too small work zones. Crane logistic—not too many crane activities at one time. Consider productivity—if break the whole floor into 12 single bays and finish each bay separately, the productivity will be poor.
- **Safety**: No potential safety issues.
- **Creativeness**: Creative Sequence.
Appendix C
AE473 SIPS Exercise Survey I

This survey is conducted for the sole purpose of research and the data collected will be kept confidential. Please give your comments and provide your responses on a scale of 1-5 (1- strongly disagree and 5- strongly agree). Thank you for your time and cooperation!

1. It was valuable to have a large scale 3D model when developing our schedule.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Disagree</td>
<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

2. The 3D model was adequately detailed to perform this exercise.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
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<th>5</th>
</tr>
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<tbody>
<tr>
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<td>Disagree</td>
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<td>Agree</td>
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</tr>
</tbody>
</table>

3. Our group adequately utilized the 3D model when developing our schedule.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
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<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

4. The 3D model helped me in generating ideas and evaluating other people’s ideas.

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<thead>
<tr>
<th>1</th>
<th>2</th>
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<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>
5. The 3D model provided a common media to keep the whole group focused throughout the process of developing the schedule.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

6. I felt confident in the initial schedule that we developed before reviewing the 4D model in the ICon Lab.

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<thead>
<tr>
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<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

7. The 4D model in the ICon Lab was helpful for examining the schedule we developed.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

8. I felt more confident in our schedule after reviewing the 4D model.

<table>
<thead>
<tr>
<th>1</th>
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<th>5</th>
</tr>
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<tbody>
<tr>
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<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

9. The 4D modeling activity helped me gain a better understanding of the SIPS process.

<table>
<thead>
<tr>
<th>1</th>
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<th>5</th>
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<tbody>
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<td>Disagree</td>
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<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

10. I enjoyed performing the exercise in the ICon Lab.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
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<th>5</th>
</tr>
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<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>
11. What challenges did you have when you performing this exercise?

________________________________________________________________________

________________________________________________________________________

12. What did you like about the SIPS activity in the ICon Lab?

________________________________________________________________________

________________________________________________________________________

13. What additional items would you like to see included in the model or the SIPS exercise?

________________________________________________________________________

________________________________________________________________________

14. Please provide any additional comments.

________________________________________________________________________

________________________________________________________________________
Appendix D

AE473 SIPS Exercise Survey II

AE473 SIPS Exercise Survey II

Team #:_____ Name

______________

This survey is conducted for the sole purpose of research and the data collected will be kept confidential. Please give your comments and provide your responses on a scale of 1-5 (1- strongly disagree and 5- strongly agree). Thank you for your time and cooperation!

15. The 4D model made it easier for us to present our group’s solution to other students in the class.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<th>4</th>
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<tbody>
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<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

16. The 4D model made it easier for me to understand other groups’ solutions.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<th>4</th>
<th>5</th>
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<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

17. The 4D model made it easier for me to understand the SIPS planning issues discussed in class.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
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<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

18. The 4D model made it easier for me to communicate with my team members when we worked on the assignment.
<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
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<td>Agree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

19. Additional comments about the presentations and in class discussions?

_______________________________________

_______________________________________

_______________________________________